

Photonic Directional Coupler for Beamsplitter and Optical MEMS Switch Applications

Silicon nitride photonics: design, fabrication and characterization for quantum applications at visible wavelengths.

Quantum Integration Technology group
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by

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Preface

This thesis is submitted in partial fulfillment of the requirements for the Master of Science degree in Microelectronics at the Faculty of Electrical Engineering, Mathematics, and Computer Science at Delft University of Technology. This research aims to design, fabricate, and characterize photonic directional couplers for beamsplitter and optical MEMS switch applications in the visible spectrum.

I would like to express my deepest gratitude to my supervisor, Dr. Ryoichi Ishihara, for the opportunity to join the QIT research group, for entrusting me with a research topic of significant impact, and for providing the necessary support to successfully complete this project. I am also immensely grateful to Dr. Carlos Errando Herranz for his guidance, invaluable advice, and consistent feedback throughout all stages of this project. Special thanks go to my daily supervisor, Maurice van der Maas, whose constant assistance and support were crucial to the completion of this work.

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As a user of Kavli Nanolab, I appreciate the support and training provided by the staff members throughout my fabrication process. Additionally, I thank all the members of the QIT group for making this year's experience more interesting.

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*Maria Eleftheriadi
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Abstract

Quantum computing promises revolutionary advancements in computational power by leveraging quantum mechanical phenomena such as superposition and entanglement. Diamond color centers have emerged as promising candidates for quantum information processing due to their long coherence times and scalability. Photonic integrated circuits (PICs), represent a mature technology that facilitates on-chip quantum operations in a compact and scalable manner. In quantum applications, PICs play a crucial role in routing and manipulating quantum information.

The transition to the "More than Moore era," following the plateauing of Moore's law, has highlighted the importance of MEMS (Micro-Electro-Mechanical Systems) technology for continued advancements in electronics. Integrating MEMS with PICs and quantum applications, due to its high performance and mass production capabilities, offers a promising avenue for large-scale device integration and multi-qubit systems.

Designing photonic devices for integration with diamond color-center qubits presents several challenges. Primarily, designing photonic devices for the visible spectrum involves challenges related to device feature sizes approaching the limits of fabrication resolution. Additional challenges include ensuring scalability in quantum computing and compatibility with complementary metal-oxide semiconductor (CMOS) electronics. This requires devices that operate with low power consumption, low actuation voltage, and minimal crosstalk, necessitating significant optimization of MEMS components. Furthermore, integrating MEMS devices demands careful consideration of the mechanical properties of the materials and the designed structures.

This project discusses the design, fabrication, and characterization of a photonic directional coupler for use in beamsplitter and optical MEMS switch configurations in the visible spectrum. The photonic beamsplitter is essential for the controlled manipulation of quantum states, crucial for executing quantum algorithms. The optical MEMS switch provides dynamic control over optical pathways, leveraging the advantages of photonics and MEMS technology. The goal of this project is to optimize the directional coupler design for footprint, and fabrication accuracy, and to propose a directional coupler-based optical MEMS switch design that features low actuation voltage and high extinction ratio. Additionally, this project aims to establish the process recipes for fabricating the designed directional couplers and MEMS components, with particular attention to the physical resolution of small feature sizes, and to evaluate the extent to which the designed performance is achieved. By addressing these topics, the project aims to contribute to the large-scale integration of diamond color center qubits for quantum computing applications.

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Introduction

1.1. Background and motivation

1.1.1. Quantum computing and diamond defect centers

The ongoing need for higher processing speed in current and future electronics continues to drive the information and semiconductor industry toward novel technologies. This natural need combined with the plateauing of Moore's law [1], underscores the necessity to explore new alternative concepts that could invigorate progress in this ever-evolving landscape. Quantum computing and Quantum Information Processing (QIP), fields that utilize the principles of quantum mechanics for information processing tasks, emerge as highly promising solutions for achieving the goal of advancing information processing capabilities. Specifically, quantum computers, as compared to classical computers, can offer an increase in memory and processing capacity, achieving an exponential speeding up of certain information processing algorithms with significant technological impact [2, 3]. What is more, quantum computers can realize tasks that have no physical counterparts like quantum cryptography which can set new benchmarks for security in computing [3].

However, as with any novel concept, quantum computing presents numerous challenges and requirements that need to be fulfilled to fully harness its potential advantages. Primarily, the core of quantum computing hardware relies on the manipulation of quantum systems in a controlled and coherent manner. In practice, this means that the quantum hardware should allow for the on-demand generation of entanglement, a key concept that sets quantum computers apart from their classical counterparts and is essential for various quantum algorithms and protocols [4]. At the same time, the quantum hardware should be capable of protecting the generated states from decoherence, to ensure reliable performance of quantum computations [5, 6]. Maintaining qubit coherence is crucial for preserving the quantum nature-related performance characteristics of a quantum system and mainly lies in minimizing the interactions with the environment [2].

The complexity of the challenges increases especially when scaling up quantum computers, which is essential for actually outperforming classical computers. In a multi-qubit quantum system, the precise addressing of individual qubits becomes significantly harder due to crosstalk which emerges as a major source of error-rate increase in QIP [2]. Additionally, the transition towards on-chip large-scale quantum computers requires hardware scalability which is basically expressed as the ability to build compact arrays of qubits interconnected in an effective way. This requirement involves a significant number of factors that need to be taken into account, like the type of qubits and connection links, their spatial distribution on the chip, as well as the compatibility of the materials and fabrication methods with cryogenic temperatures [7].

Solid-state spin qubits, based on the spin properties of particles in solid materials like silicon (Si), silicon carbide (SiC), diamond, gallium arsenide (GaAs), and indium arsenide (InAs), are among the most promising platforms for quantum computing. This type of qubits is especially favorable in terms of coherence times and scalability [7]. Among these, diamond defect centers have gained significant attention in recent years. Diamond defect centers, also known as diamond color centers, are localized defects in the crystal lattice formed by impurity atoms adjacent to vacancies. Diamond defect centers offer various advantages that position them as the optimal choice for the realization of a scalable quan-

tum computer system. Primarily, diamond color center qubits, especially nitrogen-vacancy (NV) and tin-vacancy (SnV) centers feature a weak electron-phonon coupling, which results in long coherence times, even at room temperature, a property crucial for error-resistant implementation of quantum algorithms [5, 8]. Moreover, the utilization of these solid-state qubits is favored by the significant advances in diamond fabrication methods in recent years. Diamond is already a well-studied material with mature high-quality single-crystal growth techniques enabled by the progress in chemical-vapor deposition (CVD), making large-scale device integration feasible [7, 9, 10]. An additional key advantage towards the implementation of scalable quantum systems is the optical addressability of diamond color center qubits. The electron spin of the negatively charged NV and SnV centers can be initialized via optical pumping and optically read out based on the emitted fluorescence [11, 12], utilizing the high-fidelity and efficient qubit manipulation and measurement offered by the robust optical interface and the mature photonics technology, comparing to conventional microwave techniques [10, 13].

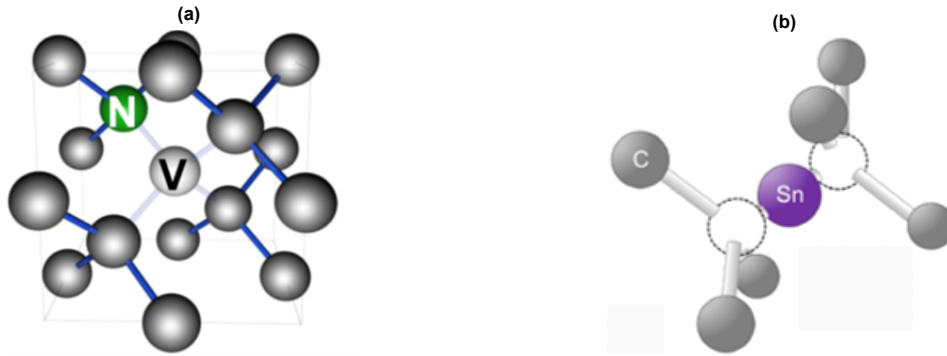


Figure 1.1: Structure of the (a) NV center [14], (b) SnV center [15] in the diamond lattice.

Among the various defect centers in diamond, NV centers are the naturally occurring defects that appear with the greatest abundance in the diamond lattice, as compared with silicon- or tin-related diamond color centers [5]. As their name suggests, a diamond NV center consists of a substitutional nitrogen atom adjacent to a carbon vacancy [7], as illustrated in Figure 1.1a. The ground state of the negatively charged NV center constitutes a spin triplet featuring three possible electron spin states, which serve as a qubit and can be manipulated by an external magnetic field allowing for performing quantum operations [16]. The transition of the NV center into the excited state can be performed via resonant optical excitation, at 637 nm, marking the Zero-Phonon Line (ZPL). However, charge noise causes the majority of photon emission to be incoherent with the ZPL of the NV center accounting for only 4% of the emitted light resulting in a limited entanglement rate and thus limited scalability prospects [8, 12, 17, 18]. This significant disadvantage has recently motivated the exploration of other diamond color centers, among which the SnV center features a 30% probability of emitting in its sharp ZPL, typically observed at 620 nm [15, 17]. SnV centers belong to group-IV color centers (comprising of a group-IV impurity atom adjacent to a vacancy in the diamond lattice, as illustrated in Figure 1.1b) [15] and they are impurities typically artificially introduced into the diamond lattice [17]. The highly coherent emission SnV centers feature and their high quantum efficiency, compared to NV centers render them a promising alternative to NV centers towards the realization of scalable quantum computing. [15].

In a photon-based scheme leveraging the optical addressability of diamond color centers, qubits are entangled using optical links [9]. On-chip optical connections realized by integrated photonics technology, present significant advantages in terms of loss and scalability when compared to free-space optical systems, enabling the compact design of large qubit arrays or modular architectures efficiently distributed on the chip [7]. Moreover, the integration of the quantum system with a Photonic Integrated Circuit (PIC) offers high-fidelity qubit operations with a low error rate owing to low losses and cross-talk. The nature of the optical signals that are guided well-confined in photonic waveguides allows for minimizing interference between adjacent channels compared to microwave signals with electromagnetic field distributions that are poorly confined in conventional planar microwave waveguiding structures. Lastly, the compatibility of PICs with cryogenic temperatures (typically below 4 K) as well as with Complementary Metal-Oxide Semiconductor (CMOS) technology is of great significance since it facilitates the 3D integration of the quantum system and the photonic circuit with the CMOS electronics in a

compact way, as seen in Figure 1.2.

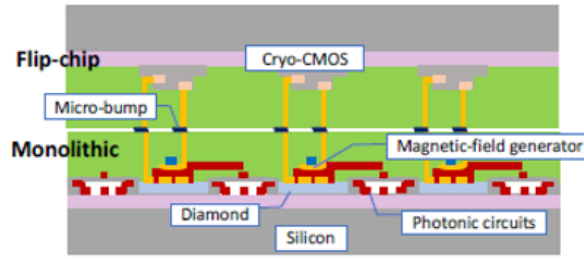


Figure 1.2: 3D integration of quantum computer chip with diamond color centers [9].

1.1.2. Photonic platform

The photon-related nature of the diamond color centers-based quantum system necessitates special consideration of the photonic platform. This platform is designed to accommodate the devices that manage the communication and manipulation of qubits realized through routing, manipulating, and detecting the photons emitted via the optical excitation of color centers. As previously mentioned, the emission spectrum of the color centers spans the upper bounds of the visible spectrum to the near-infrared (NIR) range. Specifically, the emission spectrum of NV-centers ranges from approximately 600 nm up to 800 nm, with a peak at a narrow band around the ZPL wavelength 637 nm [5, 19], which is the only band that can be utilized for efficient quantum operations, since the phonon interaction that comes with the photons in the rest of the NV centers' emission spectrum (phonon side-band, PSB) degrades the spin-photon entanglement [20]. The narrow emission band of SnV centers, with a sharp peak at 620 nm falls as well into the visible range emphasizing the importance of PIC design for these wavelengths.

Although impressive progress has been made in PIC technology to serve the optical communications industry with integrated photonic devices functioning at the telecommunication wavelengths at the NIR range, comparatively less emphasis has been placed on the development of visible-light PICs. Implementing high-performance photonic devices designed for visible-light applications and especially intended for large-scale quantum computing systems entails several challenges. Specifically, a major challenge limiting the performance of visible-range PICs is the propagation loss light experiences while being routed on the chip, which is inherently higher at shorter wavelengths [21]. This requirement is especially significant in the context of quantum applications, as increased losses result in a decreased entanglement rate. Furthermore, realizing a scalable system requires photonic devices that can be fabricated with the standard process flows. Additionally, the broad range of operations that should be compactly integrated on a single chip should be supported by a set of fundamental photonic components maintaining compatibility with cryogenic environments, CMOS technology, and performance-intensive applications. Meeting all these requirements hinges upon the selection of a suitable material platform that optimally fulfills the set criteria. Silicon nitride (Si_3N_4 , SiN) is a mature, versatile material well-suited for this purpose, displaying a large transparency window that extends into the range of interest. SiN is compatible with the common fabrication processes and exhibits excellent optical properties compared to alternative materials also transparent in the visible spectrum, achieving high confinement and hence low losses and high-density integration [21–23].

One of the most fundamental quantum operations implemented for QIP purposes and hosted on the photonic platform is entanglement. Qubit entanglement enables the execution of Bell State Measurements (BSM) that are essential in QIP. Within the framework of the photon-based quantum scheme that supports the diamond color center qubits, the generation of entanglement is achieved through a beamsplitter [7], as illustrated in Figure 1.3a. The beamsplitter is a fundamental photonic device and its design follows the design considerations set for the photonic platform. There are several beamsplitter PIC-compatible implementations deployed for QIP tasks, with the most researched being the directional coupler, the Y-branch, and the multi-mode interferometer (MMI). However, the directional coupler is the most suitable implementation for operation with single-mode waveguides, avoiding losses associated with higher-order mode coupling [24]. Further details elucidating the operation of this device are provided in the subsequent chapter.

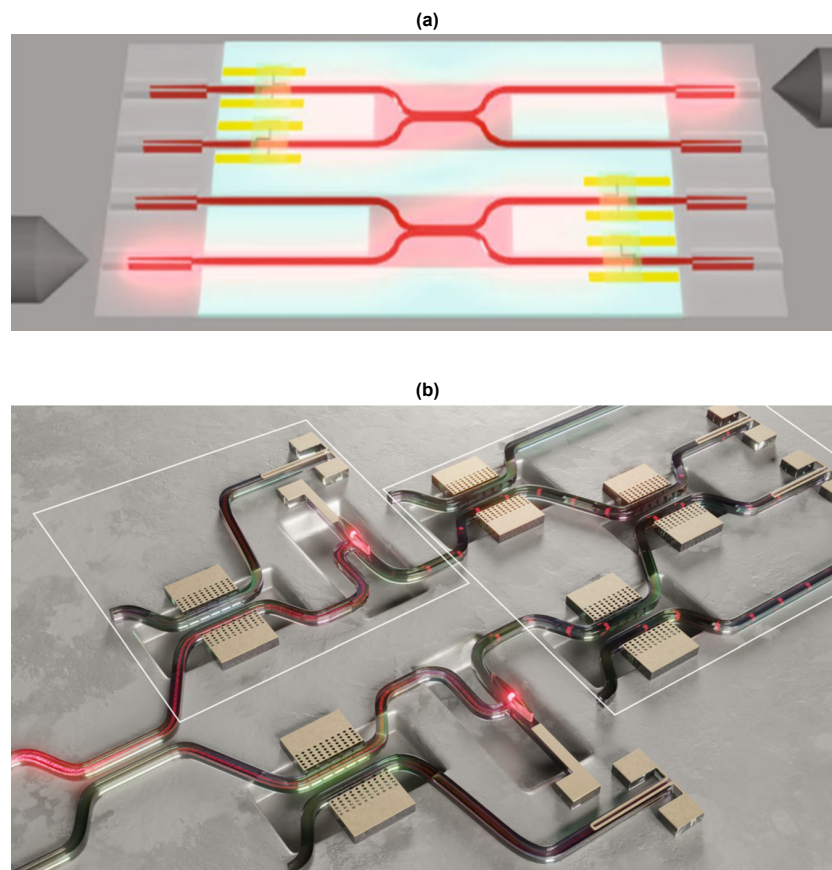


Figure 1.3: Schematic of (a) PIC architecture with integrated beamsplitters for on-chip entanglement [7]. (b) photonic circuit for quantum applications including MEMS tunable components [25].

In addition to QIP-related tasks, the photonic platform should perform a number of standard operations on the optical signal, acting as an interface between the quantum hardware and the conventional electronics. This is facilitated by the photonics-CMOS compatibility and is implemented in practice utilizing the concept of 3D integration, which enables the large-scale integration of qubits with the photonic circuit and the CMOS electronics on a single chip [9], increasing the integration density and mitigating the interconnect crowding while preserving the performance characteristics [26]. In this context, the need for communication between the electronic control signal and the quantum-photonic platform is where the critical role of the photonic switch emerges. Since the invention of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), switches have been the fundamental components in analog and digital electronics, enabling the control signal to coordinate the operation of the whole circuit. These control signals, in their essence, represent the fundamental form of information that the rest of the hardware components should be able to process and operate accordingly. The generation of digital electronic signals, typically represented as a sequence of bits, is the result of the binary switching activity - either on or off. This activity is also essential in PICs in which traditional MOSFET switches are most commonly replaced by photonic modulators capable of modulating the light wave amplitude based on an on-off keying scheme [27], or by space switches redirecting the light to the desired output port to achieve similar on-off functionality [25, 28]. The present report studies the implementation of a photonic MEMS switch, like the one illustrated in Figure 1.3b, which assumes a crucial role by allowing the electronic control signal to dictate quantum operations, effectively enabling the co-integration of CMOS electronic circuitry with the quantum computing hardware.

1.1.3. MEMS technology and switching

In the context of regenerating progress in the electronics industry, which is facing the plateauing of Moore's law, Micro-Electro-Mechanical Systems (MEMS) have emerged as a revolutionary technology that, aligning with the "More than Moore" concept, has offered significant prospects for CMOS technology [1]. MEMS technology, also known as Micro-Systems technology (MST), encompasses devices at the μm -scale that comprise both electrical and mechanically moving components. In these devices, motion is provided by the electric signal via a variety of actuation mechanisms which can be electrostatic, electromagnetic, electrothermal, or piezoelectric [29]. The most significant aspect of MEMS technology lies in its reliance on mature fabrication methods fundamental to standard semiconductor device fabrication and batch processing, making it suitable for scalable and low-cost mass manufacturing [30, 31]. MEMS technology is already mature and MEMS devices with high performance in terms of power dissipation, speed, and footprint are already widely commercialized in sensors technology [29–31]. The integration of optical MEMS in telecommunication PICs has arisen as a natural progression to meet the ever-increasing demand for optical network capacity that necessitates the realization of all-optical, large-port-count switches of compact size and low power consumption [31]. Especially optical MEMS devices have demonstrated the ability to meet the rigorous component reliability standards enduring high-temperature aging, humidity storage, thermal and mechanical shock, and vibration [32]. This progress in telecommunication extends to other fields where MEMS for PICs can be leveraged, among which quantum computing hardware is of particular interest in this report.

In the present report, optical MEMS technology is utilized to implement the photonic switch. There are multiple advantages in terms of switching performance, footprint, power consumption, and loss offered by this switching scheme that make optical MEMS switches distinct from other PIC-compatible switching mechanisms, namely, electro-optic (EO) and thermo-optic (TO) switches [33–35], as illustrated in Figure 1.4. Especially in terms of power dissipation, MEMS in PICs significantly outperform TO switching mechanisms mainly owing to the possibility for electrostatic actuation which is capacitor-driven and inherently dissipates very low power, as well as the concept of non-volatility which is summarized in requiring no power for preserving the state once the device is switched [36]. Additionally, MEMS switches can be engineered to feature switching times smaller than $1\ \mu\text{s}$ [37–41] and extinction ratio higher than 60 dB [37, 42–44] reaching even up to 80 dB [45]. This represents a substantial performance improvement over EO options, which despite their fast response, typically have lower extinction ratios [30]. Regarding footprint, high-performance MEMS switching cells can be smaller than $2.5\ \text{mm}^2$ [46, 47] reaching down to $125\ \mu\text{m}^2$ [48], competing well with the electro-optic switches that are generally at the millimeter scale. Another important performance parameter of the photonic switch is the insertion loss which has been widely reported to be lower than 1 dB per switching cell [37, 41–43, 46–57]. Other switching mechanisms, like acousto-optic, magneto-optic, or liquid crystal switches, are not analyzed as their operation relies on materials and structures that are challenging to integrate with the standard process flow and are not scalable. It is noted that the comparison cases mentioned above refer to 1×1 , 1×2 , or 2×2 unit switching cells, which will also be the focus of this report, as large-port-count switches are not relevant at this initial stage of this research.

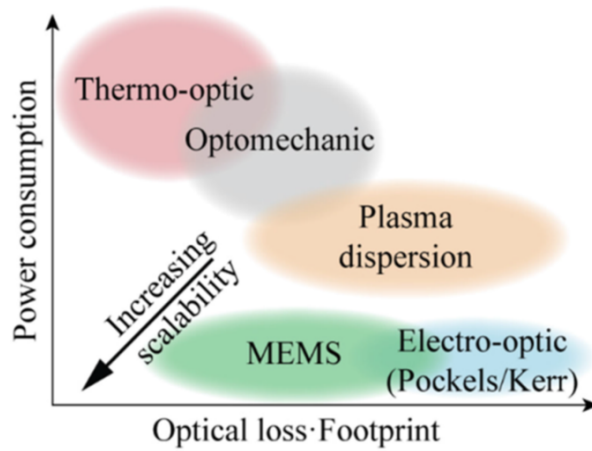


Figure 1.4: Comparison of the available PIC-compatible switching mechanisms in terms of scalability [33].

The low insertion losses exhibited by optical MEMS switches are particularly crucial for their implementation in large-scale quantum computing applications. As previously mentioned, in a photon-based quantum computer scheme it is vital to integrate photonic components that can perform the quantum operations without introducing excessive losses which dramatically increase the error rate, hindering scaling up to a larger number of qubits. In the same context, the high extinction ratio achieved by optical MEMS switches, which translates into low crosstalk, prevents decoherence and maintains low error rates. Furthermore, it is noted that MEMS technology is compatible with cryogenic operation and optical MEMS switches have already been implemented in quantum applications [25]. This characteristic sets MEMS switches apart from TO tuning mechanisms that are inherently unsuitable for operation in cryogenic environments since their functionality relies on temperature-dependent switching with local heating to typical temperatures ($\sim 50^\circ \text{C}$) that are far outside the cryogenic range [58].

At this point, it is meaningful to highlight EO switches, which has been a mature and reliable solution when it comes to PICs-compatible tuning mechanisms for many years. These switches typically utilize two phase-shifting paths forming a Mach-Zehnder Interferometer (MZI) that converts the phase shifting into amplitude modulation between on- and off- states, thus achieving switching [28]. The phase shifting is based on the EO effect which results in the change of the refractive index of the EO material, and consequently the change of the effective refractive index of the optical wave that propagates in it, in the presence of an electric field [28]. The advantage of this technology over MEMS lies in the simplicity of the design and fabrication process steps. Several EO materials are compatible with photonic integration, with lithium niobate (LiNbO_3 , LN) being a key driver in telecommunication PICs in recent years. However, materials with better EO properties than lithium niobate have been reported and extensively studied. Among these, barium titanate (BaTiO_3 , BTO) shows the most promise due to its impressively high electro-optic coefficient that allows for the production of high-performance devices with a relatively compact footprint and low, CMOS-compatible operation voltages [59–63]. Compact BTO EO switches in MZI configuration have already been reported, for quantum applications, establishing the compatibility of this technology with the cryogenic environments [27, 64]. However, ensuring high crystal quality, and therefore strong electro-optic behavior and high modulation performance for BTO and other perovskites requires careful attention to the selection of deposition techniques for epitaxial growth. Molecular beam epitaxy (MBE) arises as the most promising deposition method for this purpose, which is costly and not foundry-compatible for producing circuits with large quantities of components with high yield. On the other hand, MEMS fabrication techniques are well-established in integrated circuit (IC) fabrication technology and compatible with the standard process flow, paving the way for a new era of photonic switching mechanisms and justifying their selection for this project.

There are numerous types of optical MEMS switches when categorized based on the configuration of their photonic part. Primarily, optical MEMS switches split into free-space and guided-wave optical switches. The optical MEMS switches that are based on free-space optics are implemented using micro-mirrors that can rotate diverting the incoming beam into different outputs based on the control signal utilizing a MEMS mechanism. This is the most conventional version of optical MEMS switching that emerged many years ago and despite the progress it has seen it is not well-suited for high-performance compact large-scale implementations. This is mainly due to the fact that micro-mirror-based switches commonly have large footprints reaching up to the orders of hundreds of μs , without including the actuation mechanism, even in recently reported devices [65]. They also show long switching times in the order of ms [65, 66] since switching speed depends on the dynamics of the mirror [67]. On the other hand, guided-wave switches offer high switching speed and dense integration [68], offering high scalability prospects.

Among the guided-wave switches, there are various structures well-suited for different purposes. Wavelength-Selective Switches (WSS) usually based on Micro-Ring Resonator (MRR) configurations are suitable for narrow-band filter implementations [69]. When it comes to on-off switching schemes¹, the most common configurations include Total Internal Reflection (TIR) mechanism [39, 52, 70], Photonic Crystal (PhC) structures [71], adiabatic [37, 38, 41, 43, 45, 48] or directional [25, 44, 46, 51, 72] coupler-based devices. All these configurations have been reported with high performance in terms of extinction ratio, insertion loss, speed and footprint and are well-suited for compact design and high integration density, with their basic difference lying in the bandwidth of the application, since TIR- and adiabatic coupler- based devices are inherently broadband, while PhC- and directional coupler-based structures are inherently narrowband [67].

¹There are other switching schemes, such as phase or polarization switching which are not relevant for this project

In the present context of the diamond color centers-based system, given the narrow spectral band of interest, specifically centered around the ZPL of diamond SnV centers, the utilization of narrowband switch configurations is well justified. This report focuses on the directional coupler-based implementation of the optical MEMS switch. The main reason behind this selection lies in the fact that directional coupler configurations can feature very small footprints and are relatively simple to design and fabricate favoring scalability. When especially compared to adiabatic couplers and PhC implementations, directional coupler-based MEMS switches can be monolithically integrated, preventing fabrication issues related to misalignment.

1.2. Problem statement

The utilization of photonic directional couplers for the implementation of the beamsplitter and the optical MEMS switch in the context of a diamond color center-based quantum computer chip presents significant challenges. Primarily, although optical MEMS switches are well-established for telecommunication PICs functioning at the NIR range (1310 nm and 1550 nm), their application in quantum computing hardware is still limited. Although optical MEMS switch designs for quantum applications have already been reported [25], the visible spectrum, particularly the band around the ZPLs of NV and SnV centers remains unexplored. However, the challenge, in this context, lies not only in designing for an unexplored wavelength range but also in carefully selecting materials compatible with both PICs and the MEMS fabrication process to leverage the advantages of monolithic integration. The selected materials should not only be transparent and exhibit low propagation loss in the visible spectrum for the photonics to achieve high performance but also possess good mechanical properties such as low residual stress for the MEMS to be functional and reliable. Luckily SiN, the material of choice for this project meets these requirements but still lacks the maturity and relevant available literature when compared to pure silicon (Si) which is typically utilized in MEMS for telecommunication PICs.

Focusing more closely on the photonic directional coupler design, a special emphasis on certain performance specifications should be placed. The photonic directional coupler is primarily designed for a small footprint, to compete with the current state-of-the-art [24, 25], keeping in mind that the footprint limitations are significantly harder to achieve for the short wavelengths of the visible spectrum, posing an additional challenge for this project compared to the state-of-the-art reported devices operating at higher wavelengths. Next, the directional coupler configuration is selected for maximum fabrication accuracy, namely with deviation from 50:50 split bounded within $\pm 3\%$ for the beamsplitter and with extinction ratio higher than 15 dB [55, 73]. Lastly, the directional coupler should be designed for minimum loss, targetting insertion loss lower than 1 dB both for the beamsplitter [24, 74] and for the switch to keep up with the state-of-the-art Si counterparts [46, 51, 55].

Moving on to the implementation of the directional coupler into an optical MEMS switch, additional design requirements should be considered. The most significant of these is the high driving voltage required to actuate even state-of-the-art MEMS switches, with typical values ranging around 50 V and often even exceeding 60 V [25, 56]. In this context, one of the goals of this project is to explore optical MEMS switch designs, like the ones shown in Figure 1.5, that can operate at a CMOS-compatible voltage. In all examined cases it is aimed to maintain the actuation voltage below 60 V, to fulfill the project specifications. Furthermore, the corresponding footprint of the switch design is targetted at sizes smaller than $20000 \mu\text{m}^2$, set by the project specifications.

After having established the photonic directional coupler designs for the beamsplitter and the switch applications, aim of this project is to establish the fabrication process for the realization of the designed devices. The challenges addressed in this context are related to the small feature size of the designed devices which gives rise to aspect-ratio-dependent fabrication issues, especially hard to address in the absence of relevant literature on similar SiN devices. The addressing of the fabrication issues is quantified based on measurements performed on the fabricated devices with the measurement results targeting to match the simulations. In the same context, the last topic discussed in this project is the integration of the photonic directional coupler into an optical MEMS switch device. This entails additional fabrication challenges to be addressed with the main one of them being the suspension of the MEMS structures.

Based on the above the goals of this project are summarized as follows:

1. Design and fabrication of beamsplitters with a length smaller than $100 \mu\text{m}$, and accuracy higher than 97%

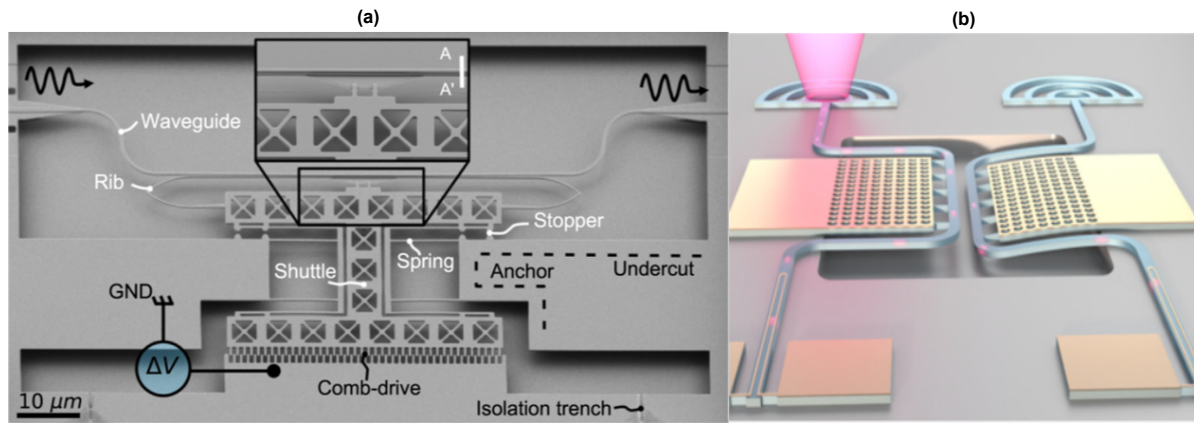


Figure 1.5: (a) SEM top-view of MEMS phase shifter actuated with a comb-drive actuator [51], (b) optical MEMS switch actuated with cantilever beams, integrated with superconducting single-photon detectors [25].

2. Design and fabrication of directional couplers intended for implementation in a switch with an extinction ratio higher than 15 dB
3. Design of directional couplers for insertion loss lower than 1 dB,
4. Proposal an optical MEMS switch design featuring an actuation voltage lower than 5 V,
5. Fabrication of suspended cantilevers that can be integrated into an optical MEMS switch with an actuation voltage lower than 60 V, and a footprint smaller than $20000 \mu\text{m}^2$.

Concluding the problem statement, this report discusses the design and fabrication of beamsplitters and optical MEMS switches for a diamond color-center-based quantum computer chip. The focus of this project is to optimize the design of the photonic components, namely the directional couplers, to meet the requirements of this application in terms of footprint, performance accuracy, and loss as well as to establish the corresponding fabrication steps, addressing both photonic design, material selection, mechanical stability challenges at the wavelength of interest. This project, therefore, aims to contribute to filling in the research gaps in SiN MEMS for PICs design and fabrication in the visible spectrum.

1.3. Thesis outline

The main content of this thesis is presented in the following five chapters, each one of which discusses an important aspect of the design and fabrication of the photonic directional couplers towards the implementation of the beamsplitter and the optical MEMS switch for the 3D integration of a quantum computer chip.

Chapter 2 provides the theoretical background of the key concepts central to this thesis project, including the role of beamsplitters in quantum computing, the fundamentals of photonic directional couplers, and the operation principles of typical optical MEMS switch configurations.

Chapter 3 covers the considerations, the simulation details, and the results of the designing procedure and the performance characterization performed to optimize the SiN photonic directional coupler design for both the beamsplitter and the optical MEMS switch applications at visible wavelengths.

Chapter 4 delves particularly into the design and simulation of optical MEMS switch configurations and provides an extensive comparison of the two prevailing switching schemes.

Chapter 5 describes the procedure followed for the fabrication of the photonic directional coupler and the optical MEMS switch, detailing the design assumptions, the process recipe, as well as the encountered issues, and the applied solutions.

Finally, Chapter 6 presents the results obtained from the fabricated directional coupler and optical MEMS switch device and the conclusions that are established.

2

Theoretical background

This chapter lays the theoretical groundwork for the key components and technologies utilized in this thesis project. The chapter begins with an in-depth exploration of the application of beamsplitters in quantum computing and the generation of entanglement. The subsequent section delves into the fundamental physics of photonic directional couplers and indicates how they are implemented in beamsplitters and optical MEMS switches. Finally, a detailed analysis of the operation principles of optical MEMS switches is provided, with particular emphasis on two different actuation configurations, crucial for the project's objectives.

2.1. Beamsplitter

As already mentioned in the previous chapter, the beamsplitter is utilized in quantum entanglement generation [7]. Entanglement is a purely quantum phenomenon, with no classical counterpart, which enables the impressive capabilities of quantum computers. Entangled states are those that cannot be expressed as product states of their components, meaning that, for instance, the state $|\psi\rangle = |a\rangle|b\rangle$ is not an entangled state [75].

An optical beamsplitter is a device that divides the incident light wave into two beams, as shown in Figure 2.1. In conventional optics, these two output beams correspond to the transmitted and the reflected light wave [28]. In the context of quantum theory, the beamsplitter is assumed to be a 2x2 component, with single photons used as input signals instead of classical light beams. It is worth emphasizing the significance of using a 50:50 beamsplitter which ensures equal probabilities of photon transmission and reflection, corresponding to equal amplitudes of transmittance and reflectance coefficients. Such a beamsplitter makes it possible to erase the "which path" information, rendering the two photons indistinguishable. This feature facilitates two-photon interference enabling effective BSM at the output of the beamsplitter, which involves projecting the output state onto one of the maximally entangled Bell states, a task that is essential in QIP. Therefore, the focus of this report on accurately designing and fabricating 50:50 beamsplitters is justified by their role in enabling these essential quantum operations.

As illustrated in Figure 2.1 and the analysis presented in [4], the output modes at the output ports 3 and 4 of the beamsplitter are represented by the following annihilation operators:

$$\hat{a}_3 = t\hat{a}_1 + r\hat{a}_2, \quad (2.1a)$$

$$\hat{a}_4 = r\hat{a}_1 + t\hat{a}_2, \quad (2.1b)$$

where the coefficients t and r represent the normalized complex transmittance and the complex reflectance of the beamsplitter respectively. These can be expressed as $t = \cos \theta$ and $r = i \sin \theta$, where θ parametrizes the transmittance and reflectance percentages [75]. By multiplying (2.1a) by the conjugate reflectance r^* and (2.1b) by the conjugate transmittance t^* , and taking their sum, we obtain the following relations expressing the input modes as functions of the output modes:

$$\hat{a}_1 = t^*\hat{a}_3 + r^*\hat{a}_4, \quad (2.2a)$$

$$\hat{a}_2 = r^*\hat{a}_3 + t^*\hat{a}_4. \quad (2.2b)$$

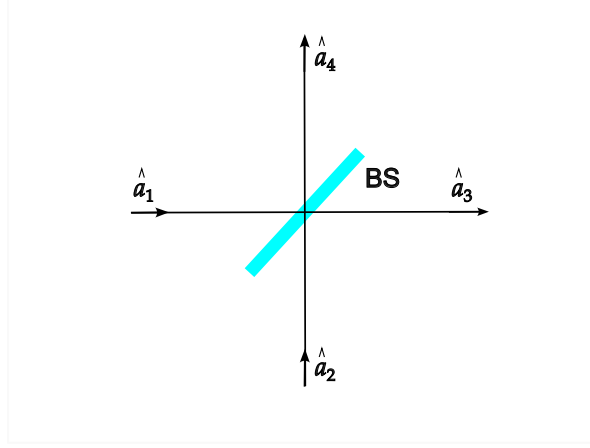


Figure 2.1: Schematic of a quantum-mechanical beamsplitter (BS) illustrated as an optical element that can either transmit or reflect light.

It is straightforward to derive the corresponding relations for the creation operators by considering the system of Eq. (2.2a) and (2.2b) and the system of Eq. (2.1a) and (2.1b) as matrix systems and taking the adjoint. This results in the following relations:

$$\hat{a}_1^\dagger = t\hat{a}_3^\dagger + r\hat{a}_4^\dagger, \quad (2.3a)$$

$$\hat{a}_2^\dagger = r\hat{a}_3^\dagger + t\hat{a}_4^\dagger. \quad (2.3b)$$

$$\hat{a}_3^\dagger = t^*\hat{a}_1^\dagger + r^*\hat{a}_2^\dagger, \quad (2.3c)$$

$$\hat{a}_4^\dagger = r^*\hat{a}_1^\dagger + t^*\hat{a}_2^\dagger, \quad (2.3d)$$

When dealing with a 50:50 beamsplitter $\theta = \pi/4$ and therefore $r = \pm it$. The phase difference $e^{\pm i\pi/2} = \pm i$ between t and r is related to the beamsplitter model [4]. Additionally, considering the principle of energy conservation, represented in this case by the relation $|t|^2 + |r|^2 = 1$, we derive $t = \pm 1/\sqrt{2}$. Given that all the possible sets of (t,r) are equivalent, we simplify by choosing $t = 1/\sqrt{2}$ and $r = it = i/\sqrt{2}$, which results in Eq. (2.1a) and (2.1b) taking the following forms:

$$\hat{a}_1^\dagger = \frac{1}{\sqrt{2}} (\hat{a}_3^\dagger + i\hat{a}_4^\dagger), \quad (2.4a)$$

$$\hat{a}_2^\dagger = \frac{1}{\sqrt{2}} (i\hat{a}_3^\dagger + \hat{a}_4^\dagger). \quad (2.4b)$$

After establishing the above equations we move on to explaining how entanglement is generated through the beamsplitter, based on the analysis presented in [4]. For this purpose, we consider two single photons introduced into the two input ports of a 50:50 beamsplitter. The corresponding input state can be written as $|1\rangle_1|1\rangle_2 = \hat{a}_1^\dagger\hat{a}_2^\dagger|0\rangle_1|0\rangle_2$, where the indices 1 and 2 represent the two input ports of the beamsplitter, $|1\rangle_1$, $|1\rangle_2$ and $|0\rangle_1$, $|0\rangle_2$ represent the single photon state and the vacuum state, respectively, as inputs at the corresponding ports. In the above equation, the principle $|1\rangle = \hat{a}^\dagger|0\rangle$ has been applied, according to which a single photon state emerges when the creation operator acts on the vacuum state. Accepting that the input vacuum state results in an output vacuum state via the beamsplitter as follows $|0\rangle_1|0\rangle_2 \rightarrow |0\rangle_3|0\rangle_4$, we straightforwardly derive that the input state $\hat{a}_1^\dagger\hat{a}_2^\dagger|0\rangle_1|0\rangle_2$ results in a corresponding output state as follows:

$$\hat{a}_1^\dagger\hat{a}_2^\dagger|0\rangle_1|0\rangle_2 \rightarrow \hat{a}_1^\dagger\hat{a}_2^\dagger|0\rangle_3|0\rangle_4. \quad (2.5)$$

By substituting the creation operators of Eq. (2.4a) and (2.4b) in Eq. (2.5) and performing the derivations, the two single photon input states transform at the following state at the output of the beamsplitter:

$$|1\rangle_1|1\rangle_2 \rightarrow \frac{i}{2} (|2\rangle_3|0\rangle_4 + |0\rangle_3|2\rangle_4). \quad (2.6)$$

The last equation clearly illustrates how the input state transforms into an entangled state at the output of the beamsplitter.

It is important to note that the optical beamsplitter described in this section, utilizing the concepts of transmittance and reflectance, represents the free-space-optics version of this device. However, in the context of an integrated quantum computer chip, the beamsplitter is realized as a photonic component. Although the concepts of transmittance and reflectance are not relevant to this guided-wave scenario, the theoretical analysis remains applicable, considering a 50:50 power split at the output of the directional coupler.

2.2. Photonic directional coupler

In the present project, the fundamental component utilized for implementing both the beamsplitter and the optical MEMS switch is the photonic directional coupler. The qualifier "photonic" is used to set it apart from radio-frequency directional couplers, but will be omitted from now on. In the context of photonics, a directional coupler is formed by two parallel waveguides in close proximity such that their electromagnetic field distributions overlap, with the optical power being coupled from one into the other [28, 76]. The waveguides that are relevant in this report are dielectric waveguides of a rectangular cross-section which ensures 2D confinement. The guided waves in the two waveguides forming the coupler are assumed to be propagating in the same direction, referring to a codirectional coupler [77]. Additionally, for the following analysis, the waveguides are assumed to have identical geometries and be phase-matched, implying that the light waves travel in them with equal propagation constants. An example schematic of a photonic directional coupler is shown in Figure 2.2.

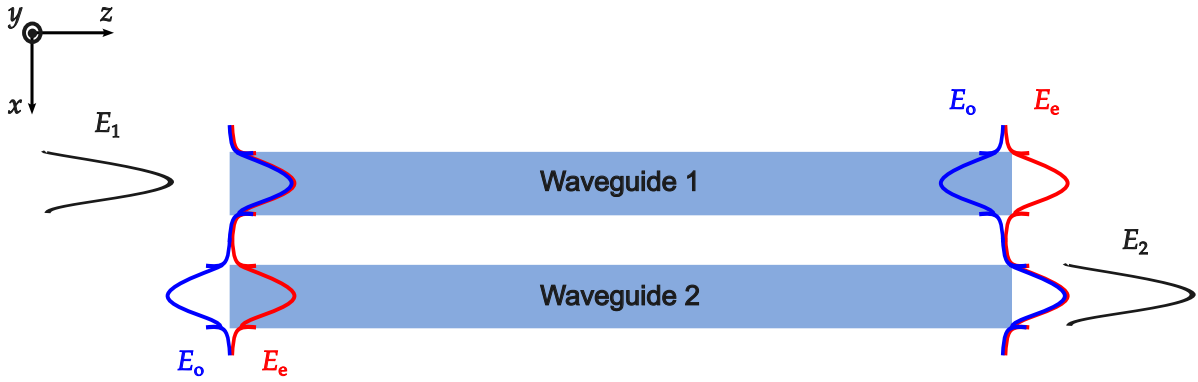


Figure 2.2: Top view schematic of a photonic directional coupler formed by two waveguides. The schematic illustrates the 1D cross-section of the input and output electric field amplitudes, analyzed in the even and odd propagating supermodes for the case of full-power transfer.

The theoretical analysis of the directional coupler is based on the Coupled-Mode Theory (CMT). As analyzed in [77], when the coupling between the two waveguides is weak, according to the perturbation theory, the electromagnetic field of the complex structure can be expressed as the sum of the eigenmodes supported in each waveguide as follows [78]:

$$\tilde{\mathbf{E}} = A_1(z) \tilde{\mathbf{E}}_1 + A_2(z) \tilde{\mathbf{E}}_2, \quad (2.7a)$$

$$\tilde{\mathbf{H}} = A_1(z) \tilde{\mathbf{H}}_1 + A_2(z) \tilde{\mathbf{H}}_2, \quad (2.7b)$$

where $\tilde{\mathbf{E}}_1$ and $\tilde{\mathbf{E}}_2$ the complex electric, and $\tilde{\mathbf{H}}_1$ and $\tilde{\mathbf{H}}_2$ the complex magnetic field profiles at the cross-section, and A_1 and A_2 the coefficients denoting the local amplitudes of the electromagnetic fields along the propagation direction z . The indices 1 and 2 denote the two waveguides forming the directional coupler and generally can be used interchangeably since the structure is symmetric, although index 1 will refer to the input waveguide in this report, as shown in Figure 2.2.

Considering that the two coupled waveguides run in parallel along the propagation direction z and their inputs and outputs are on the same z -planes (waveguides of the same length) we may ignore any butt-coupling [77]. Additionally, it is assumed that the field distribution of waveguide 1 is negligible inside the region of waveguide 2 and vice versa. After some derivations [77], the coupling mode equations

are expressed as follows:

$$\frac{dA_1}{dz} + j\kappa_{12}A_2e^{-j(\beta_2-\beta_1)z} = 0, \quad (2.8a)$$

$$\frac{dA_2}{dz} + j\kappa_{21}A_1e^{+j(\beta_2-\beta_1)z} = 0, \quad (2.8b)$$

where β_1 and β_2 the propagation constants in waveguides 1 and 2 respectively and κ_{12} and κ_{21} the coefficient denoting the coupling from waveguide 1 to 2 and 2 to 1 respectively. Each one of the coupling coefficients represents the overlap integral of the electromagnetic fields in the two waveguides including the refractive index change experienced inside the region of one waveguide due to the presence of the other, according to the following equation [77]:

$$\kappa_{mn} = \frac{\omega\varepsilon_0 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} (n_U^2 - n_n^2) \mathbf{E}_m^* \cdot \mathbf{E}_n dx dy}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{\mathbf{z}} \cdot (\mathbf{E}_m^* \times \mathbf{H}_m + \mathbf{E}_m \times \mathbf{H}_m^*) dx dy}, \quad (2.9)$$

where ω is the angular frequency, ε_0 the permittivity of vacuum, n_U the union of the refractive indices n_1 and n_2 of the two waveguides, and $\hat{\mathbf{z}}$ the unit vector along the z axis.

Assuming loss-less waveguides, the power conservation assumption, combined with the assumption of identical waveguide geometries and equal propagation constants $\beta_1 = \beta_2$ result in the reciprocity of coupling coefficients $\kappa_{21} = \kappa_{12} = \kappa$, considering real coupling coefficients [77]. Therefore, Eq. (2.8a) and (2.8b) can be simplified as follows:

$$\frac{dA_1}{dz} + j\kappa A_2 = 0, \quad (2.10a)$$

$$\frac{dA_2}{dz} + j\kappa A_1 = 0. \quad (2.10b)$$

Taking the derivative of Eq. (2.10a) and substituting it in Eq. (2.10b) results in the following differential equation:

$$\frac{d^2 A_1}{dz^2} - \kappa^2 A_1 = 0, \quad (2.11)$$

which has a solution of the form $A_1(z) = C_1 \cos(\kappa z) + C_2 \sin(\kappa z)$, where C_1 and C_2 are constants that are determined by the boundary conditions based on the excitation of the coupler. By substituting this solution in Eq. (2.10a) the following solution is derived $A_2(z) = jC_2 \cos(\kappa z) - jC_1 \sin(\kappa z)$. As previously mentioned, in the present report waveguide 1 is always considered as the input waveguide, while no input power is introduced in waveguide 2. Therefore, $A_1(0) = 1$ and $A_2(0) = 0$, giving $C_1 = 1$ and $C_2 = 0$. Based on these derivations, the amplitude coefficients are expressed as follows:

$$A_1(z) = \cos(\kappa z), \quad (2.12a)$$

$$A_2(z) = -j \sin(\kappa z), \quad (2.12b)$$

which are used to derive the following equations of power in waveguides 1 and 2 respectively:

$$P_1(z) = \cos^2(\kappa z), \quad (2.13a)$$

$$P_2(z) = \sin^2(\kappa z), \quad (2.13b)$$

confirming the power conservation assumption. From these equations, it becomes obvious that full power transfer to waveguide 2 happens when $\kappa z = (2k+1)\pi/2, k \in \mathbb{Z}$, or equivalently for directional coupler lengths equal to:

$$L = \frac{(2k+1)\pi}{2\kappa}, k \in \mathbb{Z}, \quad (2.14)$$

For the simulation-based methods implemented for this project, it is useful to express the coupling coefficient in terms of the effective refractive indices of the modes supported by the directional coupler. For this purpose, the coupling coefficient is derived as a result of mode interference, as analyzed in [76,

77]. In this context, the electric field distribution in the directional coupler cross-section is considered the result of the interference between the even and odd modes supported by the complex structure shown in Figure 2.2:

$$E(x, z) = E_e(x) e^{-j\beta_e z} + E_o(x) e^{-j\beta_o z} \Rightarrow \quad (2.15)$$

$$E(x, z) = e^{-j\beta_e z} \left(E_e(x) + E_o(x) e^{j(\beta_e - \beta_o)z} \right), \quad (2.16)$$

where the indices e and o refer to the even and the odd mode respectively. Exciting only waveguide 1 is clearly translated into $E_1(x) = |E_e(x) + E_o(x)|$, while full power transfer at waveguide 2 is equivalent to $E_2(x) = |E_e(x) - E_o(x)|$ (illustrated in Figure 2.2) which happens at $(\beta_e - \beta_o)z = (2k + 1)\pi, k \in \mathbb{Z}$. Therefore, using Eq. (2.14) and the general equation $\beta = 2\pi n_{\text{eff}}/\lambda$, where n_{eff} the effective refractive index and λ the free-space wavelength, the coupling coefficient and the corresponding lengths are given by the following relations:

$$\kappa = \frac{\pi (n_{\text{eff},e} - n_{\text{eff},o})}{\lambda}, \quad (2.17)$$

$$L = \frac{(2k + 1) \lambda}{2 (n_{\text{eff},e} - n_{\text{eff},o})}, k \in \mathbb{Z}. \quad (2.18)$$

The case of $k = 0$ corresponds to the smallest directional coupler length at which full power transfer takes place, which is defined as the coupling length $L_c = \lambda/2 (n_{\text{eff},e} - n_{\text{eff},o})$. Next, substituting Eq. (2.17) in Eq. (2.13a) and (2.13b), the (normalized) power in waveguides 1 and 2 respectively are given by the following relations:

$$P_1(z) = \cos^2 \left(\frac{\pi (n_{\text{eff},e} - n_{\text{eff},o})}{\lambda} z \right), \quad (2.19a)$$

$$P_2(z) = \sin^2 \left(\frac{\pi (n_{\text{eff},e} - n_{\text{eff},o})}{\lambda} z \right). \quad (2.19b)$$

Looking more closely into Eq. (2.18), in combination with Eq. (2.19a) and (2.19b) it is straightforward to derive that setting the length L determines the power distribution at the output of the device. This is actually done by selecting the order of interference between the even and the odd mode at the output, which is denoted by the coefficient m in the following equation:

$$L = \frac{m\lambda}{2 (n_{\text{eff},e} - n_{\text{eff},o})}, \quad (2.20)$$

where m can take positive values determining the functionality of the directional coupler based on Eq. (2.19a) and (2.19b). The most interesting cases in the context of the present project correspond to the following values:

- $m = (2k + 1)/2, k \in \mathbb{Z}$ results in equal power at the outputs of the two coupled waveguides, equivalently in a 50:50 power split (considering loss-less structures),
- $m = 2k, k \in \mathbb{Z}$ results in the power exiting the coupler from the input waveguide, and
- $m = 2k + 1, k \in \mathbb{Z}$ corresponds to the case examined earlier in this section, in which all input power is coupled to waveguide 2 at the output.

It is easy to observe that the first one of these cases corresponds to a beamsplitter, while the other two cases correspond respectively to the on and the off state of a switch, indicating how a directional coupler is theoretically applied in beamsplitter and switch implementations.

2.3. MEMS switches

As discussed in Chapter 1, MEMS technology offers significant advantages in terms of hardware compatibility and scalability, and optical MEMS switches, in particular, provide superior performance compared to other PIC-compatible switching mechanisms. This section examines the typical fabrication techniques implemented in MEMS technology, as well as the key characteristics of the most common

optical MEMS switch configurations. Next, two of the most relevant actuation mechanisms are analyzed in the corresponding subsections.

MEMS technology refers to devices at the μm -scale that consist of both electrical and mechanical components, manufactured using standard IC batch-processing methods [79]. The most common silicon MEMS fabrication techniques include bulk micro-machining and surface micro-machining. In bulk micro-machining, the mechanical structures are typically formed by anisotropic etching inside the substrate, while in surface micro-machining the structures are formed by patterning and selectively etching materials deposited on the substrate [35, 80]. Surface micro-machining typically involves sacrificial layer etching to release the mechanical structures, bypassing the constraints associated with anisotropic materials and etching-stop techniques required in bulk micromachining, rendering surface micro-machining more flexible in terms of material selection and suitable for small resolution patterns, as needed in PICs [35, 81].

An important characteristic of MEMS devices is the actuation mechanism they employ. As detailed in [29], actuation in MEMS devices is most commonly electrothermal, electromagnetic, piezoelectric, or electrostatic. Electrothermal actuation relies on the thermal force generated by the different temperature responses of different components when driven. It involves high power dissipation which, combined with its temperature-dependent operation, renders this mechanism unsuitable for cryogenic temperatures. In electromagnetically actuated MEMS, motion is generated in the presence of a magnetic field. This is created by utilizing integrated coils and magnetic materials limiting the application flexibility and in combination with the high power dissipation, making this type of actuation less advantageous for compact PICs operating in cryogenic environments. Piezoelectric actuation on the other hand features low power dissipation but its application flexibility is still limited by the material selection since this mechanism necessitates the integration of piezoelectric materials that undergo mechanical deformation when voltage is applied generating motion. Unlike the other actuation mechanisms, electrostatic actuation offers very low power dissipation allowing for integration in quantum applications, and is additionally easy to configure utilizing the principle of capacitance. In this mechanism, motion is created according to Coulomb's law, due to the attractive force generated between two oppositely charged components, typically a fixed and a movable one. This method not only ensures low power consumption, fast response, and simple configuration but also is compatible with the metal/oxide/semiconductor material stack that can also support PICs, favoring its application in optical MEMS switching technology [30, 82].

Focusing on electrostatic actuation, there are two common configurations typically implemented in optical MEMS switches: the comb-drive and the parallel-plate actuator [76]. The main difference between these two mechanisms lies in their structures that affect the distribution of the generated electric field lines. This structural difference is typically leveraged in the way motion is generated. Comb-drive actuators are typically utilized for in-plane actuation, namely motion parallel to the substrate, while parallel-plate actuators result in out-of-plane motion, most commonly along the direction that is perpendicular to the substrate. These two mechanisms, as well as their implementation in a directional coupler-based optical MEMS switch, are explicitly described in the following subsections.

2.3.1. Comb-drive actuator

A directional coupler-based implementation of an in-plane actuated optical MEMS switch is shown in Figure 2.3. The actuation mechanism utilized here is a comb-drive with folded springs [51]. The notation of a four-port device is used for the directional coupler, according to which, Ports 1, 2, 3, and 4 correspond to the input, isolated, through or bar, and drop or cross ports respectively, with the Ports 1 and 3, and Ports 2 and 4 denoting the input and output ports of waveguides 1 and 2 respectively.

In the configuration shown in Figure 2.3, the input signal is inserted in waveguide 1 (Port 1), which is the fixed waveguide. Waveguide 2 is attached to the comb-drive actuator and is movable. The length of the coupled waveguides is designed such that full power transfer takes place at the output of the directional coupler, having all the power exiting from waveguide 2 (Port 4), when no voltage is applied, as shown in Figure 2.3a. This is the default off-state. When voltage V is applied, as shown in Figure 2.3b, the device is actuated. In this case, the voltage difference between the two comb-drive components results in a static electric field $\vec{E}$ and a corresponding electrostatic force $\vec{F}_e$ that pulls the movable part of the comb-drive towards the fixed one, as illustrated in Figure 2.3b. This results in waveguide 2 being displaced with respect to waveguide 1, by a lateral displacement d . Provided that the dynamics of the structure have been set such that d is large enough so that light no longer couples

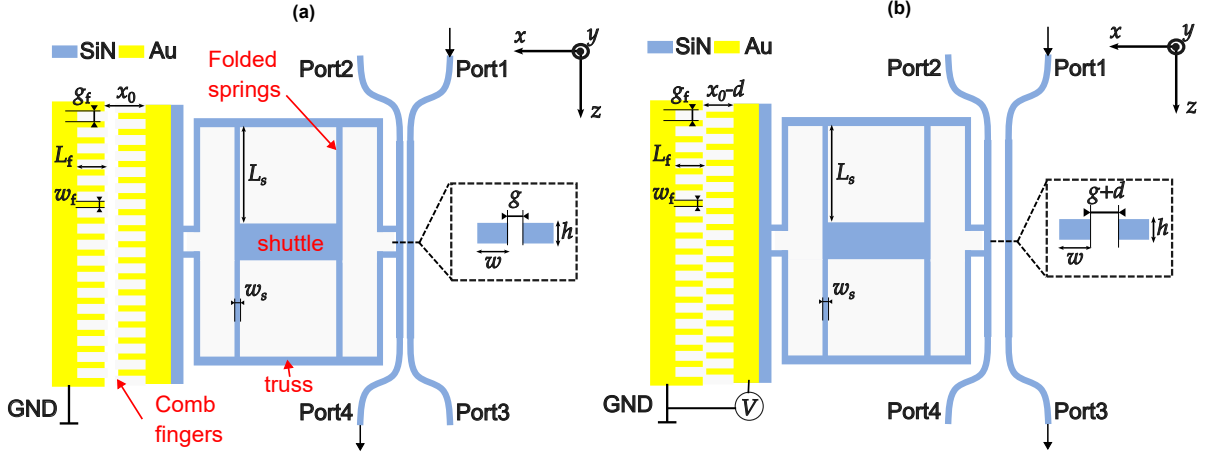


Figure 2.3: Simplified top-view schematic (not in scale) of the (a) off- and, (b) on-state of a directional coupler-based optical MEMS switch actuated using a comb drive actuator with folded springs. The insets illustrate the cross-section of the directional coupler. The substrate is not indicated for simplicity.

to waveguide 2, the switch is in the on-state. In this state, all power remains in waveguide 1 and exits from Port 3.

Looking more closely into the actuation mechanism, the capacitance between the two sets of comb-fingers is given by the following equation:

$$C = 2N \frac{\varepsilon w_f t_m}{x_0 - d} + 2N \frac{\varepsilon (L_f - x_0 + d) t_m}{g_f}, \quad (2.21)$$

where N the number of fingers on each finger-set $\varepsilon = \varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m the permittivity of vacuum since air represents the dielectric medium in this case, w_f the width of each finger, x_0 the default distance between the tip of the finger and the finger-set base when zero voltage is applied, d the displacement induced when voltage is applied, t_m the thickness of the metal layer, L_f the length of each finger and g_f the lateral gap between the sidewalls of two neighboring fingers. In the above equation, the first component represents the capacitance attributed to the front part of the fingers and the second corresponds to the sidewall capacitance [76]. Based on the expression of the capacitance and the potential energy stored in the system, the resulting electrostatic force as a function of the displacement is expressed as follows [83]:

$$F_e(d) = \frac{1}{2} \frac{\partial C}{\partial d} V^2 = N \varepsilon t_m \left(\frac{w_f}{(x_0 - d)^2} + \frac{1}{g_f} \right) V^2 \quad (2.22)$$

Usually, the electrostatic force is given in a simplified form in which fringing fields are neglected, and in this context, the sidewall capacitance is not taken into account [51]. This simplification results in an overestimation of the actuation voltage and is allowed when the thickness of the beam t_m is large enough compared to g_f [84]. However, this is not the case in this report as t_m and g_f are examined in comparable ranges of values.

As can be seen in Figure 2.3, the comb drive is attached to folded springs which enable the mechanical motion of the device. The design of the spring structure consists of four folded springs, consisting of two beams, attached to rigid trusses and corresponds to a spring constant (for motion along the x direction) equal to [44, 51, 83, 84]:

$$k = \frac{2Ehw_s^3}{L_s^3}, \quad (2.23)$$

where E Young's modulus, is characteristic of the material of the structure, w_s the width of each beam, and L_s the length of the spring. The corresponding restoring force as a function of the displacement is

calculated from Hooke's Law as follows:

$$F_k(d) = -kd, \quad (2.24)$$

where the minus sign denotes the opposition to the direction of motion and displacement, which by default is assumed as the positive direction.

Applying the concept of balance of forces (Newton's First Law) considering a case of movement with constant velocity, by equating Eq. (2.22) and Eq. (2.24), substituting Eq. (2.23), and performing some derivations, the actuation voltage as a function of the displacement d is given by the following formula:

$$V(d) = \sqrt{\frac{1}{N\epsilon t_m \left(\frac{w_f}{(x_0 - d)^2} + \frac{1}{g_f} \right)}} \frac{2Ehw_s^3 d}{L_s^3}. \quad (2.25)$$

Eq. (2.25) shows the dependency of actuation voltage on the displacement. For increasing displacement to high values the actuation voltage enters the unstable region marked by the pull-in voltage. The pull-in voltage is the maximum applied voltage that can be supported by the mechanics of the structure [76, 83]. This value is derived as $V_{\text{pull-in}} = V(d_{\text{max}})$, where d_{max} is the displacement at which the first-order derivative of Eq. (2.25) becomes zero.

2.3.2. Parallel-plate actuator

There are several configurations following the principle of parallel-plate actuator, all consisting of two conductive surfaces placed in parallel with respect to one another so that an electrostatic field is formed when there is some voltage difference applied between them. This report examines the model of a cantilever beam with a uniformly distributed load, fixed at one end in the context of optical MEMS switching. The corresponding directional coupler-based switch structure is shown in Figure 2.4. As with the previous switch scheme, Ports 1 and 3, and Ports 2 and 4 denote the input and output ports of waveguides 1 and 2 respectively.

Similarly to the case of in-plane actuation, it is assumed that the light inputs the structure in waveguide 1 (Port 1). Nominally, when no voltage is applied, as shown in Figure 2.4b, the directional coupler is designed such that 100% of the power exits from Port 4, corresponding to the off-state of the switch. When voltage V is applied to the right beam, the one attached to waveguide 2, an electrostatic field is created pointing to the grounded Si substrate. The resulting electrostatic force pulls the cantilever beam towards the substrate, as illustrated in Figure 2.4c, resulting in waveguide 2 being displaced vertically with respect to its default position, by a displacement d . Based on the previous analysis, it is clear that the on-state is obtained providing that the induced displacement is large enough such that no power can couple to waveguide 2.

Starting again from the capacitance between the cantilever beam and the grounded substrate, corresponding to the two parallel plates, the formula that applies is the following [76]:

$$C = \frac{\epsilon w_b L_b}{y_0 - d}, \quad (2.26)$$

where $\epsilon = \epsilon_0$ the permittivity of vacuum, since still the dielectric medium is air (the structure is suspended on top of the substrate), w_b the width and L_b the length of the beam as shown in Figure 2.4a, $y_0 = h + t_{\text{SiO}_2}$ the nominal distance between the beam and the conductive substrate, where h the SiN thickness and t_{SiO_2} the SiO₂ thickness and d the induced displacement. Applying again the equation of the potential energy stored in the system we derive the electrostatic force equal to:

$$F_e(d) = \frac{1}{2} \frac{\partial C}{\partial d} V^2 = \frac{\epsilon w_b L_b}{2(y_0 - d)^2} V^2. \quad (2.27)$$

According to the Euler-Bernoulli beam theory, the spring constant of this structure is given by the following formula [25]:

$$k = \frac{E w_b t_b^3}{4 L_b^3}, \quad (2.28)$$

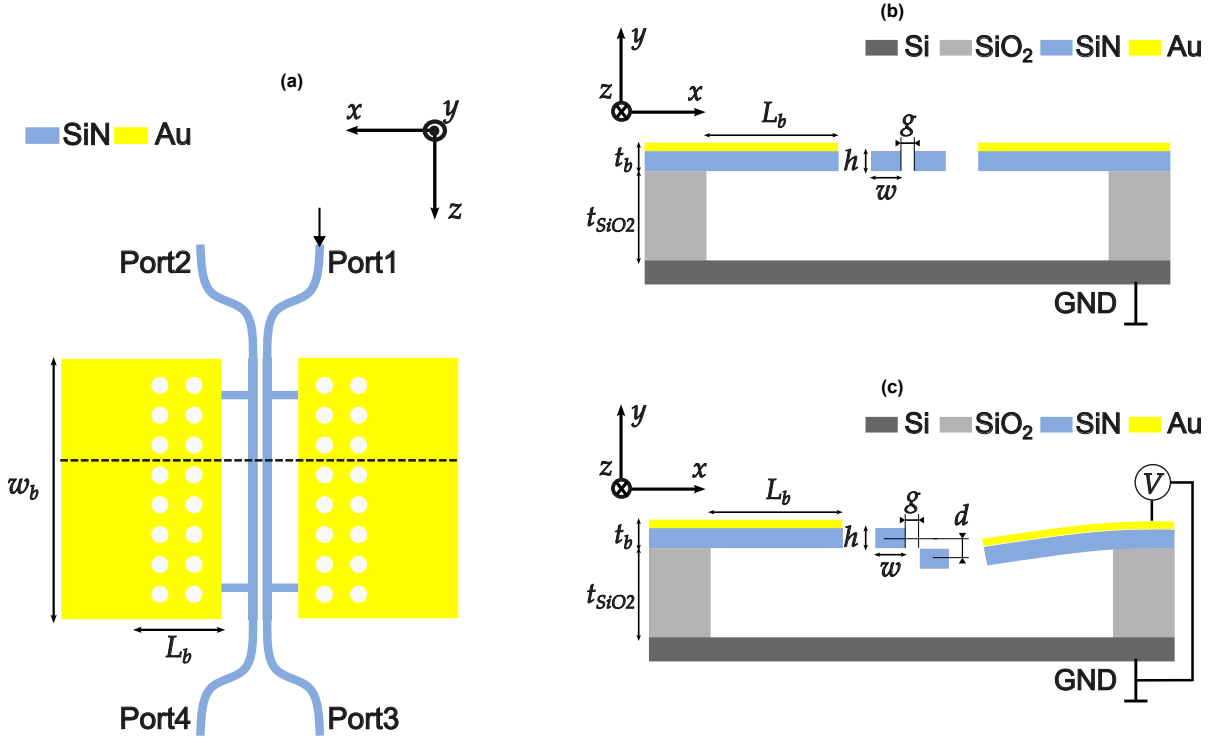


Figure 2.4: (a) Simplified top-view schematic of a directional coupler-based switch actuated using a cantilever beam. The substrate is not indicated for simplicity. The dotted line marks the plane along which the cross-section of the switch is illustrated in its (b) off- and, (c) on-state. The schematics are not in scale.

where E is Young's modulus and t_b is the thickness of the beam, calculated as the sum of the SiN and metal film thicknesses, as shown in Figure 2.4. Continuing, according to Hooke's law, the restoring force applied to the beam is given by the following equation:

$$F_k(d) = kd. \quad (2.29)$$

It is noted that in this case, the restoring force is assumed to be positive, since it points towards the positive y -axis, opposing to the downward bending of the beam.

Applying the balance of forces for the cantilever beam, equivalently setting the Eq. (2.27) and Eq. (2.29), utilizing Eq. (2.28) and performing the derivations, the actuation voltage for this structure is derived as follows:

$$V(d) = \sqrt{\frac{E(y_0 - d)^2 dt_b^3}{2\epsilon L_b^4}}. \quad (2.30)$$

As explained in the previous subsection, the maximum displacement that the mechanics of the structure can support defines the pull-in voltage which marks the stable region of operation for the structure.

Photonic directional coupler design

The foundational element for the implementations discussed in this report is the photonic directional coupler. This chapter details the design procedure of the directional coupler and provides an extensive analysis of its performance characteristics. The design procedure is based on a simulation model setup which is presented in the first section. Based on this model, the following sections study the inherent trade-offs of the device in terms of dimensions, bandwidth, fabrication-error tolerance, and loss. The key conclusions drawn from this study are summarized at the end of the chapter.

3.1. Simulation model

In the present project, the simulations were performed with RSoft CAD from RSoft Photonic Device Tools, utilizing the FemSIM FEM, BeamPROP BPM and FullWAVE FDTD simulation modules. The structure that was simulated is shown in Figure 3.1. The blue rectangle denotes the structure mainly used in Finite Element Method (FEM) simulations performed with FemSIM FEM, while the black rectangle denotes the structure simulated with Beam Propagation Method (BPM) and Finite Difference Time Domain (FDTD) simulations performed with BeamPROP BPM and FullWAVE FDTD respectively. The substrate is set as SiO_2 in the case of the beamsplitter and as air for the directional couplers implementing the switch to simulate them as suspended.

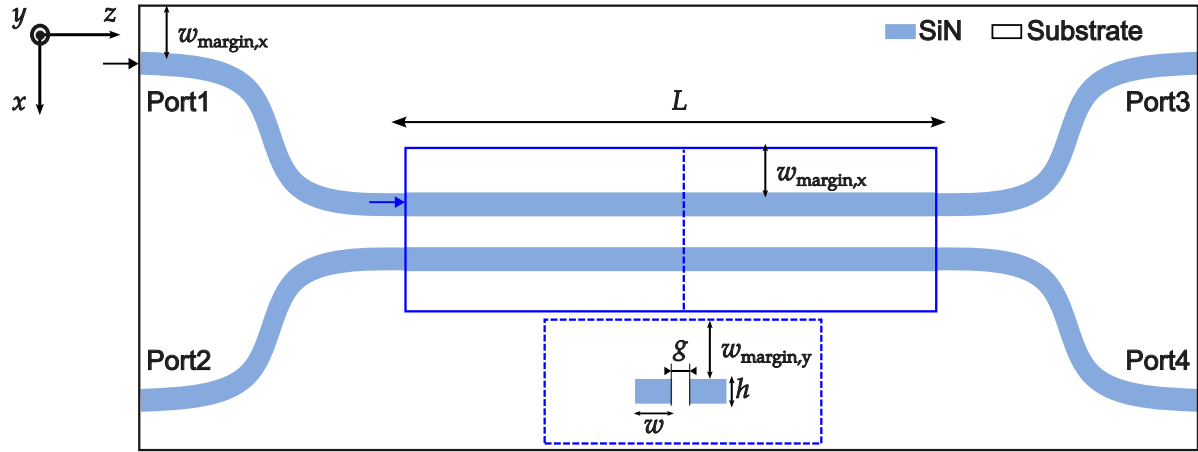


Figure 3.1: Top-view schematic of the simulated directional coupler (not in scale). The black and blue rectangles denote the models simulated with BeamProp and FullWave, and FEM respectively. The input wave for each model is denoted with an arrow. The inset illustrates the cross-section along the plane marked by the dotted lines. The substrate is set as SiO_2 or air.

FEM considers the two-dimensional cross-section of the structure and divides it into finite elements, typically triangles or tetrahedra, each one of which contributes to the numerical representation of the field components. The solution is a polynomial approximation of the complex differential equations describing the spatial field distribution, with certain boundary conditions. Although FEM does not take

into account the 3D structure, its use is reasonable in the case of the directional coupler structure which has the same cross-sectional geometry along its length [77]. From FEM simulations the effective refractive index profiles of the supported modes are extracted.

BPM is based on the approximation of the Helmholtz equation assuming propagation in a single direction and small propagation angles. BPM is ideal for examining the full version of the structure shown in Figure 3.1, including the S-bend-shaped waveguides outside the coupling region, for which FEM stationary mode analysis would be insufficient [77]. BPM is used to extract the power of the propagating modes. It is noted that although the FDTD method produces more accurate results, BPM can still achieve high accuracy for the studied case in which the light propagates in a waveguide of cross-sectional geometry that varies relatively little along the propagation direction and most importantly can allow for time-manageable simulations.

FDTD calculates the electromagnetic field as a function of time and space by solving the full version of Maxwell's equations. For this reason, FDTD is suitable for accurately modeling structures regardless of their geometry complexity. However, it is a computationally intensive and time-consuming technique, especially for the examined structure sizes ranging between $10\text{ }\mu\text{m}$ and $300\text{ }\mu\text{m}$. Therefore, this method is only used in loss simulations in the present report to extract the power monitored at certain parts of the structure.

All simulations were performed for the wavelength $\lambda = 632.8\text{ nm}$, which falls into the illumination band of NV centers [85] and is also close to the ZPL of SnV centers. This wavelength was selected to match the available laser diode used to measure the fabricated devices. Although the selected λ is not exactly equal to the ZPLs of interest the general design conclusions drawn in this chapter are applicable for a broader band that contains both the SnV and NV centers ZPL. The key simulation parameters, common for all performed simulations are provided in Table 3.1. FDTD simulations were performed with a grid size equal to $0.02\text{ }\mu\text{m}$ (taking into account the rule of thumb: grid size $< \lambda/10$).

Table 3.1: Numerical values of the parameters used in simulations, including the free-space wavelength λ , the refractive indices of the simulated materials n_{SiN} , n_{air} , and n_{SiO_2} , the width w and height h of the waveguides, the size of the grid along the x, y, and z direction and the size of the margins $w_{\text{margin},x}$ and $w_{\text{margin},y}$ between the structure and the simulation window.

Parameter	Value
λ	632.8 nm
n_{SiN}	2.023
n_{air}	1
n_{SiO_2}	1.457
w	$0.4\text{ }\mu\text{m}$
h	$0.25\text{ }\mu\text{m}$
grid size	$0.01\text{ }\mu\text{m}$
$w_{\text{margin},x}$	$2\text{ }\mu\text{m}$
$w_{\text{margin},y}$	$1.5\text{ }\mu\text{m}$

In addition to the parameters provided in Table 3.1, it is noted that the substrate and cover materials were simulated as of semi-infinite thickness. The refractive indices of the simulated materials were set as the default values provided by the simulation software for the simulation wavelength.

The waveguide height is determined by the foundry, equal to the SiN thickness on the wafers, considering fully etched strip waveguides. The waveguide width was chosen for directional coupler operation with only two supported modes, the even and the odd one, for SiO₂ substrate, although a larger waveguide width would favor lower propagation losses. The effective refractive index of the higher order mode supported in the directional coupler for increasing waveguide width, both for SiO₂ and air set as substrate is shown in Figure 3.2. For SiO₂ substrate the higher-order mode exists only for widths larger than $0.4\text{ }\mu\text{m}$, while for the case of the suspended structure, an even lower width is required to ensure operation with only two modes. However, $w = 0.4\text{ }\mu\text{m}$ is selected for both tested substrates to simplify the experiment and as a compromise between the propagation losses and coupling to higher-order modes. It is also noted that the propagation losses resulting mainly from the sidewall roughness

are not simulated for this project, but are expected to be relatively high in the experimental device potentially preventing from performing valid measurements and drawing safe conclusions in case a width smaller than $0.4 \mu\text{m}$ is used.

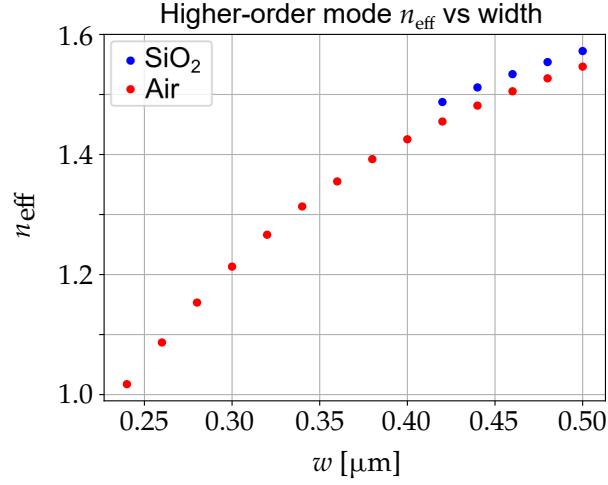


Figure 3.2: Plot of the effective refractive index n_{eff} of the first-emerging higher-order mode as a function of the waveguide width w , extracted for simulation with SiO₂ (blue) and air (red) set as substrate.

The grid size was selected as a compromise between simulation accuracy and time. Convergence simulations were performed to confirm the accuracy offered by the grid size, as seen in Figure 3.3, as well as the simulation window size with plots provided in Appendix A.

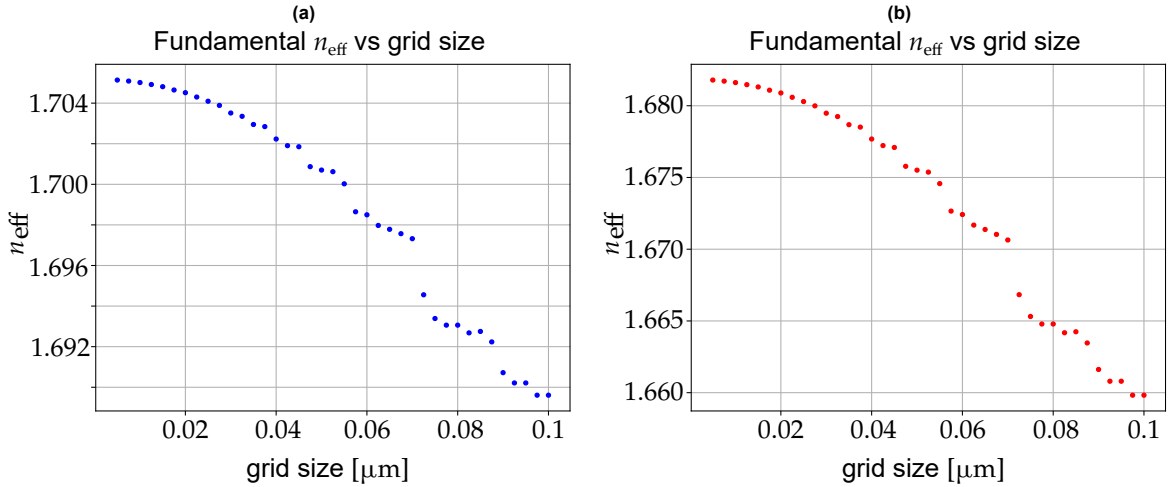


Figure 3.3: Plot of effective refractive index n_{eff} of the fundamental mode as a function of the grid size extracted from FEM simulation with (a) SiO₂ and, (b) air set as substrate, for $g = 0.15 \mu\text{m}$.

3.2. Device size

The footprint of the photonic directional coupler is mainly set by its length, namely the distance along the propagation direction for which the coupled waveguides are in close proximity and in parallel. As already examined in Chapter 2, the length of the directional coupler for a given wavelength, based on Eq. (2.20) is determined by the following factors: interference order m and the effective refractive index difference between the even and the odd mode $n_{\text{eff},e} - n_{\text{eff},o}$.

Assuming that the device is designed to have certain functionality, namely to operate as a beamsplitter or a switch, the interference order is considered as set. Therefore, the length only depends on the difference $n_{\text{eff},e} - n_{\text{eff},o}$ which is a result of the electromagnetic field distribution in the cross-sectional

geometry of the structure. For given waveguide dimensions, the only experimentally realistic way to tune the difference $n_{\text{eff,e}} - n_{\text{eff,o}}$ is by adjusting the gap between the coupled waveguides.

Simulating the structure of Figure 3.1 with FEM and the simulation parameters provided in Table 3.1, for gap g ranging between $0.1 \mu\text{m}$ and $0.3 \mu\text{m}$ and applying Eq. (2.20) for $m = 1/2$ and $m = 1$ results in the length of the beamsplitter and the switch configurations ¹ that can be seen in Fig 3.4a and 3.4b respectively.

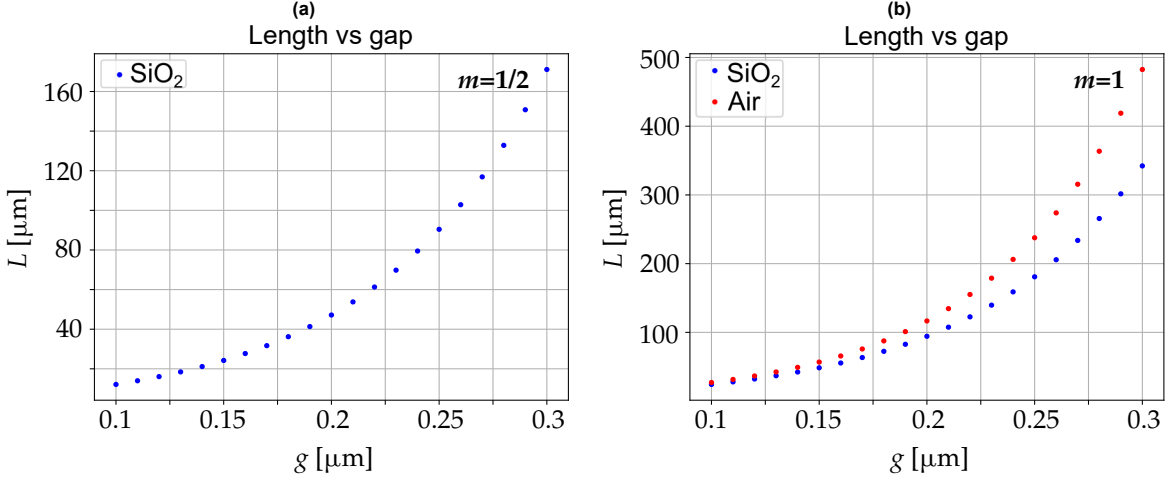


Figure 3.4: Plot of the length L as a function of the gap g between the coupled waveguides extracted from FEM simulation of (a) a beamsplitter ($m = 1/2$) and, (b) a switch configuration ($m = 1$).

The conclusion drawn from Figures 3.4a and 3.4b matches the intuition since a wider spacing between the coupled waveguides weakens the coupling and thus a longer propagation length is required to achieve a given power ratio at the output. It is noted that the lower limit of the examined gap range is set by keeping the E-beam resolution expectations at realistic levels. The upper limit of the range is set by the footprint limitations of the device, based on which coupling lengths larger than $300 \mu\text{m}$ are not examined. An additional comment regarding Fig 3.4b is that both SiO_2 and air substrate are examined for the case of the switch configurations, since although the case of the air as a substrate is the only realistic one for the suspended structure, the SiO_2 substrate study corresponds to the fabrication experiment described in Chapter 5.

It is noted that in this section only the coupler length was examined, as the most relevant design parameter determining the footprint of a directional coupler device. However, the curved waveguides at the input and the output of the coupler, shown in Figure 3.1, are considered as well in the footprint estimations in the present report. For the case of simple circular S-bends of radius R and angle φ the footprint of the directional coupler (dc), including the S-bend-shaped waveguides is calculated as follows:

$$\text{Footprint}_{dc} = (L + 4R \sin \varphi) \times (g + w + 4R(1 - \cos \varphi)). \quad (3.1)$$

The factor 4 is due to the fact that the structure consists of two S-bends along the x and two along the z -axis, each one of which consists of two circular bends. The parameters R and φ are examined in Section 3.5 in the context of loss simulations.

3.3. Simulation over wavelength

As previously mentioned, the simulation wavelength of 632.8 nm falls into the band of interest for this project and is equal to the emission wavelength of the laser diode used in the measurements. The emission of diamond color centers usually extends in a narrow range of wavelengths around the ZPL, thus examining the spectral dependency of the device is meaningful. It is noted that a directional coupler is an inherently narrowband device and therefore, this section does not aim to study the bandwidth as

¹The directional coupler intended to be integrated into an optical MEMS switch will be referred to as switch configuration from now on in this report.

a performance metric, but rather to provide an overview of the expected device behavior around the design wavelength.

For this purpose, the short version shown in Figure 3.1 is simulated using FEM and the simulation parameters provided in Table 3.1. The free space wavelength is swept over the range $[600, 690]$ nm and the normalized transmission to Port 4 is derived by substituting the coupled waveguide length $z = L$ in Eq. (2.19b) from the following equation:

$$P_4 = \sin^2 \left(\frac{\pi (n_{\text{eff},e} - n_{\text{eff},o}) L}{\lambda} \right). \quad (3.2)$$

At the design wavelength, P_4 is expected to be equal to 0.5 for the beamsplitter (50:50 beam split) and equal to 1 (full power transfer at the off-state) for the switch. The resulting plots for the beamsplitter and switch implementations are shown in Figure 3.5a and 3.5b respectively. In both cases, two different interference orders have been examined, for a gap equal to $g = 0.1 \mu\text{m}$.

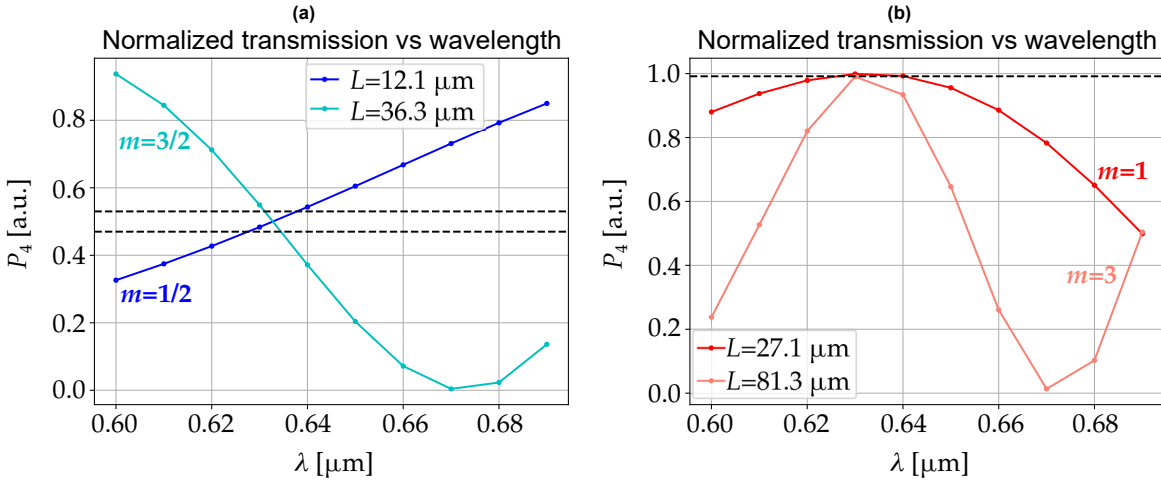


Figure 3.5: Plot of the normalized transmission P_4 as a function of the free-space wavelength λ extracted from FEM simulation for (a) beamsplitters of $m = 1/2$ and $m = 3/2$ on SiO_2 substrate, with the dotted lines marking the $\pm 3\%$ accuracy range and, (b) switch configurations of $m = 1$ and $m = 3$ with air set as substrate and the dotted line denoting the $ER = 20$ dB, for $g = 0.1 \mu\text{m}$.

From Figures 3.5a and 3.5b it becomes evident that the structures that correspond to higher interference order have smaller bandwidth. To draw this conclusion a $\pm 3\%$ deviation threshold has been set for the beamsplitter, defined as the deviation percentage from the 50:50 power split [73]. The accuracy metric set for the switch is the extinction ratio for the off-state defined as:

$$ER_{\text{off}} = 10 \log \left(\frac{P_{4,\text{off}}}{P_{3,\text{off}}} \right), \quad (3.3)$$

where $P_{4,\text{off}}$ and $P_{3,\text{off}}$ the output powers at Ports 4 and 3 respectively at the off-state of the switch. The extinction ratio for the off-state of the switch is set equal to $ER = 20$ dB (the simulation data were not enough for calculating the bandwidth for $ER \geq 30$ dB). Plots similar to Figure 3.5 were derived for devices of gaps varying in the range $[0.1, 0.3] \mu\text{m}$ based on which, the derived bandwidth versus gap is plotted in Figures 3.6a and 3.6b for beamsplitter and switch respectively.

Figure 3.6 shows that the bandwidth of the directional coupler decreases with increasing gap. Considering the results provided in Figure 3.4, an increasing gap between the coupled waveguides is equivalent to an increasing device length. This agrees with the findings of Figure 3.5 since an increasing interference order also results in an increasing length. An additional conclusion drawn from Figure 3.6 confirms the expected behavior of directional coupler-based devices which are generally narrow-band when compared to the 300 nm bandwidth that adiabatic coupler-based devices achieve [67].

3.4. Fabrication variation-sensitivity study

Two fabrication errors that are relevant to the experimental realization of the directional coupler are examined in this section: waveguide width variation potentially caused by descum and/or etching and

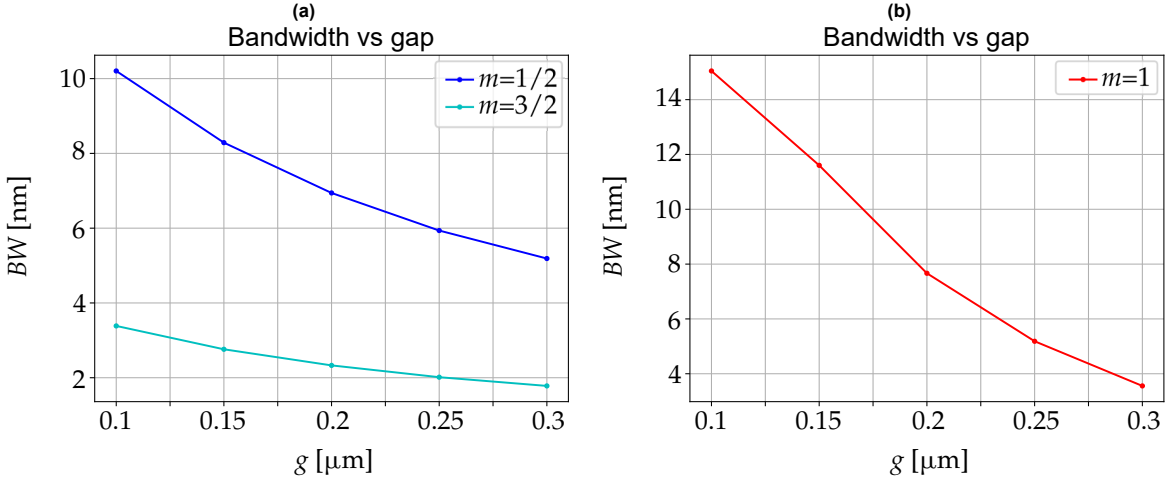


Figure 3.6: Plot of the bandwidth BW as a function of the gap g between the coupled waveguides extracted from FEM simulation for (a) beamsplitters of $m = 1/2$ and $m = 3/2$, with $\pm 3\%$ accuracy on SiO_2 substrate and, (b) switch configuration of $m = 1$ with $ER = 20$ dB and air set as the substrate.

substrate oxide height variation caused in the case of overetching. These two cases are illustrated in Figures 3.7a and 3.7b respectively.

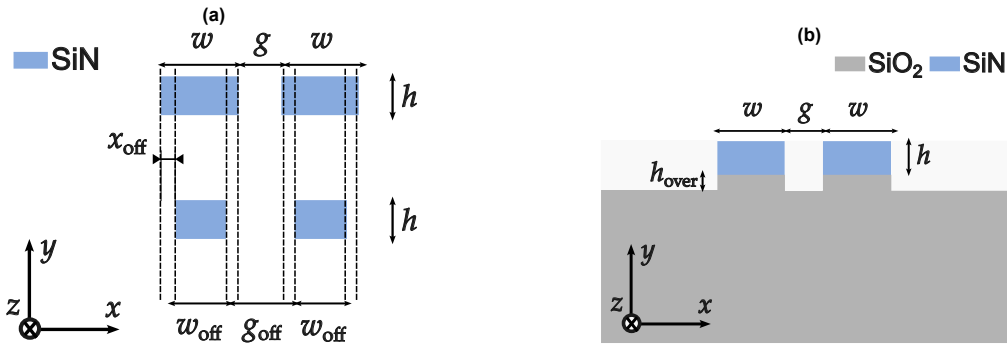


Figure 3.7: Cross-section schematic (out of scale) of the directional coupler with (a) width and gap and, (b) waveguide height variations due to potential fabrication errors.

For this study, both beamsplitter and switch configurations of two different interference orders were simulated. The short device version of Figure 3.1 was modeled with FEM and the simulation parameters provided in Table 3.1. The simulated waveguide width and gap, incorporating the dimension offset induced by potential fabrication errors, were expressed with regards to the nominal ones as

$$w_{\text{off}} = w + 2x_{\text{off}}, \quad (3.4a)$$

$$g_{\text{off}} = g - 2x_{\text{off}}, \quad (3.4b)$$

where x_{off} was swept in the range $[-0.015, 0.015]$ μm , which is a realistic range based on the experiment. The normalized transmission to Port 4, derived from implementing Eq. (3.2) is plotted for the four directional couplers with $g = 0.1$ μm in Figures 3.8a and 3.8b.

Figure 3.8 shows results similar to the ones derived in the previous section. The devices that correspond to higher interference orders show a larger sensitivity to fabrication errors. Plots similar to Figure 3.8 were derived for devices with gap varying in the range $[0.1, 0.3]$ μm based on which a comparison between devices of different gaps, and thus different lengths is possible by looking at Figures 3.9a and 3.9b. The derived results confirm that longer devices are less tolerant to fabrication errors.

Regarding the tolerance of the directional coupler to overetching of the bottom oxide cladding, the simulated normalized transmission to Port 4 P_4 as a function of the overetching depth h_{over} , for the

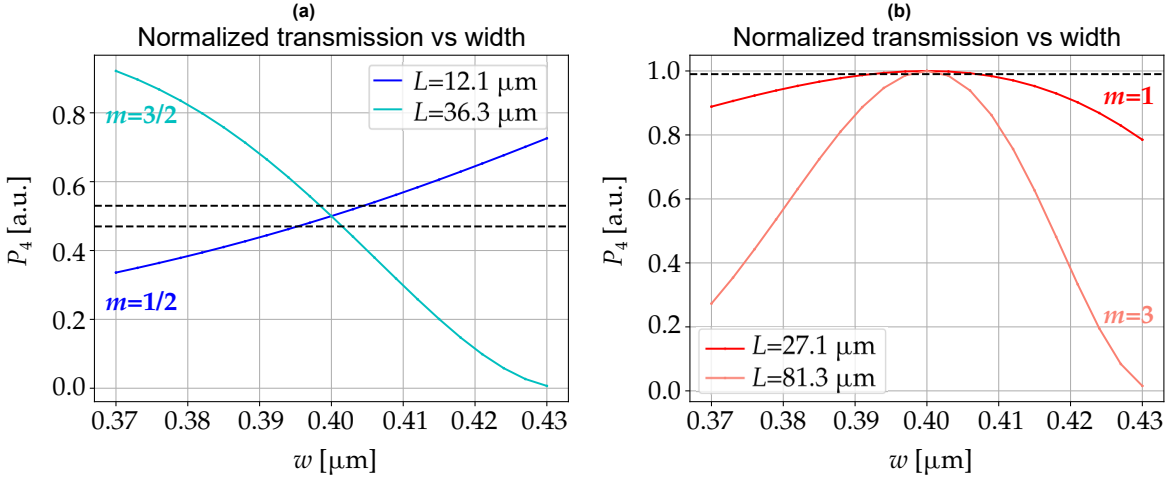


Figure 3.8: Plot of the normalized transmission P_4 as a function of the waveguide width w extracted from FEM simulation for (a) beam splitters of $m = 1/2$ and $m = 3/2$ on SiO_2 substrate, with the dotted lines marking the $\pm 3\%$ accuracy range and, (b) switch configurations of $m = 1$ and $m = 3$ with air set as substrate and the dotted line denoting the $ER = 20 \text{ dB}$, for $g = 0.1 \mu\text{m}$.

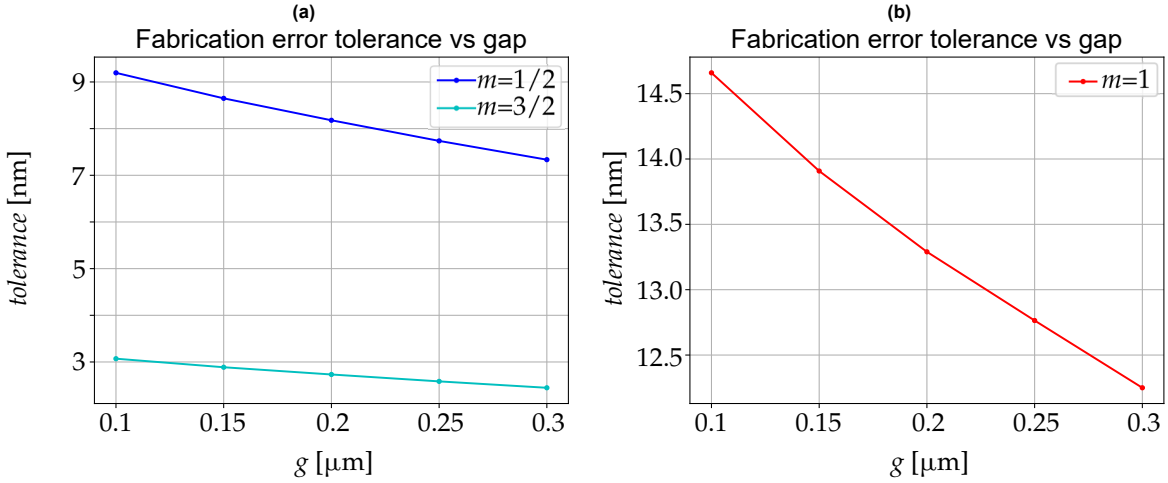


Figure 3.9: Plot of the tolerance to width variation as a function of the gap g between the coupled waveguides extracted from FEM simulation for (a) beam splitters of $m = 1/2$ and $m = 3/2$, with $\pm 3\%$ accuracy on SiO_2 substrate and, (b) switch configuration of $m = 1$ with $ER = 20 \text{ dB}$ and air set as the substrate.

same beam splitters and switch configurations is shown in Figures 3.10a and 3.10b respectively. The height h of the SiN layer remains equal to the nominal in these simulations, corresponding to a perfect selectivity of the etching against SiN in a real overetching scenario. The corresponding fabrication error tolerances expressed in [nm] are plotted in Figures 3.11a and 3.11b respectively. The conclusions that are drawn are similar to the previous case.

3.5. Loss simulation

A key performance parameter of all photonic devices, but especially of an optical MEMS switch is insertion loss [30]. Given that sidewall roughness is not included in simulations and therefore propagation losses are not accounted for, there are primarily two sources of losses considered for this structure: radiation losses and mode-mismatch losses [86]. Both types of losses are related to the abrupt directional changes introduced by the curved waveguides in which the guided mode is shifted towards the outside sidewall [87, 88]. Firstly, this shifting causes the guided mode to couple to radiative modes accounting for the radiation losses. Secondly, the shifting of the mode with respect to the propagation axis results in mode mismatch at the interfaces between oppositely bent waveguides as well as between curved

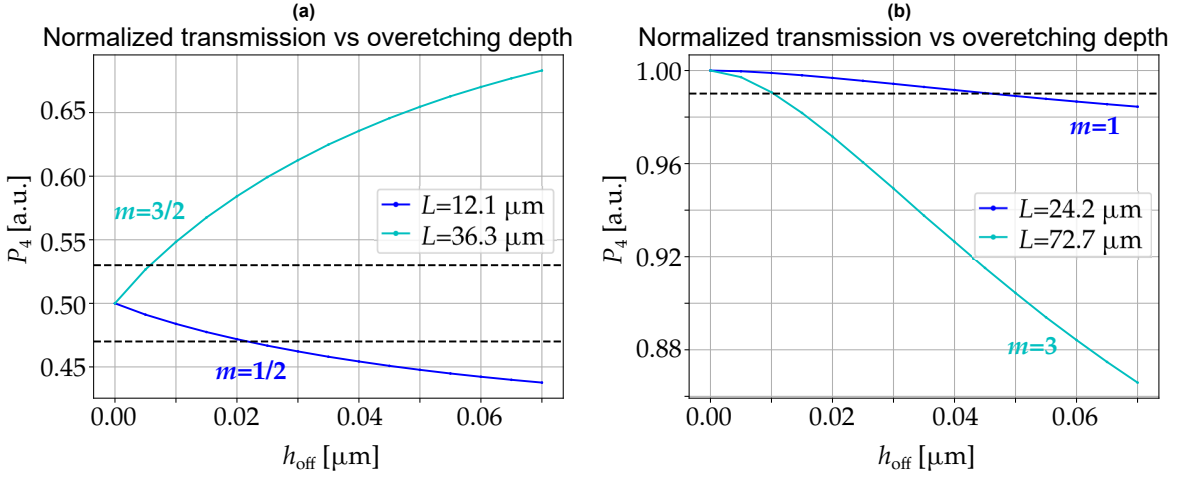


Figure 3.10: Plot of the normalized transmission P_4 as a function of the overetching depth h_{off} extracted from FEM simulation for (a) beamsplitters of $m = 1/2$ and $m = 3/2$ on SiO_2 substrate, with the dotted lines marking the $\pm 3\%$ accuracy range and, (b) switch configurations of $m = 1$ and $m = 3$ with air set as substrate and the dotted line denoting the $ER = 20 \text{ dB}$, for $g = 0.1 \mu\text{m}$.

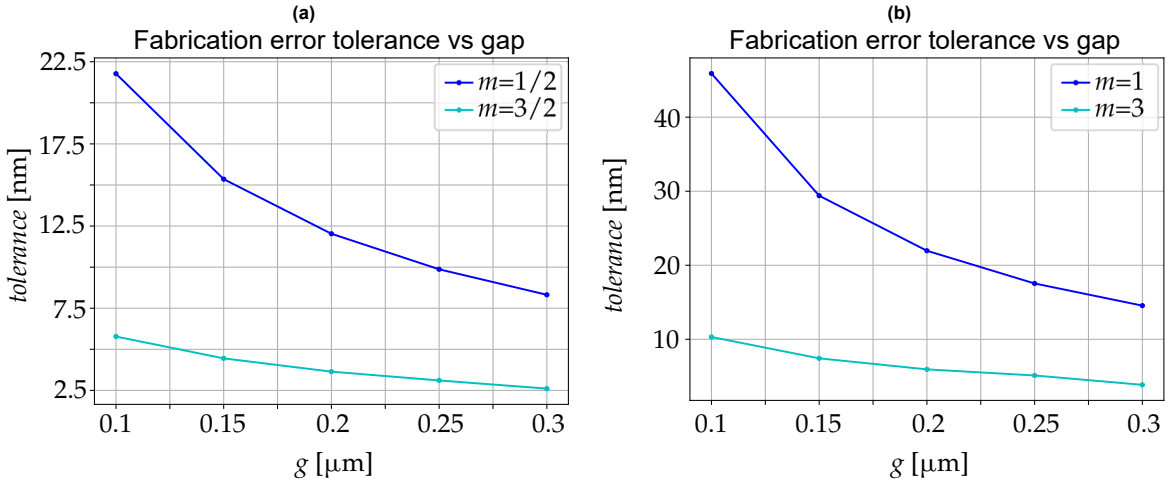


Figure 3.11: Plot of the tolerance to oxide overetching as a function of the gap g between the coupled waveguides extracted from FEM simulation for (a) beamsplitters of $m = 1/2$ and $m = 3/2$, with $\pm 3\%$ accuracy on SiO_2 substrate and, (b) switch configuration of $m = 1$ with $ER = 20 \text{ dB}$ and air set as the substrate.

and straight waveguides [87].

The lossy part of the directional coupler device is the S-bend-shaped waveguides placed at the input, responsible for smoothly transitioning to the coupling region where the coupled waveguides should be in close proximity and at the output of the directional coupler, to restore the independence of the two waveguides, as shown in Figure 3.1. Focusing on the input curved structure shown in Figure 3.12, the lossy part is marked by the planes z_1 and z_6 . The design parameters defining the structures of this part are the bend radius R and the bend angle φ . To investigate the losses R and φ which are swept in the ranges $[1, 35] \mu\text{m}$ and $\{30^\circ, 45^\circ, 60^\circ\}$ respectively. Both SiO_2 and air are examined as substrates to study the losses for both the beamsplitter and switch configurations.

3.5.1. Bend loss

The radiation losses induced by the curved waveguides are more accurately referred to as bend losses. Bend loss here is calculated as the total radiation loss experienced by the guided wave while it propagates along the two oppositely curved bends, without including the mode-mismatch losses introduced at the transition region. For this simulation, the bend loss simulation feature of FEM is used, with a

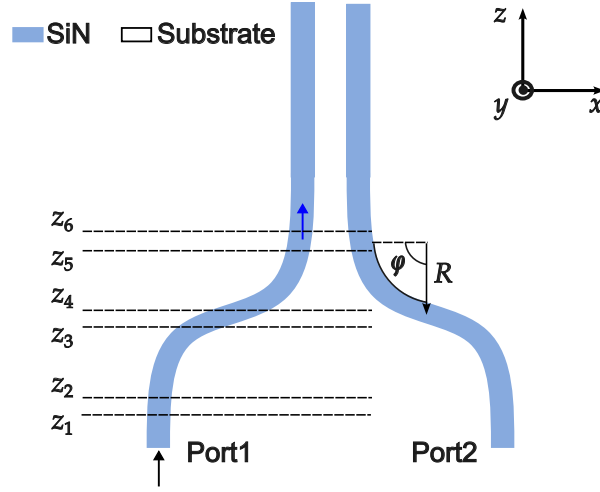


Figure 3.12: Top-view schematic (not in scale) of the S-bend-shaped waveguides at the input of the directional coupler. The substrate is set as SiO_2 or air. The dotted lines mark the regions around the 'lossy' interfaces.

Perfectly Matched Layer (PML) thickness equal to $0.5 \mu\text{m}$. From this simulation the imaginary effective refractive index $\text{Im}\{n_{\text{eff}}\}$ profiles are extracted as a function of the bend radius R . Next, the attenuation constant is calculated in rad/m as a function of the bend radius from the following formula:

$$\alpha(R) = \frac{2\pi}{\lambda} \text{Im}\{n_{\text{eff}}(R)\}. \quad (3.5)$$

Subsequently, the radiation loss is calculated in dB/m from the relation $RLoss(R) = 20\alpha(R) / \ln(10)$, and the total bend losses are calculated in dB as follows:

$$BLoss(R, \phi) = 4 \frac{2\pi R \phi}{360^\circ} RLoss(R), \quad (3.6)$$

where the factor 4 accounts for the four bends of the structure of Figure 3.1. The total bend losses as a function of R for $\phi = 30^\circ$, for SiO_2 and air substrates, are shown in Figures 3.13a and 3.13b respectively.

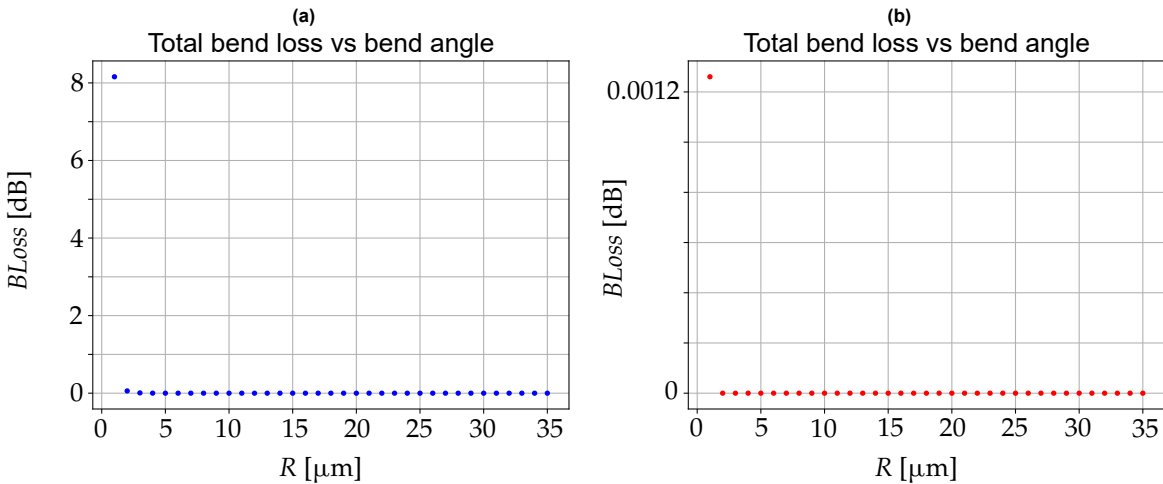


Figure 3.13: Plot of bend loss $BLoss$ as a function of the bend radius R for $\phi = 30^\circ$ for (a) SiO_2 and, (b) air set as substrate.

In general, higher bend losses are expected for smaller bend radii, due to the directional changes being more abrupt [86]. This is confirmed in Figure 3.13, although most of the radii examined are too large to reveal this trend and therefore, the derived bend loss as a function of the bend radius remains relatively constant, for $R > 2 \mu\text{m}$. As far as the bend angle is concerned, the total bend loss is expected

to increase linearly with ϕ based on Eq. (3.6). This is logical since the coupling to radiative modes lasts longer in the case of bends with longer circumferences. Therefore, in the design the bend angle is chosen to be small, considering of course that reducing the bend angle further below 30° is expected to start increasing the effective length of the directional coupler, affecting the functionality of the device. The angle at which this effect takes place is not investigated in this report.

It is noted that insertion loss simulation was performed with FDTD, based on a different model which is described in Appendix A. The simulation results do not match intuition implying that there might have been an error in the simulation set-up settings. Due to the time limitations of this project, the issue was not identified. However, the derived low bend loss is already promising for operation with total insertion loss lower than 1 dB.

3.6. Summary

The goal of this final section is to summarize the results presented in the previous sections in some general beamsplitter design principles. Looking back on sections 3.2, 3.3, and 3.4 it becomes certain that to achieve a small footprint and a low sensitivity to wavelength and fabrication process variations the device should have a short length. This corresponds to a narrow gap between the coupled waveguides and a low interference order. Regarding the results presented in section 3.5, for the photonic directional coupler to feature low bend losses, the curved waveguides should be designed with a small bend angle and bend radius not smaller than $2\text{ }\mu\text{m}$. However, to design the bend radius, accurate mode mismatch loss simulations should also be performed and taken into account.

The simulations performed for the SiO_2 and air substrates, respectively for the beamsplitter and switch configurations, produced fundamentally equivalent results. However, the beamsplitter and the switch designs are examined separately, since for the switch the MEMS actuation mechanism should additionally be taken into account on how it affects the optimum design parameters. Therefore the switch design principles follow the actuation mechanism simulations that are presented in the subsequent chapter.

4

Optical MEMS switch design

This chapter focuses on the implementation of the photonic directional coupler into an optical MEMS switch design with optimized performance in terms of actuation voltage and footprint. For this purpose, the study of the optical MEMS switch is broken down into its two main components: the photonic part and the actuation mechanism. In this context, the analysis begins with the photonic components by first studying which directional coupler design parameters can be adjusted toward the performance optimization of the MEMS switch. Subsequently, the emphasis is placed on the design of the actuator by analyzing the relevant trade-offs. In this analysis, two actuation mechanisms are examined: the comb-drive actuator and the cantilever beam, which were presented in detail in Chapter 2.

4.1. Directional coupler for MEMS switch design

This section continues the analysis of the photonic directional coupler performed in the previous chapter. However, the description detailed in this chapter is only relevant to the switching functionality of the directional coupler.

As presented in Section 2.3, the switching activity is based on the displacement of one of the coupled waveguides with respect to the other. The two actuation schemes studied in this report result in displacements along different directions, with the in-plane actuation scheme forcing a lateral displacement, while the out-of-plane actuation scheme induces a vertical displacement. The displacement required for implementing the switching activity corresponds to the situation in which all power exits from Port 3 (on-state), referring to Figures 2.3b and 2.4c. This section aims to explore how large this displacement is by separately examining the two cases of displacement, lateral and vertical, and subsequently by comparing the findings.

The simulations performed in this section utilize the short version of the device shown in Figure, the simulation parameters of Table 3.1 and FEM. In all cases examined, the displacement is swept in the range $[0, 0.7] \mu\text{m}$ and the minimum required displacement is extracted as the value for which the normalized transmission to Port 4, calculated from Eq. (3.2), reaches a threshold value $P_{4,\text{on}}$ close to zero. This threshold value is set by the extinction ratio at the on-state according to the following equation:

$$ER_{\text{on}} = 10 \log \left(\frac{P_{3,\text{on}}}{P_{4,\text{on}}} \right), \quad (4.1)$$

where $P_{3,\text{on}}$ and $P_{4,\text{on}}$ the output powers at Ports 3 and 4 respectively at the on-state of the switch. It is noted that the normalized transmission in Port 3 is derived in a similar way as P_4 , by setting $z = L$ in Eq. (2.19a), or equivalently from the conservation of power in a lossless directional coupler: $P_3 = 1 - P_4$.

The way the switching from the off to the on state was described until now assumes a coupling of $m = 1$. However, the cases of higher interference orders function based on a different principle. Assuming $m = 3$, the on-state (power exiting from Port 3) may not correspond to separating the coupled waveguides sufficiently so that coupling does not take place, but to displacing one waveguide such that the difference $n_{\text{eff},e} - n_{\text{eff},o}$ matches the length of the device, given by Eq. (2.20), to $m = 2$. For this purpose, in the context of the simulation, while displacement is swept, the length $L(m = 2)$ is extracted.

The on-state corresponds to the displacement for which the extracted L ($m = 2$) is derived equal to the actual length L ($m = 3$) of the simulated device. The accuracy with which L ($m = 2$) converges to L ($m = 3$) is related to the ER.

4.1.1. Lateral displacement derivation

The lateral displacement is equivalent to an increased gap between the coupled waveguides and it is studied for both SiO_2 and air substrates (with the SiO_2 substrate simulations only used to support the experiment described in the next chapter). The derived normalized transmissions to Ports 3 and 4 as well as the ER_{on} for $m = 1$ and $g = 0.1 \mu\text{m}$ are given in the plots of Figures 4.1a and 4.1b for SiO_2 and air substrate respectively. The respective plots that illustrate how displacement is derived for structures supporting an interference order of $m = 3$ are shown in Figures 4.2a and 4.2b respectively, with the displacement derived for $g = 0.1 \mu\text{m}$ being indicated.

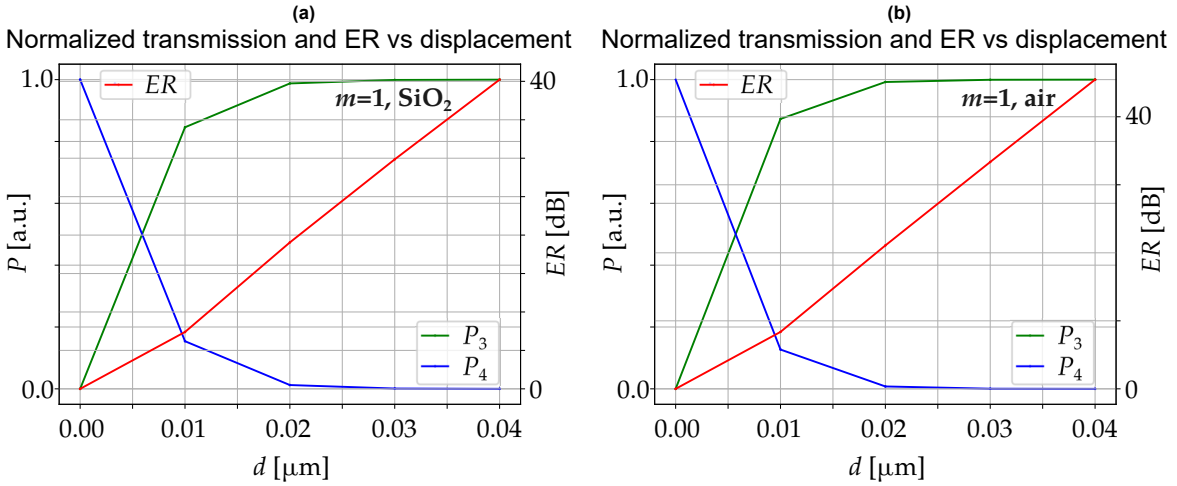


Figure 4.1: Plot of normalized transmissions P_3 and P_4 (left axis) and extinction ratio ER_{on} (right axis) as a function of lateral displacement d in the case of $m = 1$ for (a) SiO_2 , and (b) air substrate.

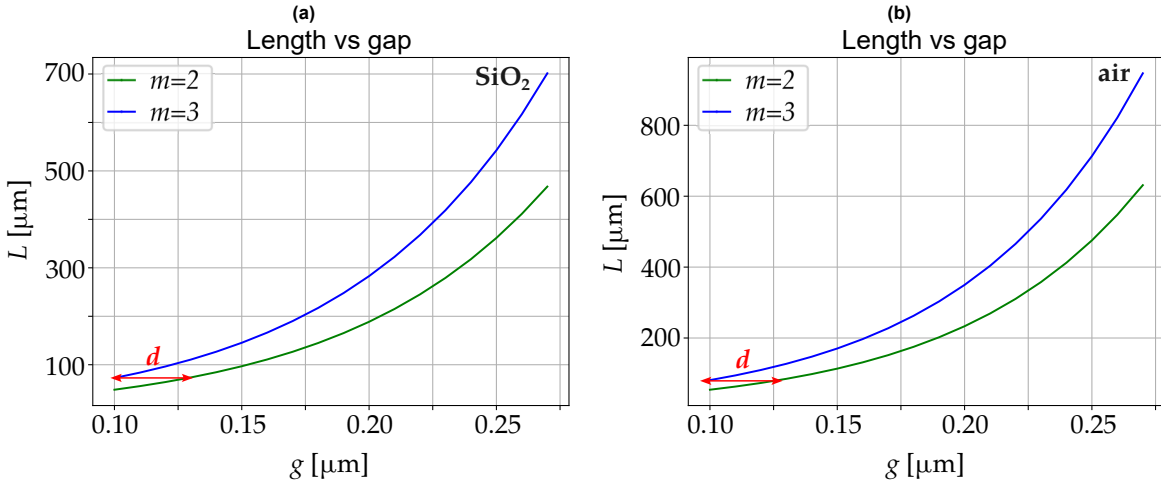


Figure 4.2: Plot of the directional coupler length L as a function of the gap g for $m = 2$ and $m = 3$, in the case of (a) SiO_2 , and (b) air substrates. The plots illustrate the derivation of the lateral displacement d for $g = 0.1 \mu\text{m}$.

The plots of Figure 4.1 indicate how the displacement is chosen for a given ER_{on} specification. From both Figures 4.1 and 4.2 it already becomes obvious that the results produced for the two different substrates are roughly equivalent. The derived displacements for all examined cases are summarized in Figure 4.4.

4.1.2. Vertical displacement derivation

The vertical displacement is only examined for the case of the suspended structure, as the only realistic scenario. The normalized transmissions to Ports 3 and 4 and the ER_{on} for the cases of $m = 1$ and $m = 3$ are given in the plots of Figures 4.3a and 4.3b respectively. It is noted that in Figure 4.3a, the ER_{on} is only plotted for displacements which ensure $P_3 > P_4$, approaching the on-state.

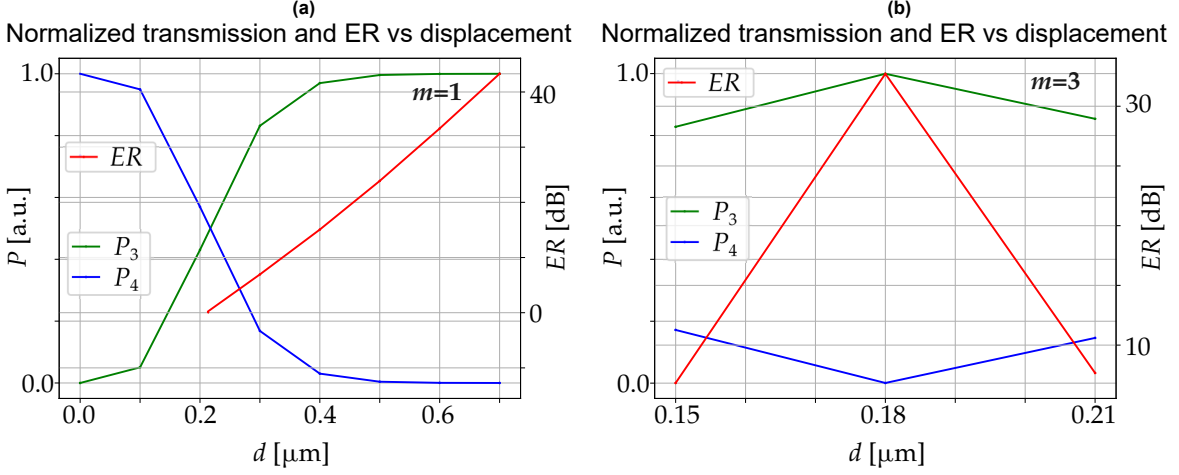


Figure 4.3: Plot of normalized transmissions P_3 and P_4 (left axis) and extinction ratio ER_{on} (right axis) as a function of vertical displacement d for directional couplers with (a) $m = 1$ and $g = 0.1 \mu\text{m}$, and (b) $m = 3$ and $g = 0.2 \mu\text{m}$.

Similarly to the lateral case, in Figure 4.3a the displacement is chosen for a specific ER_{on} requirement, while Figure 4.3b shows how the ER_{on} varies around the required displacement. The derived displacements for all examined cases are provided in Figure 4.4. It is already observed from Figure 4.3 that the displacement required by the $m = 1$ structures is larger than the displacement required by higher interference order structures. One can also observe the sensitivity of the ER_{on} achieved by $m = 3$ structures to small displacements.

4.1.3. Lateral vs vertical displacement

The lateral and vertical displacement results derived in the previous subsections are summarized in the plot of Figure 4.4. It is noted that the plotted displacement values correspond to switching with $ER_{on} = 30 \text{ dB}$.

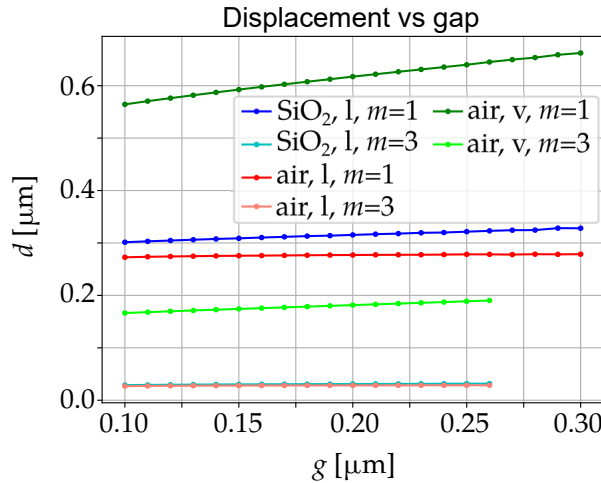


Figure 4.4: Plot of lateral (l) and vertical (v) displacement d as a function of the gap g between the coupled waveguides for $ER_{on} = 30 \text{ dB}$.

Clearly, the displacement required by a switch configuration with a given m , ER_{on} and substrate

remains relatively constant and independent from the gap, especially in the case of lateral displacement. However, there is an observable increase in the required vertical displacement for directional couplers with an increasing gap and length. Additionally, Figure 4.4 clearly illustrates that the structures that support modes of higher interference order m can be switched with smaller displacements. Another important conclusion drawn from this plot is that the required displacement to switch the power from Port 4 to Port 3 is quite larger along the vertical than along the lateral direction. Additionally, there seems to be no linear relationship between the lateral and vertical displacements. The conclusions derived for the required displacement are translated into actuation voltage requirements in the following section.

4.2. Actuation scheme design

This section studies the actuation mechanism and explores the relation between the photonic components, studied in the previous section, and the electrostatic actuator, establishing the design principles of the optical MEMS switch. Two types of actuation mechanisms are examined, one for in-plane and one for out-of-plane actuation. These two mechanisms map to the lateral and vertical displacements analyzed in the previous section. For the in-plane actuation the comb-drive actuator with folded springs is studied, while for the out-of-plane actuation, the cantilever beam is selected, as they were described in Chapter 2. In the following subsections, the key design parameters of two actuation schemes are swept within a range of realistic numerical values aiming to explore the inherent trade-offs and establish the principles for design optimization. The goal of this section is to compare the two schemes in terms of some key performance metrics of the optical MEMS switch: the actuation voltage and the footprint.

4.2.1. In-plane actuation modelling

An example in-plane actuation scheme is represented by the comb-drive actuator of Figure 2.3, with the parameters presented in Table 4.1 [89].

Table 4.1: Numerical values of the parameters used for the modeling of the comb-drive actuator, including Young's modulus E and thickness h of the SiN, the thickness of SiO₂ substrate t_{SiO_2} and the metal layer t_{m} , the maximum required lateral displacement d derived in Section 4.1, the number of fingers of each comb component N_{f} , the width w_{f} and length L_{f} of each finger, the gap g_{f} between two neighboring fingers, the nominal lateral overlap between the fingers related to the distance between the comb components as $x_0 = L_{\text{f}} - \text{overlap}$, the number of folded springs N_{s} and the width w_{s} and the length L_{s} of the spring.

Parameter	Value
E	180 GPa [25]
h	0.25 μm
t_{SiO_2}	2 μm
t_{m}	0.25 μm
d	0.28 μm
N_{f}	40
w_{f}	300 nm
L_{f}	1.3 μm
g_{f}	200 nm
<i>overlap</i>	200 μm
N_{s}	4
w_{s}	300 nm
L_{s}	15 μm

As previously explained the high actuation voltage reported by similar optical MEMS switch architectures [90] is the primary metric that needs to be optimized to render such devices CMOS-compatible and scalable. For the parameters provided in Table 4.1 the calculated actuation voltage, based on Eq. (2.25), is 20.4 V. It is noted that the lateral displacement required by a directional coupler with $m = 1$ and $g = 0.3 \mu\text{m}$ is taken into account here, as the worst-case scenario. The thickness of the metal layer

t_m is set equal to the SiN thickness h to remove the dependency of the voltage on these two layers (as would be the case for the Si counterparts).

This section attempts a reduction of the actuation voltage to values lower than 5 V to achieve CMOS compatibility. For this purpose, the design parameters that can affect the actuation voltage are swept in a range of fabrication-realistic values. Specifically, the number of fingers N_f is swept in $[10, 50]$ with the upper bound being limited by the device footprint. The widths w_f and w_s of the fingers and the springs are swept in the ranges $[0.05, 1] \mu\text{m}$ and $[0.05, 0.35] \mu\text{m}$ respectively, with the lower bounds being limited by the minimum tested width of structures that can be resolved with our current fabrication process. The length L_f of the fingers is swept in the range $[0.5, 6] \mu\text{m}$ with the lower bound being limited by the distance between the finger sets, while the overlap between the fingers is swept in $[0.05, 0.9] \mu\text{m}$ with the upper bound being limited by the stability of the structure. The gap between the fingers g_f is swept in $[0.1, 0.7] \mu\text{m}$ with the lower bound being limited by the fabrication process. The derived plots of the actuation voltage as a function of g_f and w_f , L_f and *overlap*, N_f and the spring design parameters L_s and w_s are shown in Figures 4.5a, 4.5b, 4.5c and 4.5d respectively. For the derivation of the actuation voltage in each one of the plots, the parameters that are not swept correspond to the ones given in Table 4.1.

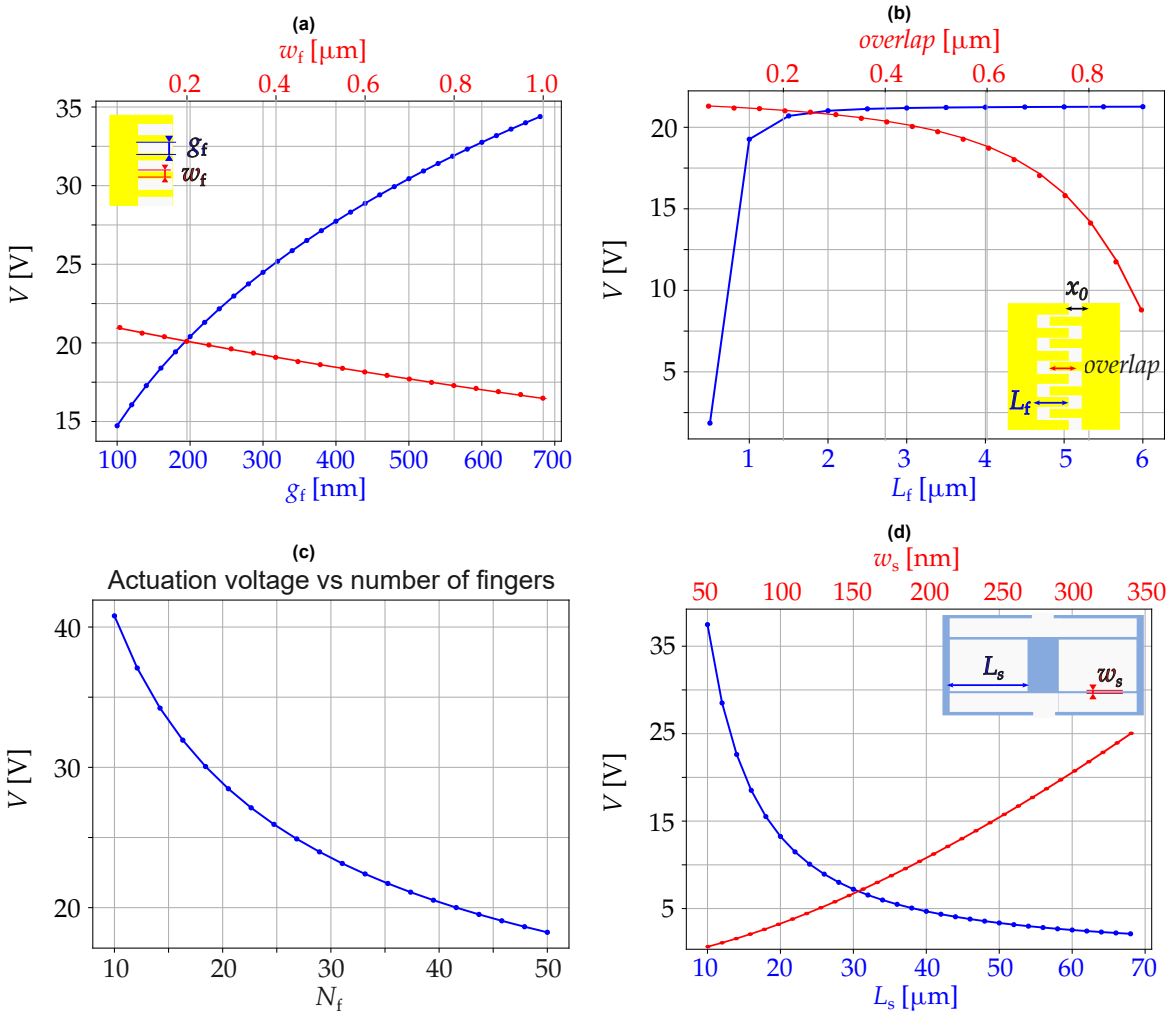


Figure 4.5: Plot of the actuation voltage V as a function of (a) the gap g_f (blue) and the width w_f (red) of the fingers, (b) the length L_f (blue) and the overlap (red) between the fingers, (c) the number N_f of fingers, and (d) the length L_s (blue) and width w_s (red) of the spring.

Taking a closer look at Figure 4.5, it becomes evident that certain design parameters can reduce the actuation voltage more effectively than others. The parameter that seems to have a dominant effect on the actuation voltage is the spring length L_s . Therefore, the proposed design approach here

is increasing the spring length to a value that will not affect the footprint and tuning the rest of the parameters appropriately.

Regarding the footprint, it is obvious from Figure 2.3, that the size of the device along the x -axis is primarily determined by the mechanics and secondarily by L_f , g and w . The design of the mechanics is beyond the scope of this project, therefore, a similar design is deployed from the available literature [51] to roughly estimate the footprint of the device. In this context, the size of the mechanics along the x -axis is considered roughly equal to $60 \mu\text{m}$. Additionally, considering that the parameters w_f , g_f and N_f are roughly set by the fabrication process and the actuation voltage requirements, not providing significant tuning flexibility, the size of the device along the z -axis is dominated either by the spring length L_s or the total length of the directional coupler. Specifically, if an $m = 1$ directional coupler is selected, L approaches $120 \mu\text{m}$ for $g = 0.2 \mu\text{m}$ (Figure 3.4), and including S-bends for $\varphi = 30^\circ$ and $R = 10 \mu\text{m}$ in this calculation, the length reaches $140 \mu\text{m}$, allowing the L_s to go up to $40 \mu\text{m}$ without altering the footprint. This is also the case if $m = 3$ is selected for the directional coupler. Taking these into account, a rough estimation of the footprint of the device is given by the following formula:

$$\text{Footprint}_{\text{comb}} = (L + 4R \sin \varphi) \times (x_0 + 2w + g + 2R(1 - \cos \varphi) + x_{\text{mechanics}}), \quad (4.2)$$

where $x_{\text{mechanics}}$ is found in [51]. If a directional coupler of $g \leq 0.15 \mu\text{m}$ is selected, the first one of the factors in Eq. (4.2) should be replaced by $(2L_s + L_{\text{shuttle}})$, since in this case the spring length dominates the footprint along x -axis. L_{shuttle} is the length of the shuttle to which the springs are attached (Figure 2.3). The metal pads where the voltage is applied are not considered in this footprint estimation.

Now, taking these footprint considerations into account, to lower the actuation voltage below 5 V the spring design is tuned with the length of the spring set equal to $L_s = 35 \mu\text{m}$ and the width of the spring equal to $w_s = 250 \text{ nm}$, while the rest of the design parameters are the ones shown in Table 4.1. It is noted that this design would require special considerations of the mechanics of the spring, however, the realization of this device is beyond the scope of this project and is only examined theoretically. With these adjustments, the actuation voltage as a function of the displacement is given in Figure 4.6. The pull-in voltage and the corresponding maximum allowed displacement are marked with the dotted line. This line represents the transition from the stable to the unstable operation region of the actuator.

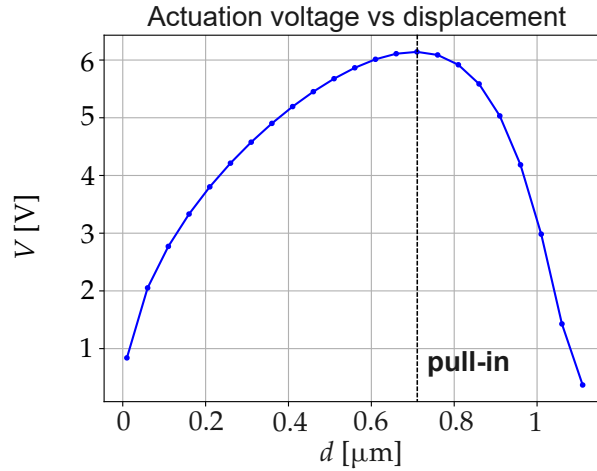


Figure 4.6: Plot of the actuation voltage V as a function of the lateral displacement d . The dotted line marks the displacement at which the pull-in effect occurs.

4.2.2. Out-of-plane actuation modelling

For the out-of-plane actuation scheme, the cantilever beam of Figure 2.4 is deployed. The design parameters used for the modeling of the structure are given in Table 4.2 [25]. The width of the cantilever beam is set equal to the length of the directional coupler so that the suspended waveguides are sufficiently supported, although no mechanical simulations were performed in this project. It is noted that only Young's modulus of SiN is considered.

Similarly to the previously examined actuation mechanism, here again, studying the design parameters that could be tuned toward reducing the actuation voltage is the main focus. The case of the

Table 4.2: Numerical values of the parameters used for the modeling of the cantilever beam, including Young's modulus E and thickness h of the SiN, the thickness of SiO₂ substrate t_{SiO_2} , the thickness of the metal layer related to the total beam thickness based on $t_m = t_b - h$, the maximum required vertical displacement derived in Section 4.1, the width w_b and length L_b of the beam and the total length of the supporting structures L_{support} that connect the waveguides to the beam.

Parameter	Value
E	180 GPa [25]
h	0.25 μm
t_{SiO_2}	2 μm
t_m	100 nm
d	0.66 μm
w_b	L
L_b	10 μm
L_{support}	1.85 μm

cantilever beam is especially challenging to design for CMOS-compatible actuation voltage since the reported voltage values so far reach up to 300 V, while for the parameters of Table 4.2 the actuation voltage is calculated equal to 269.7 V, for the vertical displacement required by the directional coupler with $m = 1$ and $g = 0.3 \mu\text{m}$. Based on Eq. (2.30), the main design parameters that can be explored for the case of this actuator are the length and the thickness of the beam. Considering that the thickness h of SiN layer is determined by the foundry, only the thickness of the metal layer is tunable in a real scenario. Sweeping L_b and t_m in the ranges $[8, 43] \mu\text{m}$ and $[10, 100] \text{ nm}$ respectively results in the plots of Figure 4.7a. The sweep range of the beam length is not extended to larger values which would correspond to a decrease in the resonance frequency resulting in the beam coupling to vibrations [30]. Generally, the oxide thickness also affects the actuation voltage, but similarly to the SiN thickness, it is determined by the foundry. However, it is worth investigating how both of these layer thicknesses could affect the actuation voltage with the corresponding plot shown in Figure 4.7b. For the derivation of the actuation voltage in each of the presented plots, the parameters that are not swept correspond to the ones given in Table 4.2.

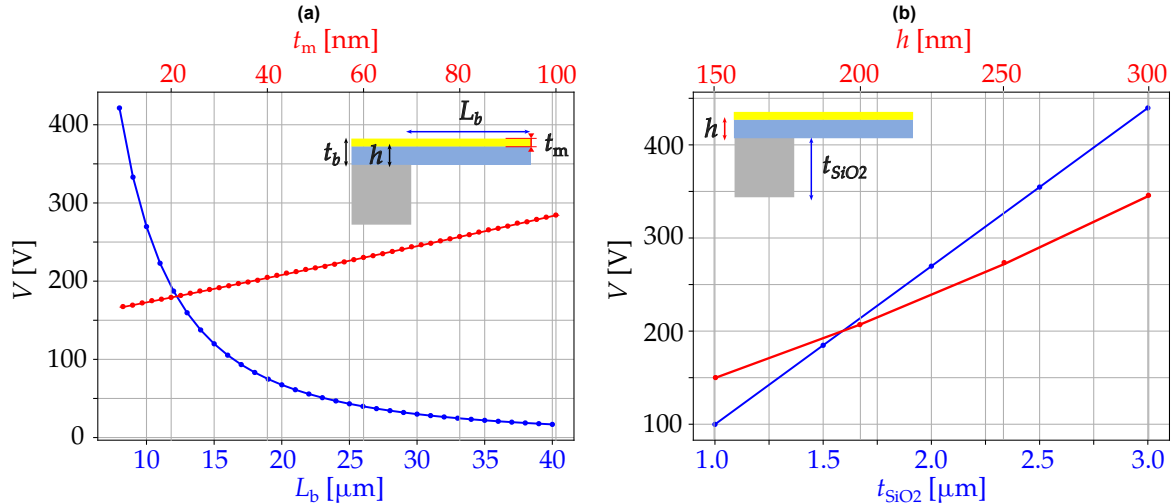


Figure 4.7: Plot of the actuation voltage V as a function of (a) the beam length L_b (blue) and the thickness of the metal layer t_m (red), and (b) the thickness of the SiO₂ bottom layer t_{SiO_2} (blue) and the thickness of the SiN layer h (red).

From Figure 4.7, it becomes clear that setting the beam length equal to values close to the upper bound of the examined range is the most effective way to approach CMOS-compatible operation. However, taking into account also Figure 4.7b it becomes obvious that for transitioning to actuation voltage values below 10 V with this actuation mechanism it is essential that the selection of foundry wafers

should prioritize smaller oxide thickness and/or lower SiN thickness. For the rest of the present report, the foundry-determined t_{SiO_2} and h are set to the values provided in Table 4.2.

Regarding, now the footprint, there are certain considerations that need to be taken into account. It is clear that along the z -axis (propagation direction) the size of the device is dominated by the beam width (equal to the length of the coupled waveguides) and the S-bends. Along the x -axis the size is primarily determined by the beam length, considering that the design parameters of the directional coupler and the supporting anchors are relatively fixed. The length of the fixed part of the cantilever beam, which is related to the mechanical stability of the structure, also contributes to the footprint. This length is assumed to be equal to the beam length both here and in Chapter 6, however, a careful consideration of the mechanics of the structure is required to optimize this parameter towards a smaller footprint. Taking all these into account, a rough estimation of the footprint is provided by the following formula:

$$\text{Footprint}_{\text{beam}} = (L + 4R \sin \varphi) \times (2w + g + 2L_{\text{support}} + 4L_b). \quad (4.3)$$

The design of the supporting anchors is not optimized in this project and is found in literature [25]. The metal pads are not included in the calculation.

Considering the footprint limitations, the design optimization for lower actuation voltage is performed primarily by reducing the metal layer thickness to the lowest possible value and then tuning the beam length appropriately. In this context, these two parameters are set equal to $t_m = 10 \text{ nm}$ and $L_b = 40 \mu\text{m}$ respectively. The corresponding simulated actuation voltage as a function of displacement is shown in Figure 4.8. The plot also illustrates the maximum allowed displacement at which the pull-in effect occurs.

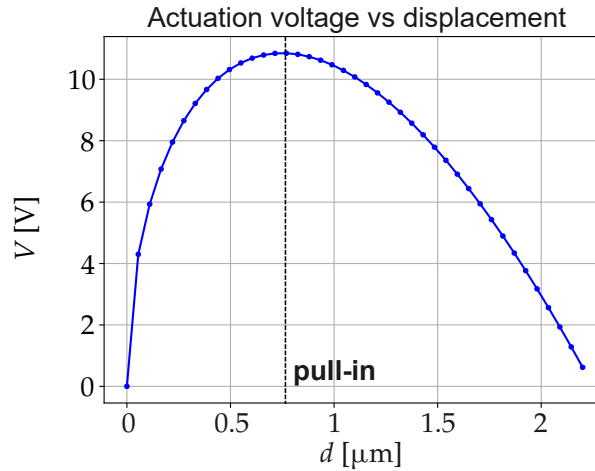


Figure 4.8: Plot of the actuation voltage V as a function of the vertical displacement d . The dotted line marks the displacement at which the pull-in effect occurs.

It is observed that for displacements around $0.6 \mu\text{m}$ the actuation voltage cannot be reduced to values lower than 10 V with the present foundry. However, for the displacements around $0.2 \mu\text{m}$ required by directional couplers that support higher-order interference $m = 3$, actuation voltages below 8 V are achievable. A detailed presentation of the two proposed switch designs, as well as comparison of the performances they achieve is performed in the following section.

4.2.3. Comb-drive vs cantilever beam

Looking collectively at the results obtained in this section, for the displacements derived in subsection 4.1.3, the corresponding actuation voltages achieved by the proposed in-plane and out-of-plane actuation mechanisms are plotted in Figure 4.9. For each of the two mechanisms, directional couplers of both $m = 1$ and $m = 3$ are examined. The footprint for $g = 0.2 \mu\text{m}$ derived from Eq. (4.2) and (4.3), as well as the pull-in voltage and the maximum allowed displacement shown in Figures 4.6 and 4.8 for each of the two actuation mechanisms are summarized in Table 4.3.

Obviously, the planar actuation scheme based on the comb drive actuator with folded springs can feature lower actuation voltages and a smaller footprint than the cantilever beam-based actuator. How-

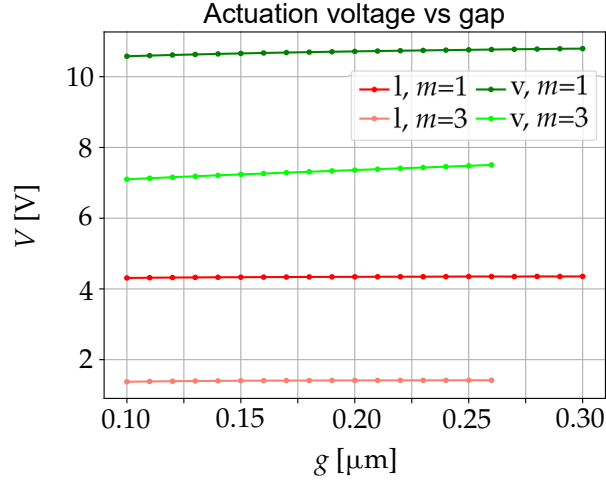


Figure 4.9: Plot of the actuation voltage V , corresponding to the lateral (l) and vertical (v) displacement values for $ER_{\text{on}} = 30$ dB, as a function of the gap g between the coupled waveguides.

Table 4.3: Summary of the performance achieved by the comb drive (CD) and the cantilever beam (CB) actuators, separately examined for directional couplers of $m = 1$ and $m = 3$ and $g = 0.2 \mu\text{m}$, in terms of actuation voltage V , footprint, pull-in voltage $V_{\text{pull-in}}$ and maximum allowed displacement d_{max} .

Configuration	V [V]	Footprint [$\mu\text{m} \times \mu\text{m}$]	$V_{\text{pull-in}}$ [V]	d_{max} [μm]
CD $m = 1$	4.34	137×65	6.14	0.71
CD $m = 3$	1.41	390×65	6.14	0.71
CB $m = 1$	10.72	137×165	10.85	0.77
CB $m = 3$	7.51	390×165	10.85	0.77

ever, even the cantilever beam can approach CMOS-compatible voltages, especially if the integrated directional coupler operates between the interference orders $m = 3$ and $m = 2$ and foundry wafers with lower SiN and oxide thickness are selected. As far as the footprint is concerned, careful consideration of the mechanics of both actuator mechanisms may allow for reducing down to smaller sizes. It is noted that the footprints presented in Table 4.3 correspond to the worst-case scenarios of $g = 0.2 \mu\text{m}$ and that all examined configurations can achieve footprints that fulfill the project goals for smaller gaps.

4.3. Summary

This chapter closes with a summary of the key conclusions drawn from the analysis of both the photonic part and the actuation mechanism comprising an optical MEMS switch. Regarding the photonic part, from section 4.1 it becomes clear that leveraging the extremely low displacement that the 3rd-order interference directional couplers require is very advantageous, regardless of the actuation scheme, concluding on the directional coupler design optimization for application in a switch configuration.

Focusing on the actuation schemes, for both in-plane and out-of-plane actuation the trade-off between actuation voltage and footprint has been thoroughly examined, and optimized designs have been proposed. The comb drive actuator can achieve CMOS-compatible voltages, with a relatively small footprint achieving the set project goals with $m = 1$ and $g = 0.2 \mu\text{m}$, showing a clear advantage compared to the cantilever beam actuator performance. However, all the configurations examined in subsection 4.2 can achieve the project goals, with g tuned appropriately. Taking these into consideration, combined with the time-restricted nature of the present project and the design and fabrication complexity of the comb drive actuator, only the cantilever beam is realized experimentally. The architecture of the cantilever beam-based actuator is simple in terms of mechanical design and operation compared to the comb-drive actuator which requires special consideration of the folded spring-based components to reach an optimized functional design. The fabrication of the cantilever beam and the derived results are detailed in the following chapters.

5

Device fabrication

This chapter describes the procedure followed to establish the fabrication processes of the photonic directional coupler and the optical MEMS switch. The procedure begins with a brief description of the design considerations taken into account for the directional coupler fabrication and the measurement setup used for obtaining the results. Continuing, the fabrication issues tackled in this project are analyzed by explicitly presenting the conducted experiments. The second part of this chapter focuses on the design and fabrication process details of the optical MEMS switch. Lastly, the conclusions drawn in this chapter are summarized in the final section.

5.1. Photonic directional coupler fabrication

5.1.1. Design layout and measurement setup

Aiming to study the directional coupler design trade-offs set by the fabrication process as well as confirm or disprove the conclusions derived from the simulations, several devices of different (g, L) sets, as well as devices supporting different interference orders are included in the design layout. For certain g and m , the L is derived from Eq. (2.18), based on the effective refractive index difference extracted from simulations. Additionally, versions of the devices with $m = 1$ and $m = 3$ are included with varying lateral displacement between the coupled waveguides modeled as an extension of the gap. With these devices, the validity of lateral displacement results presented in Section 4.1 is intended to be investigated confirming or disproving the actuation voltage performance predicted for the comb-drive actuator scheme. No attempt to confirm the loss simulations is made, due to the sidewall roughness of the waveguides that significantly increased the loss of the fabricated devices compared to the simulated ones. It is noted that optimizing the waveguide fabrication process for lower propagation loss is beyond the scope of this project. The layout includes directional couplers with the design parameters shown in Table 5.1. An example directional coupler layout as well as more details about the design can be found in Appendix B.

Table 5.1: Numerical value ranges of the waveguide width w , the gap g between the coupled waveguides, the interference order m , the bend radius R , the bend angle φ and the displacement d that correspond to directional couplers included in the layout.

Parameter	Value
w	$0.4 \mu\text{m}$
g	$[0.1, 0.3] \mu\text{m}$
m	$\{1/2, 1, 3/2, 3\}$
d	$[0, 0.4] \mu\text{m}$
R	$25 \mu\text{m}$
φ	45°

The measurement setups used for this project are shown in Figure 5.1, and they are similar in their principle. The difference between the measurements with the two different setups is the angle at which light is coupled to the grating couplers, 18° for the setup of Figure 5.1a, set in advance, and 24° with the setup of Figure 5.1b, optimized for maximum coupling. It is noted that both setups were used for collecting the ratios of the extracted output powers, and therefore, potential differences in the input and output power levels between the different setups or even between different measurement sessions do not affect the validity of the results.

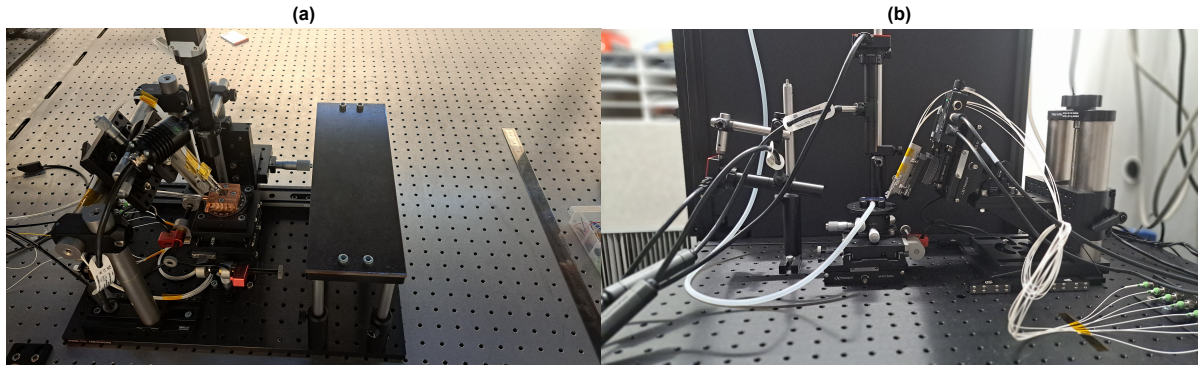


Figure 5.1: Setups for optical measurements consisting of the alignment stage where the sample is placed, the fiber array, and a camera.

Both narrowband and broadband measurements are performed. The light source used for the narrowband measurements is a laser diode (LD) with emission at 633 nm , while for the broadband measurements, a superluminescent diode (SLD) with a center wavelength at 635 nm and 6 nm 3dB-bandwidth is used. In both cases, the light source is connected to the fiber array through a paddle polarisation controller for polarization optimization for maximum power. A camera is used for real-time visualization of the alignment and light coupling process. The output fiber is connected to a power meter in the case of the narrowband and to a spectrometer in the case of the broadband measurements. In both cases, the data are extracted as output power at Ports 3 and 4.

5.1.2. Photonic directional coupler fabrication

The process recipe used for the fabrication of the photonic directional coupler is similar to the recipe established for the photonic waveguide fabrication. However, certain adjustments are still made due to fabrication issues related to the structure of the directional coupler. A detailed description of the process recipe is provided in Appendix B.

The directional coupler fabrication is based on the patterning of the SiN layer, which is performed with Electron-beam (E-beam) exposure, development, and etching steps. The patterning is performed with positive resist, meaning that a $3\text{ }\mu\text{m}$ -wide area around the structures is exposed with E-beam. This results in waveguide structures with lower sidewall roughness and, thus, lower propagation losses. The directional coupler fabrication process, compared to the standard waveguide fabrication, should tackle potential issues that arise from the narrow gap regions between the waveguides. In this context, the development and etching steps are reviewed and adjusted accordingly to ensure effective patterning even of the small-size features included in the layout. Specifically, the development time is examined and the etching is attempted with and without a carrier wafer. The adjustments are described explicitly in the following subparagraph.

Aspect ratio dependent fabrication - Issue identification

A crucial fabrication issue addressed in this project is the difficulty in fully etching SiN in the gap regions between the coupled waveguides. The structures obtained from two fabrication runs are used to characterize this issue. Both samples are fabricated using the recipe introduced in the previous subsection, but for 1 min development time and etching without a carrier wafer. The second sample is additionally overetched for three minutes, in an attempt to investigate the effect of etching duration on the issue. The samples obtained after these two fabrication runs are measured using the setup of Figure 5.1a,

and the measurement results are shown in Figures 5.2a and 5.2b respectively for beamsplitters and switch configurations of different g and m . The measurement results are expressed in the form of the normalized transmission to Port 4 which is calculated from the extracted output powers as follows:

$$P_4 = \frac{P_{\text{Port4}}}{P_{\text{Port3}} + P_{\text{Port4}}}, \quad (5.1)$$

where P_{Port3} and P_{Port4} the measured power at Ports 3 and 4 respectively, after normalization with the power extracted from the reference structures Ref3 and Ref4 (Figure B.2a) respectively. These measurements were performed with the LD at 633 nm.

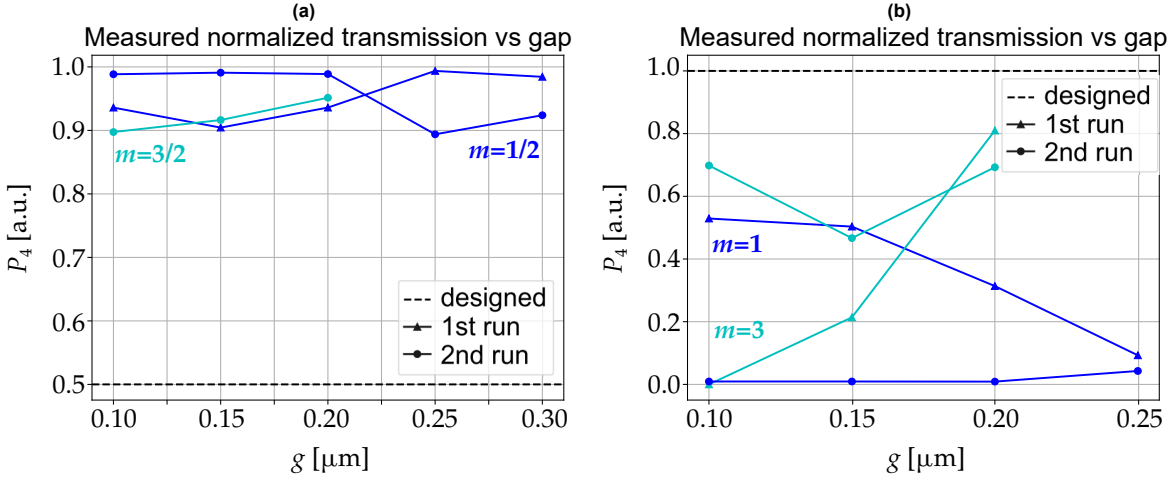


Figure 5.2: Plot of the measured normalized transmission P_4 at 633 nm as a function of the designed gap g between the coupled waveguides for (a) beamsplitters of $m = 1/2$ and $m = 3/2$, and (b) switch configurations of $m = 1$ and $m = 3$. The results come from two different samples (1st and 2nd fabrication run). The dotted lines mark the expected normalized transmission based on the design parameters.

From Figure 5.2 it becomes clear that the behaviour of the fabricated devices deviates significantly from the designed behaviour. It also becomes evident that the issue affects all designed gaps, and is not resolved with overetching (2nd fabrication run). This observation reflects the criticality of this issue. As previously explained, the directional couplers included in the layout have been designed through simulations to behave either as beamsplitters or as switches in their off-state (full power transfer at Port4), with careful selection of the gap and the corresponding coupling lengths. However, the behaviour obtained in Figures 5.2 suggests that the fabricated devices have an effectively narrower gap, which acts towards reducing the effective coupling length, based on Figure 3.4.

The obtained directional coupler behaviour was attributed to a residual SiN layer existing in the narrow region between the waveguides. Due to the higher effective index SiN features compared to air, the existence of a SiN layer instead of air in the gap causes the propagating modes to confine closer to the inner sidewalls of the coupled waveguides, making the coupling stronger. The thickness of this layer is expected to be small considering the fact that it is not inspectable in a top view SEM image, like the one shown in Figure 5.3a, rendering this issue even more challenging to tackle. In an attempt to observe the remaining SiN layer, the sample is cleaved along the coupling region and subsequently subjected to a 1.5 min-long wet-etching step with Buffered Oxide Etch (BOE) 7:1, aiming to remove part of the bottom cladding SiO_2 at the cross-section region, increasing the layer contrast under SEM. This approach makes the remaining thin SiN layer inspectable, both in top and side view as seen in Figures 5.3b and 5.3c respectively. The existence of SiN, rather than any other material (like resist residues) in the gap is confirmed additionally under SEM Nova Nano, with the results shown in Figure 5.3d.

To fully characterize this phenomenon the thickness of the remaining SiN layer is estimated using simulations and based on the measurement results collected from the two fabricated samples. This estimation is based on the modeling of the structure with the cross-section shown in Figure 5.4a, simulated using FEM and the parameters provided in Table 3.1. The additional SiO_2 layer under the waveguides represents the overetching and its height h_{over} is adjusted after the sample is measured with a profilometer. The thickness t_{SiN} of the inner SiN layer is swept in the range $[0.01, 0.1] \mu\text{m}$ with

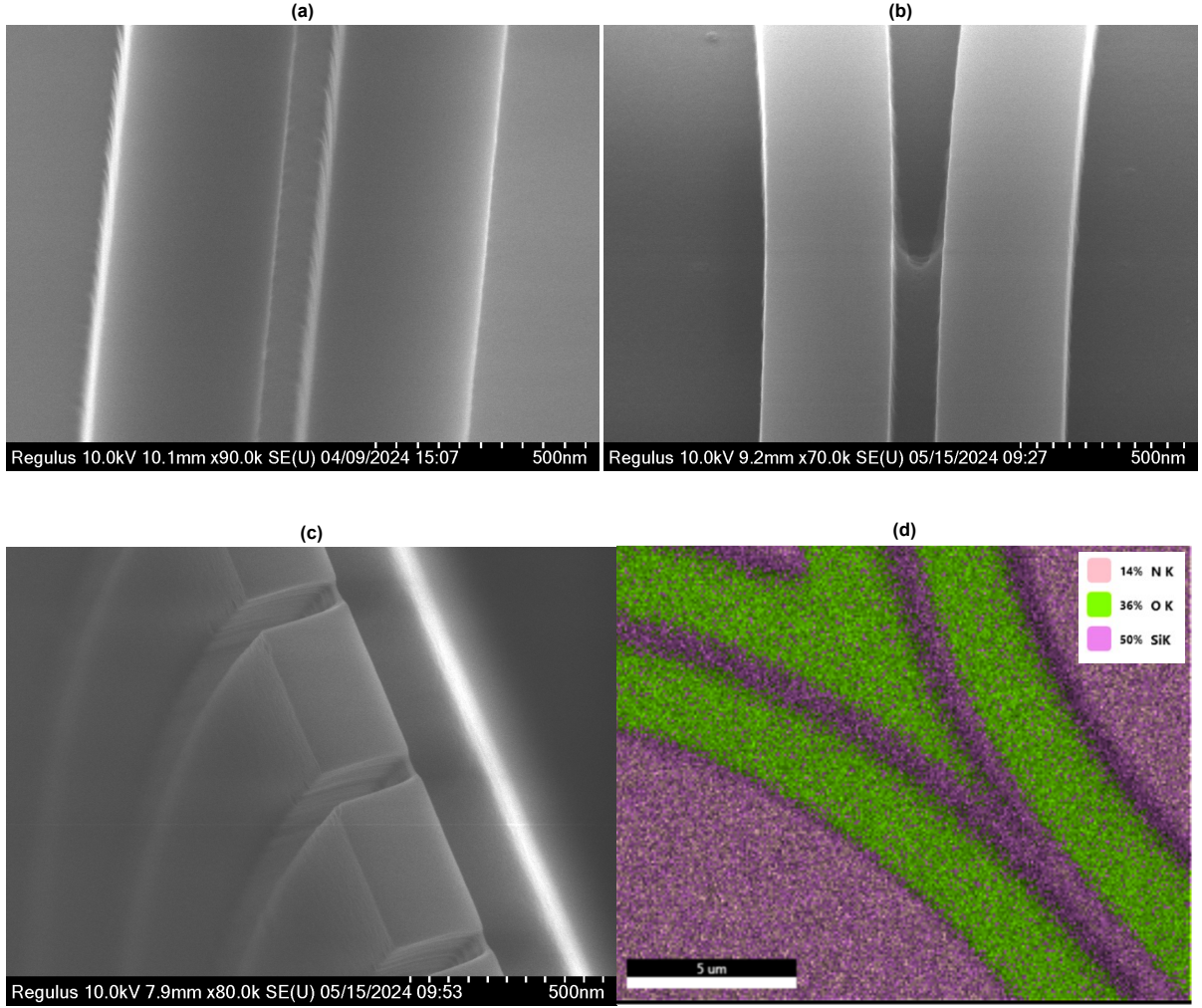


Figure 5.3: (a) Top-view SEM of a directional coupler from the first fabrication run illustrating that the residual thin SiN layer between the coupled waveguides is hardly observable, (b) top, (c) side view SEM of the HF-etched sample revealing the thin SiN layer remaining in the narrow-gap areas, and (d) top-view Nova Nano EDX spectroscopy of a directional coupler from the second fabrication run indicating that SiN is not completely etched in the narrow-gap region between the coupled waveguides.

a step size of 5 nm. For each simulated t_{SiN} , the normalized transmission in Port 4 is calculated using Eq. (3.2) as a function of the gap ranging in $[0.1, 0.3] \mu\text{m}$. Subsequently, the measurement results are roughly matched to a (t_{SiN}, g) set which represents the estimation of t_{SiN} for a given gap g . The derived results of the estimated t_{SiN} as a function of g are shown in Figure 5.4b. The corresponding plots of the designed, the measured (fabricated), and the estimated (simulated) normalized transmission for both of the fabricated samples are shown in Figures 5.4c and 5.4d for the beamsplitters and switch configurations respectively.

From Figure 5.4b it becomes obvious that the remaining SiN layer thickness decreases with an increasing gap, which is the expected trend for an aspect ratio-dependent effect. Figures 5.4c and 5.4d show that the measurement data do not perfectly agree with the estimated behavior of the fabricated directional couplers. This limited accuracy with which the measurement results are approached in certain cases can be attributed to a number of differences between the fabricated and the simulated structures. Firstly, the actual refractive indices of SiN and SiO₂ might differ to some extent from the simulated refractive indices set equal to the default values provided by RSoft¹. In the same context, the overetching depth h_{over} , is derived from the inspection of the sample with a profilometer, which

¹They might also differ from wafer to wafer, but this variation is not relevant in this case as both samples are parts of the same wafer

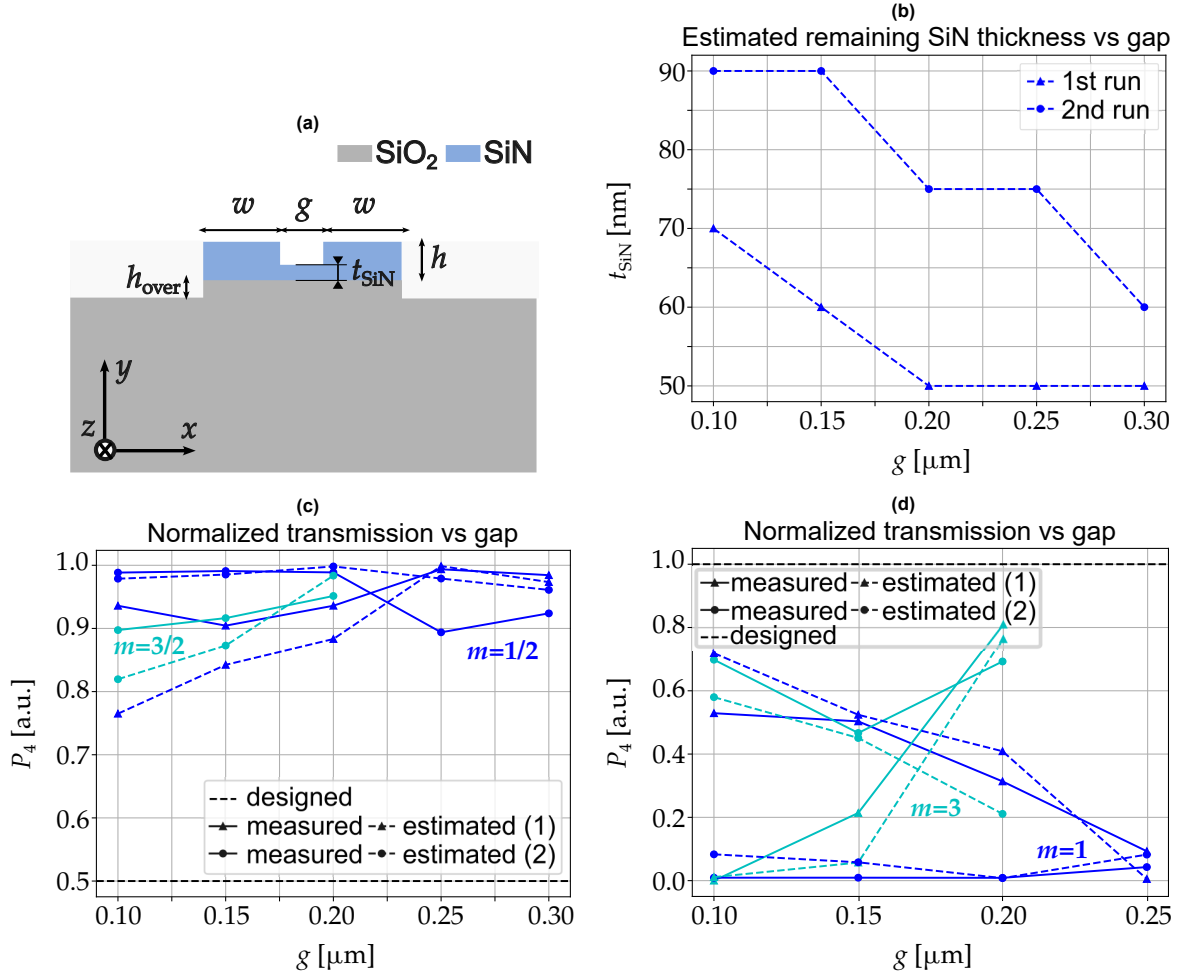


Figure 5.4: (a) Cross-section schematic of the simulated directional couplers incorporating the remaining SiN layer and the overetching effects, (b) Plot of the estimated remaining SiN layer thickness t_{SiN} as a function of the gap g between the coupled waveguides estimated for the two fabricated samples, (c) Plot of the normalized transmission P_4 as a function of the gap g derived from measurements (measured) and FEM simulations with the corresponding estimated t_{SiN} for beam splitters of $m = 1/2$ and $m = 3/2$, and (d) switch configurations of $m = 1$ and $m = 3$. The dotted lines represent the designed values.

features a certain accuracy range. Specifically, the h_{over} value that is applied in the simulation model is the result of multiple measurement repetitions with the profilometer which typically ranged ± 10 nm around the selected value, which based on Figures 3.10 is enough for partially accounting for the achieved estimation accuracy level. Additionally, all structures are simulated with vertical sidewalls and flat surfaces, although this is not always the case for the fabricated structures, especially in the narrow-gap areas, as can be seen in Figure 5.3a. Furthermore, the performed simulations are based on numerical approximations of finite accuracy. Lastly, the accuracy of the measurement results is limited not only because the alignment for maximum coupling is performed manually, but also due to the random conditions affecting the measurement setup.

Aspect ratio dependent fabrication - Solution

The residual SiN layer between the coupled waveguides is a major challenge to be tackled for the successful fabrication of the directional coupler. The reason for this is not only the behavior deviation from the designed performance but most importantly the integration of the directional coupler in the optical MEMS switch device. In the MEMS device the remaining SiN layer will keep the waveguides attached to one another preventing actuation.

The issue of the remaining SiN layer is a result of the aspect ratio-dependent fabrication that results in the high aspect ratio features being inefficiently patterned and requiring adjustments in the fabrication recipe. The most common such effect is the Aspect Ratio Dependent Etching (ARDE), also

known as Reactive Ion Etching (RIE) lag. ARDE is defined as the varying etching rate as a function of the aspect ratio [91]. ARDE is expressed in the higher-aspect ratio structures being etched with a drastically reduced rate, resulting in a non-uniform etch rate and the smallest features, in this case, the narrowest gaps, not being fully etched. Additionally, the remaining SiN layer can be attributed to improper development due to the development rate having a similar dependency on the aspect ratio of the structures [92, 93]. Specifically, the developer flow rate into small features is slowed down resulting in a decreased development rate [93].

Since the issue shown in Figure 5.3 could be a result of a combination of the two potential effects, they are both examined by conducting a common experiment [94]. A trench pattern consisting of waveguides spaced by gaps of width varying in the range $[0.05, 0.6] \mu\text{m}$ is designed. and exposed multiple times on two samples. The two samples are developed for different times, one for 1 min and one for 1.5 min and cleaved along a plane parallel to the trenches, such that intact sets of $[0.05, 0.6] \mu\text{m}$ -wide trenches remain on all parts of the samples. The four parts are etched with RIE, with only two of them being etched on a carrier wafer, while the other two are etched in the absence of a carrier wafer, resulting in the following four test samples:

1. 1 min development and etching without a carrier wafer
2. 1.5 min development and etching without a carrier wafer
3. 1 min development and etching with a carrier wafer
4. 1.5 min development and etching with a carrier wafer

The descum step is omitted to study the effect of the development independently. After etching and resist stripping, the four samples are cleaved along a plane crossing the trenches. The cross-sections of the resulting samples 1,2,3 and 4 are inspected under SEM and the corresponding images are shown in Figures 5.5a, 5.5b, 5.5c and 5.5d respectively.

The inspection of the sample under SEM, as shown in 5.5, cannot result in a reliable estimation of the SiN layer thickness remaining in each gap, due to poor contrast between the SiN and the SiO_2 layer. To enhance the contrast a BOE 7:1 wet-etching step is performed, followed by another inspection of the cross-section under SEM. Based on the last inspection, a rough estimation of the thickness of the remaining SiN layer in the smallest gaps is provided in Table 5.2. It is noted that sample 4 was damaged and no reliable conclusions can be drawn from it. The values missing from Table 5.2 cannot be extracted from inspection due to local damage after the wet etching step. Especially, for gaps larger than $0.1 \mu\text{m}$, the SiN layer is too thin to measure, and in some cases, it collapses.

Table 5.2: Thickness of the remaining SiN layer between the waveguides spaced by gaps equal to $g = [0.05, 0.1, 0.15, 0.2] \mu\text{m}$ on each one of the fabricated test samples. The omitted values cannot be extracted from the available SEM pictures due to damage.

Sample	$g = 0.05 \mu\text{m}$	$g = 0.1 \mu\text{m}$	$g = 0.15 \mu\text{m}$	$g = 0.2 \mu\text{m}$
1		$0.25 \mu\text{m}$		
2	$0.35 \mu\text{m}$	$0.2 \mu\text{m}$	$0.15 \mu\text{m}$	$< 0.1 \mu\text{m}$
3	$0.32 \mu\text{m}$	$0.2 \mu\text{m}$	$< 0.1 \mu\text{m}$	

From the data presented in Table 5.2 useful conclusions are drawn regarding the development time and the etching step that can work towards the improvement of the cross-section profile. Although sample 4 could not be inspected, the obtained profile shown in Figure 5.5d, already shows great improvement in the verticality of the sidewalls and the remaining SiN layer (especially if one looks closer at the narrowest gap). Additionally, the results provided in Table 5.2 indicate that both longer development and etching on a carrier wafer separately achieve lower remaining SiN thickness compared to the case of sample 1. These observations indicate that both development and etching are ineffective in the case of the samples discussed in Figures 5.3.

It is noted that the thicknesses reported in Table 5.2 are much smaller than the ones estimated with simulations as presented in Figure 5.4b. This is attributed to the fact that Table 5.2 only reports the layer thicknesses although an additional effective narrowing of the gap induced by the non-perfectly vertical sidewalls takes place. This is visible in Figure 5.5 in which the narrower the gap, the less vertical and the more rounded the sidewalls look. This effect adds to the layer thickness in terms of the resulting

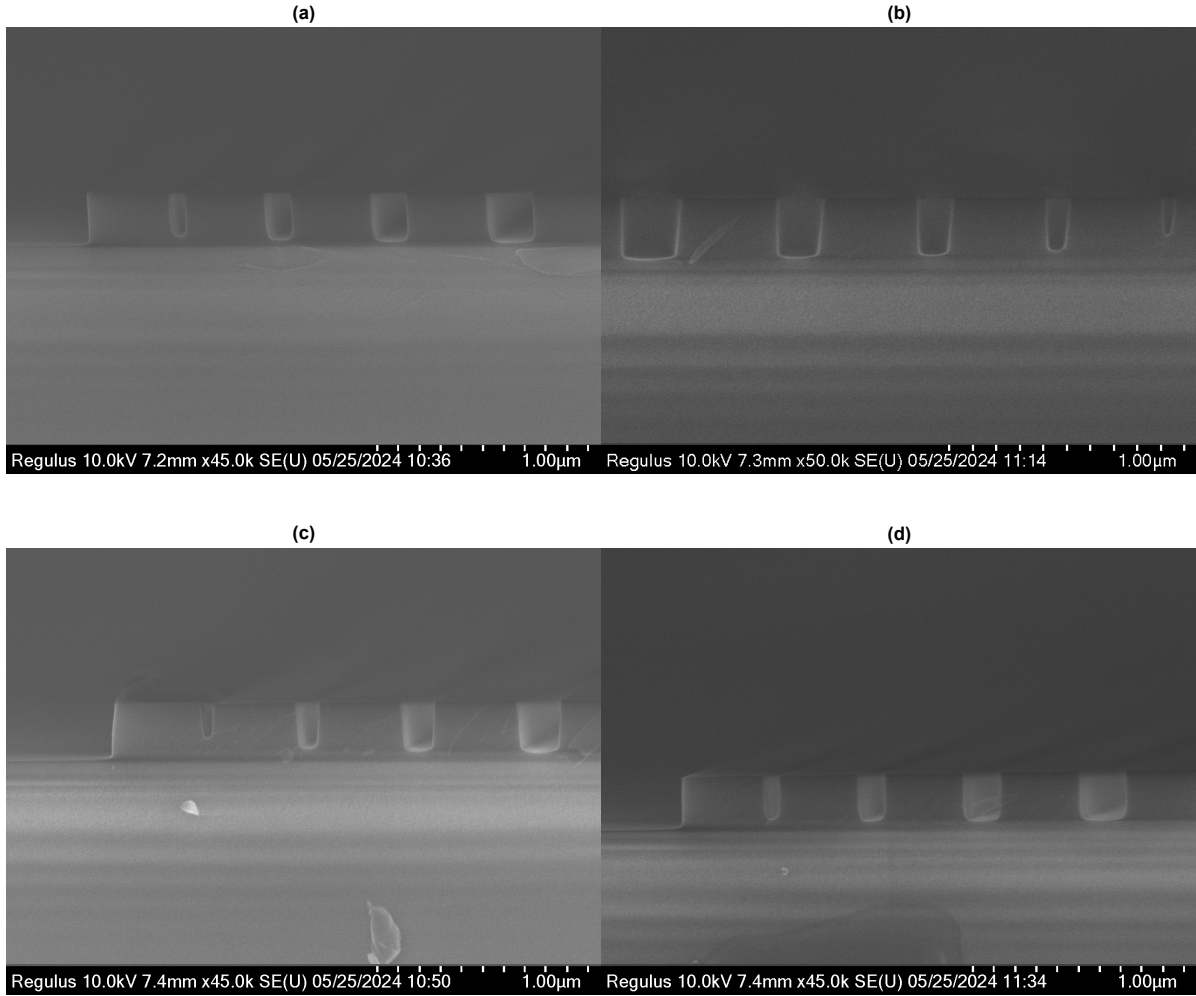


Figure 5.5: Cross-section SEM of the trench pattern patterned with (a) 1 min development and etching without a carrier wafer, (b) 1.5 min development and etching without a carrier wafer, (c) 1 min development and etching with a carrier wafer, and (d) 1.5 min development and etching with a carrier wafer. The first trenches of width in the range $[0.05, 0.6] \mu\text{m}$ with step $0.05 \mu\text{m}$ are illustrated.

directional coupler behavior, which will deviate more from the designed one when the inner sidewalls of the waveguides extend in the region where only air should exist. The result of this effect, although not modeled in the simulated structure of Figure 5.4a, is taken into account in the simulations in the form of an overestimation of the remaining SiN layer thickness.

5.2. Optical MEMS switch fabrication

5.2.1. Design layout

The design layout intended for this fabrication process consisted of three parts, aiming to draw conclusions on the fabrication of different parts of the device independently. Specifically, the first part of the layout contained variations of the optical MEMS switch devices, like the one shown in Figure 2.4. The key parameter that was varied for the designed structures was the beam length, aiming to investigate how the fabrication process applies to devices of different sizes. The design parameters defining the devices included in the layout are given in Table 5.3.

The design of the structure and the number of the anchors attaching the waveguides to the cantilever beam, as shown in Figure 5.6 is beyond the scope of this project and is based on [25]. The disks covering the cantilever, shown both in Figure 2.4a and 5.6 correspond to holes in the real structure intended to let HF reach through SiN and remove the SiO_2 underneath the cantilevers. Therefore, the

Table 5.3: Numerical value ranges of the waveguide width w , the gap g between the coupled waveguides, the bend radius R , the bend angle φ , the beam length L_b , beam width w_b , the length L_{anchor} , width w_{anchor} of the anchor, the length L_{taper} of the taper of the anchors, the length L_{tip} and width w_{tip} of the tip of the anchors, the distance d_{anchor} between the anchors, the radius of the holes on the SiN r_h and the metal layer r_{mh} .

Parameter	Value
w	$0.4 \mu\text{m}$
g	$0.15 \mu\text{m}$
R	$25 \mu\text{m}$
φ	45°
L_b	$\{8, 16, 24, 32, 40\}$
w_b	$109 \mu\text{m}$
L_{anchor}	$1.5 \mu\text{m}$
w_{anchor}	$0.25 \mu\text{m}$
L_{taper}	$1.5 \mu\text{m}$
L_{tip}	$1.6 \mu\text{m}$
w_{tip}	$0.3 \mu\text{m}$
d_{anchor}	$20.9 \mu\text{m}$
r_h	$0.75 \mu\text{m}$
r_{mh}	$0.95 \mu\text{m}$

main consideration when designing the holes is to set the distance d_{holes} between them small enough for the SiO_2 to be completely etched away. Since BOE, utilized for this purpose, is isotropic the distance between the holes is such that the maximum lateral etching distance is not larger than the SiO_2 layer thickness. With this in mind, the diagonal distance between the holes, as shown in Figure 5.6a, is given by the relation $d_{\text{holes}} \leq t_{\text{SiO}_2}/2$. Subsequently, the number of holes is determined by L_b and w_b . The minimum distance between the holes as well as the minimum distance between the holes and the edges d_{edge} of the cantilever is bounded by fabrication limitations and set after multiple fabrication repetitions. Nonuniform development issues (as seen in Appendix B) resulting from the wide range of feature sizes comprising the structure, require scaling up design parameters like the diameter of the holes, the distance between the holes, and the distance between the holes and the edges of the cantilevers.

The second part of the layout contains single cantilevers and the corresponding metal pads, while the photonic components are omitted, as shown in Figure 5.7. The cantilevers included in this part are identical to the ones used in the first part of the layout. The purpose of these structures is to test the fabrication of the cantilevers independently from the photonics.

Lastly, the third part of the layout contains the same single cantilevers as before but without the metal layer, as shown in Figure 5.8a. These structures are intended for experimenting with the fabrication of the SiN cantilevers and drawing conclusions on how the strain properties of SiN impact on the cantilever structure. With this approach, the effect of the metal deposition on the dynamics of the cantilever is examined independently. This part of the layout contains additionally certain test structures, some of which are seen in Figure 5.8b, used for drawing conclusions regarding the strain properties of the material.

5.2.2. Optical MEMS switch fabrication

This section focuses on the fabrication of the design layout detailed in the previous section. The recipe for the fabrication of the photonic directional coupler presented in the previous chapter is integrated into the fabrication process of the optical MEMS switch, which requires additional steps, mainly related to the deposition of metal and the HF wet etching. Metal is deposited to create the metal pads and to make the cantilever beams conductive. HF etching is performed to remove the SiO_2 layer, resulting in the suspended MEMS structures. The process recipe followed for the fabrication of the optical MEMS

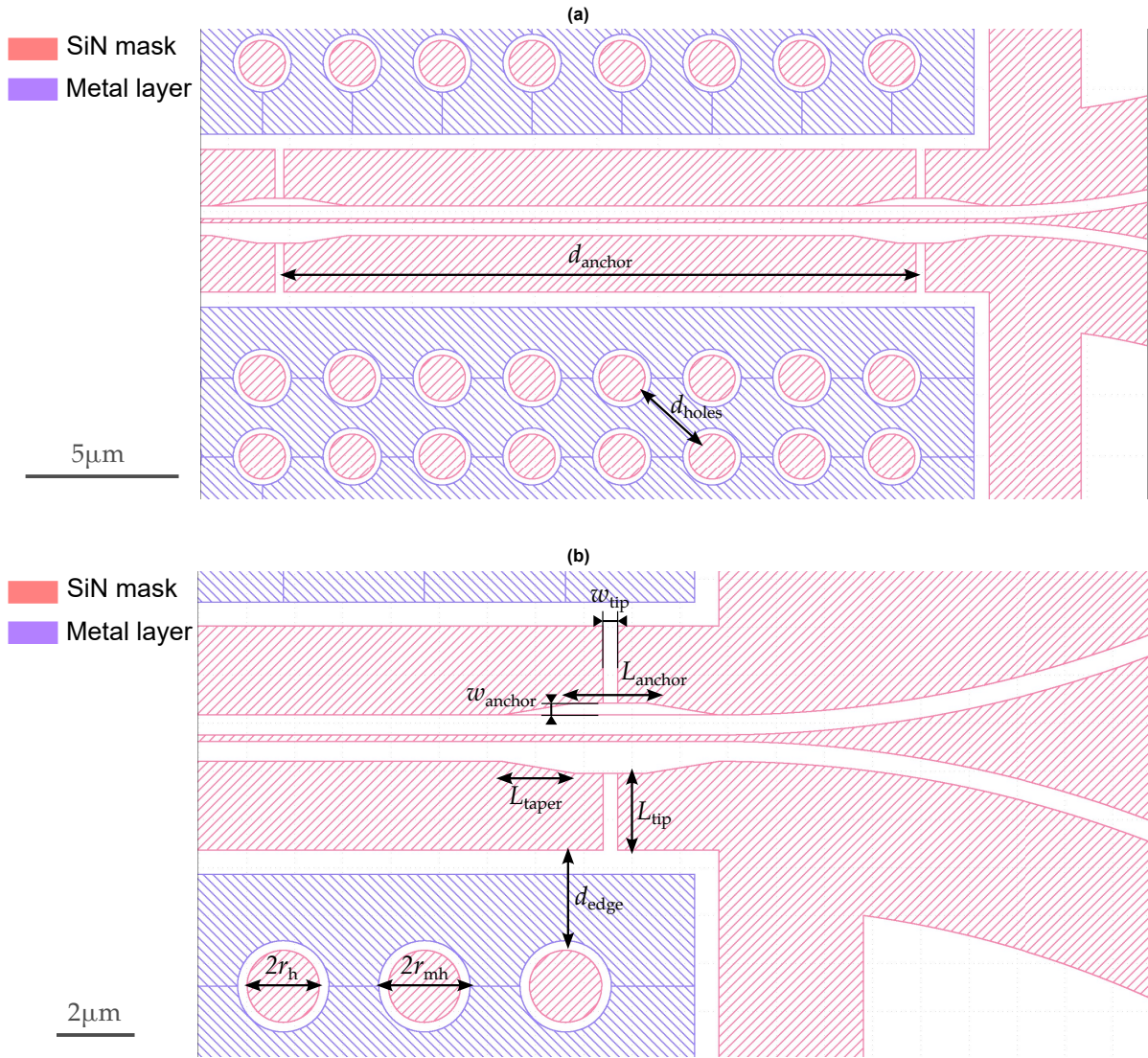


Figure 5.6: Partial layout of the optical MEMS switch focusing on (a) the positioning, and (b) the design of the anchors and the holes. The colored areas correspond to the resist masks and the white areas to the suspended structure.

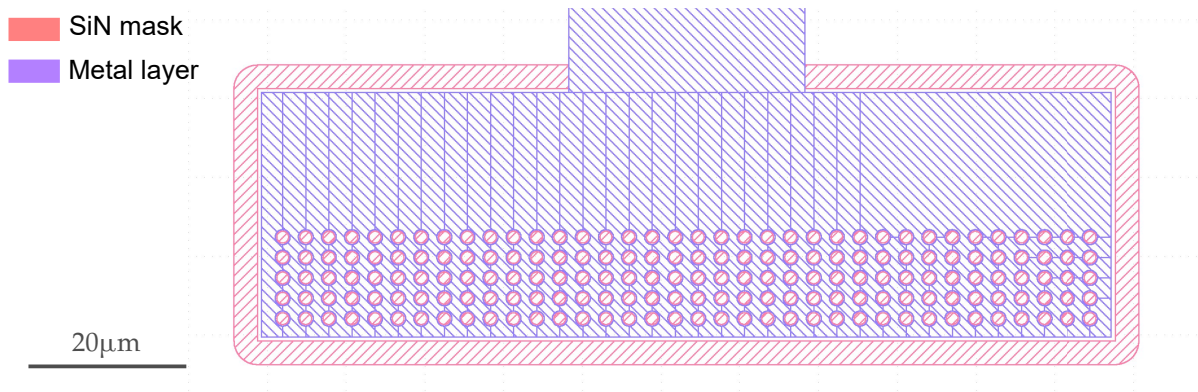


Figure 5.7: Single cantilever beam layout of $L_b = 16\mu\text{m}$ and $w_b = 109\mu\text{m}$. The metal pad is omitted from the illustration. The colored areas correspond to the resist masks.

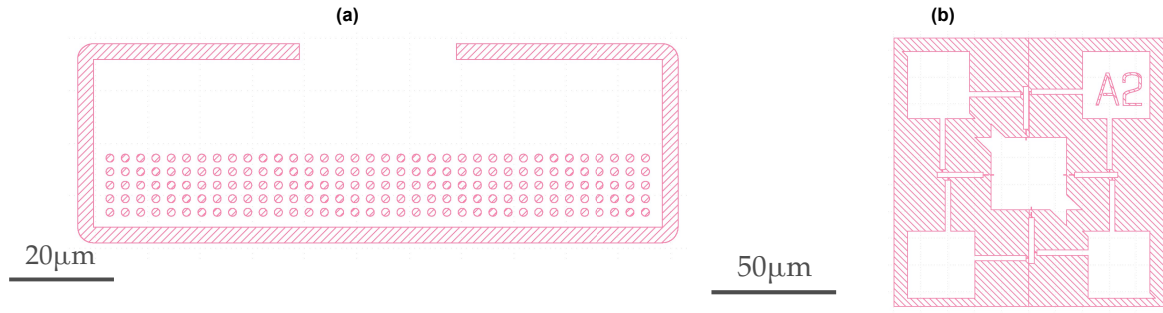


Figure 5.8: Layout of (a) a single cantilever beam, and (b) a strain test structure patterned on the SiN layer. The colored areas correspond to the resist mask and the white areas to the patterned structure.

switch is detailed in Appendix B. The results derived from the inspection of the fabricated samples are also presented in this section.

The process steps comprising the fabrication recipe are established after multiple repetitions of the fabrication process, due to patterning issues detailed in Appendix B. To obtain a sufficient undercut after exposure and development and ensure the metal is present only in well-defined areas, allowing for successful lift-off, lift-off resist precedes the photoresist spin-coating. Regarding the UV exposure, the dose and defocus parameters, in combination with the selected photoresist, were established after multiple attempts of unsuccessful development (see Appendix B). As far as the metal deposition is concerned, the deposited Au layer thickness is not optimized. A thin Cr layer is deposited before Au to enhance adhesion. Both Cr and Au were selected as materials that can withstand the BOE process. Another crucial step in this process is the lift-off which becomes increasingly difficult with the small feature sizes included in the pattern (see Appendix B). NMP is established as the most effective solvent for this process, among other solvents that were tested, like DMSO, DMF, and AR 600-71.

An additional UV exposure and development step is required for the patterning of the HF mask. The HF etching duration is roughly determined based on the BOE standard operating procedure and fine-tuned based on experimental results. Specifically, the sample is cleaved into the three parts of the design and the first part is etched for 30 min and inspected under the SEM, as shown in Figure 5.9. Since BOE is isotropic, the precise etch rate is determined by finding out the lateral distance underneath SiN up to which SiO₂ is removed, which is observed from a color contrast. This distance divided by the etching time gives the etch rate. For the present process, the etching rate was derived to be roughly equal to 75 nm/min. For the samples presented in this section, no HF mask was applied, having the whole surface of the sample etched, releasing all the structures, including the photonics. All cantilevers included in this part of the sample ended up collapsing. It is noted that this first part of the sample is sacrificed for determining the etch rate, and therefore, no further results are extracted from it.

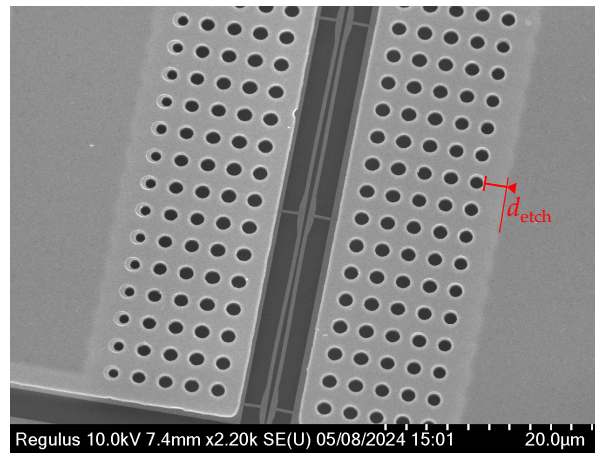


Figure 5.9: Partial top view SEM of the optical MEMS switch after BOE etching. The etching depth is determined from the color contrast observed around the holes and the edges of the cantilever beams, as denoted by d_{etch} .

5.3. Summary

The key conclusion drawn from this chapter is the significance of establishing a fabrication process that can accurately produce the designed structures to achieve the performance goals. The criticality of the aspect ratio-dependent fabrication is illustrated by the significance of the deviation between the designed and fabricated derived directional coupler behavior. The identification of the issue is the first step towards its solution and was only possible after exhaustive inspection of the fabricated samples, simulation tests, and measurements. The establishment of the causes that gave rise to this effect was based on an extensive literature review. The results derived from the trench-pattern fabrication experiment are concrete and useful for adjusting the directional coupler fabrication recipe toward tackling the residual SiN layer. This is attempted in the next chapter.

Addressing the issue of the residual SiN layer is a prerequisite for the successful fabrication of the optical MEMS switch. However, the optical MEMS switch fabrication process is additionally complicated by several other issues presented in this chapter, with the most significant of them being the effect of the feature size on the patterning (UV exposure, development, metal lift-off) of the cantilevers, necessitating design adjustments. Additional fabrication details are addressed in the following chapter in which the resulting fabricated structures are reviewed thoroughly.

Results and discussion

This chapter is dedicated to the results derived from the fabricated photonic directional couplers and optical MEMS switch components. The first part of the chapter details the obtained directional coupler devices after the fabrication recipe was adjusted for high aspect ratio features. The second section presents the obtained MEMS cantilevers and the conclusions drawn from them. The final section discusses the results obtained in this project and indicates solutions for further improvement.

6.1. Photonic directional coupler devices

After fully characterizing the aspect ratio-dependent fabrication issue and updating the fabrication recipe accordingly, the directional coupler fabrication is repeated with the same design layout described earlier in this report. The obtained devices are measured using both the LD and the SLD, for narrowband and broadband measurement respectively. The narrowband measurement results derived from this sample, for beamsplitters and switch configurations, are shown in Figures 6.1a and 6.1b respectively. The fabricated structure was overetched for 3 min, resulting in a $h_{\text{over}} = 20$ nm thick layer of SiO_2 underneath the waveguides. By considering this overetching depth and simulating the structure of Figure 5.4a, as explained previously, the estimation of the t_{SiN} as a function of g is derived as shown in Figure 6.1c. For these estimated thicknesses, the simulated behavior of the fabricated devices is shown in Figures 6.1a and 6.1b.

The measurement results derived from the fabricated switch structures as a function of displacement are presented in Figures 6.2a and 6.2b for directional couplers of $m = 1$ and $m = 3$ respectively. From Figure 6.2a it is clear that for lateral displacement equal to $d = 0.3 \mu\text{m}$ the power received in Port 4 is zero confirming the simulation results shown in Figure 4.4 for the case of SiO_2 substrate. Figure 6.2b gives similar conclusions since for a lateral displacement of $d = 0.03 \mu\text{m}$ the coupling switches to $m = 2$. However, the derived power in this case is offset from zero because of the residual SiN layer which is present at a gap equal to $g + d = 0.18 \mu\text{m}$, which corresponds to the examined case. Taking these results into account, the predicted performance of the fabricated structures is given in Table 6.1. Specifically, for the fabricated beamsplitters the achieved accuracy is presented, while for the switch configurations the predicted extinction ratio for the off- and on-state, as derived based on Figures 6.1b and 6.2, as well as the predicted actuation voltage that would correspond to the suspended version of the devices, based on the confirmed displacement values of Figure 6.2, combined with Figure 4.9. It is noted that it is safe to draw conclusions for the suspended device versions based on the equivalence between the SiO_2 and air substrate lateral displacement results established in Subsection 4.1. The case of $g = 0.1 \mu\text{m}$ is not included in Table 6.1 since it deviates substantially from the designed behavior and the performance cannot be evaluated.

From Figure 6.1 and Table 6.1 it becomes clear that the adjustments made in the recipe resulted in the fabricated structures noticeably approaching the designed directional coupler behavior. Especially for gaps larger than $0.15 \mu\text{m}$ the results are approaching an extinction ratio $ER_{\text{off}} = 20$ dB for the off-state. Based on Figure 6.2a, for displacements equal to $0.3 \mu\text{m}$, the on-state of the switch is achieved with zero power at Port 4, implying an extinction ratio higher than $ER_{\text{on}} = 30$ dB. This is the case for all fabricated $m = 1$ switch structures. However, this might probably be related to the low input powers

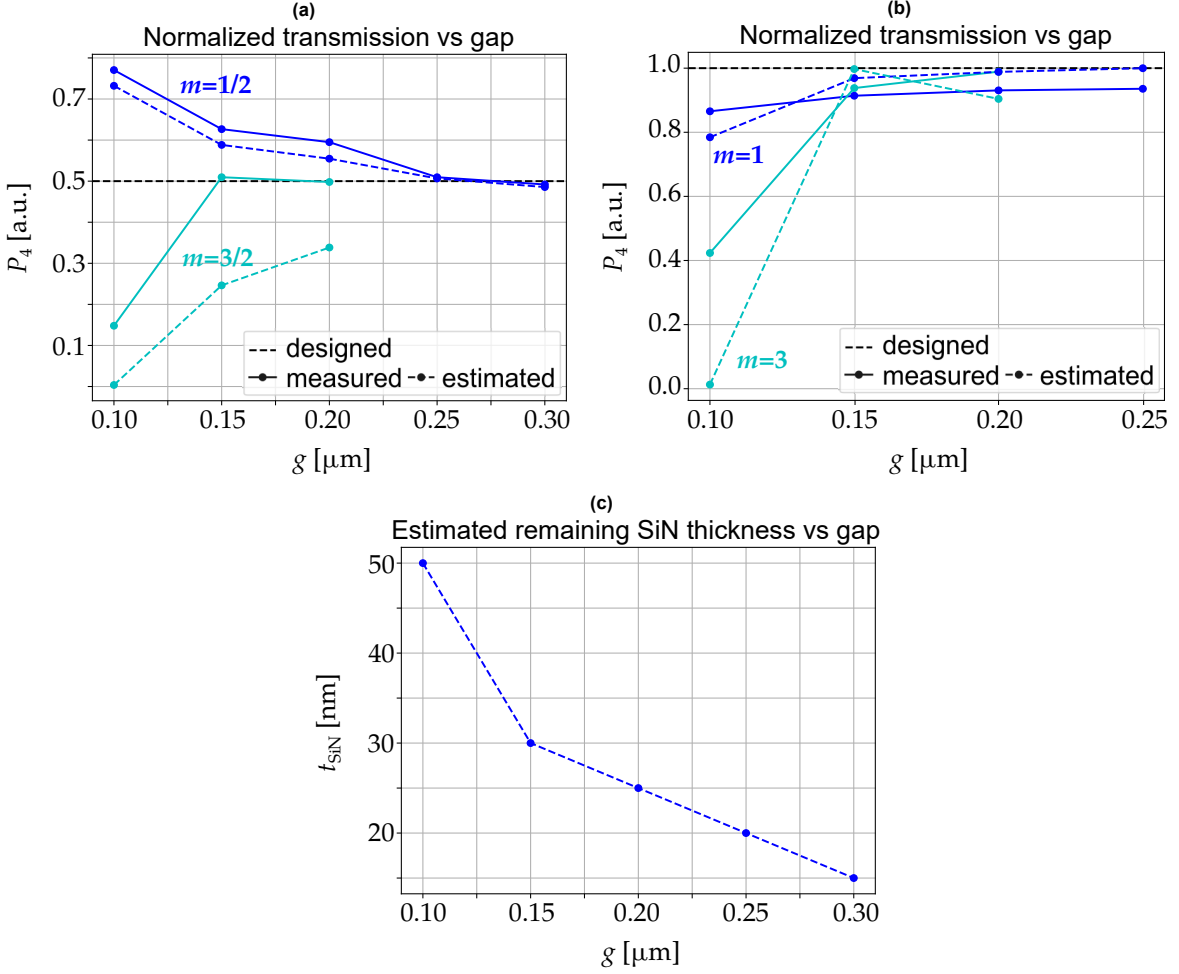


Figure 6.1: Plot of the normalized transmission to P_4 as a function of the gap g derived from measurements (measured) and simulations with the corresponding t_{SiN} (estimated) of (a) beamsplitters of $m = 1/2$ and $m = 3/2$, and (b) switch configurations of $m = 1$ and $m = 3$, (c) Plot of the estimated remaining SiN layer thickness t_{SiN} as a function of the gap g between the coupled waveguides simulated for the final fabrication run. The dotted lines represent the designed values.

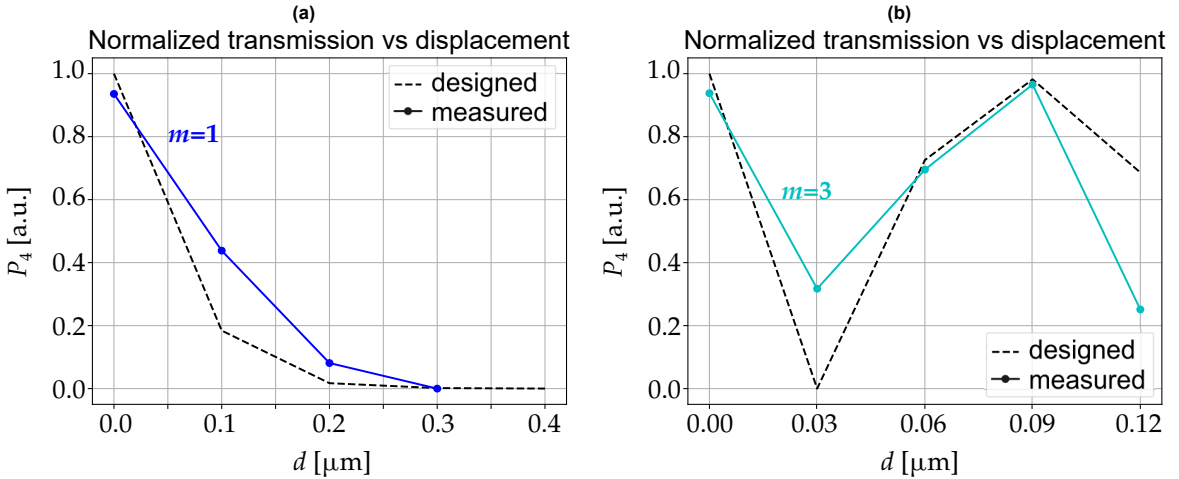


Figure 6.2: Plot of the normalized transmission P_4 as a function of the lateral displacement d derived from measurements (measured) of the fabricated directional coupler of (a) $m = 1$ and $g = 0.2 \mu\text{m}$, and (b) $m = 3$ and $g = 0.15 \mu\text{m}$. The dotted lines represent the designed values.

Table 6.1: Predicted performance of the fabricated directional couplers for gaps equal to $g = [0.15, 0.2, 0.25, 0.3] \mu\text{m}$. The performance is given in terms of absolute deviation from the designed performance for the beamsplitters and the extinction ratio for the off- and on-state of the switch. The predicted actuation voltage required by the equivalent suspended versions is also provided and it corresponds to the optimized version of the comb-drive actuator presented in Subsection 4.2.1.

Device	m	Deviation [%]	ER_{off} [dB]	ER_{on} [dB]	V [V]
$g = 0.15 \mu\text{m}$	1/2	25.3			
	3/2	1.9			
	1		10.3	≥ 30	4.5
	3		15	3.3	1.4
$g = 0.2 \mu\text{m}$	1/2	19			
	3/2	0.4			
	1		13.4	≥ 30	4.5
	3		19.6	2.6	1.41
$g = 0.25 \mu\text{m}$	1/2	1.9			
	1		11.6	≥ 30	4.5
$g = 0.3 \mu\text{m}$	1/2	1.6			

used in the measurements and should be verified in future research with measurements with higher input power.

Another interesting conclusion drawn from Table 6.1 is that beamsplitters that support higher interference order show better immunity to the fabrication error discussed in this chapter. This behavior contradicts the simulation results presented in Figure 3.10a, according to which the longer beamsplitter devices are expected to deviate more from the designed performance. This probably indicates some non-uniformity of the fabrication variation that is not taken into account in simulations and is compensated in the actual device when the coupling interaction takes place for longer propagation lengths.

Although the results obtained from the last fabrication run show significant improvement compared to the measurement results shown in Figures 5.2a and 5.2b, there is still a substantial deviation from the desired performance. An important thing to note is that moving on to the fabrication of the optical MEMS switch with a suspended directional coupler requires the incomplete etching issue to be fully tackled, since not only it alters the directional coupler behavior but also it keeps the coupled waveguides connected preventing them from being on-demand displaced from one another.

There is a clear trade-off between the extinction ratio and the actuation voltage in the on-state that can be leveraged to prioritize one of the two performance metrics. However, for both extinction ratio and actuation voltage specifications to be fulfilled and the remaining SiN layer to be fully eliminated, further adjustments in the fabrication recipe, particularly in the development and etching steps should be made. Regarding development, increasing the flow rate of the developer in the region of the narrow gaps is necessary. A vibration-inducing tool-aided development could work towards this direction or in the case of the manual immersion development moving the sample along the direction in which the development rate should be increased by increasing the flow might also be useful [92]. Additionally, further experimenting with the development time can potentially result in further optimization of the fabrication recipe. As far as etching is regarded, the most effective measure towards eliminating the remaining SiN layer is switching to Inductively Coupled Plasma (ICP) etching, which is the common etching technique for SiN [94, 95].¹ Even moving one step further to Atomic Layer Etching (ALE) [96] or quasi-ALE [97, 98], can potentially have a more drastic effect on the discussed issue. These methods are based on a cyclic process which provides a better control of the etching rate, independent of the aspect ratio of the features, since etching is performed layer-by-layer.

¹It is noted that ICP etching was not available by Kavli Nanolab for the process flow of the devices discussed in this report.

6.2. Optical MEMS switch devices

As explained in the previous chapter, the optical MEMS switch design layout consisted of three parts containing various structures for testing the fabrication process of each of the crucial components independently. The first part, containing the full version of the switch devices was presented in Section 5.2. The present section presents the fabricated devices from the second and the third parts as well as the obtained conclusions.

6.2.1. SiN cantilever beams

Example structures from the third part of the layout are seen in Figure 6.3. Here no metal is deposited and only the SiN layer is patterned and released with BOE. The resulting SiN cantilevers show an upward bending, with this effect being more prominent for cantilevers of increasing size. Interestingly, not only the beam length but also the beam width seems to have an effect on this phenomenon based on the obtained structures. This becomes evident when looking closely at Figures 6.3a and 6.3b, and observing that the cantilever of the larger beam width shows larger deflection, although its length is shorter. When comparing structures of the same width shown in Figures 6.3b and 6.3c, the resulting upward deflections seem roughly equivalent.

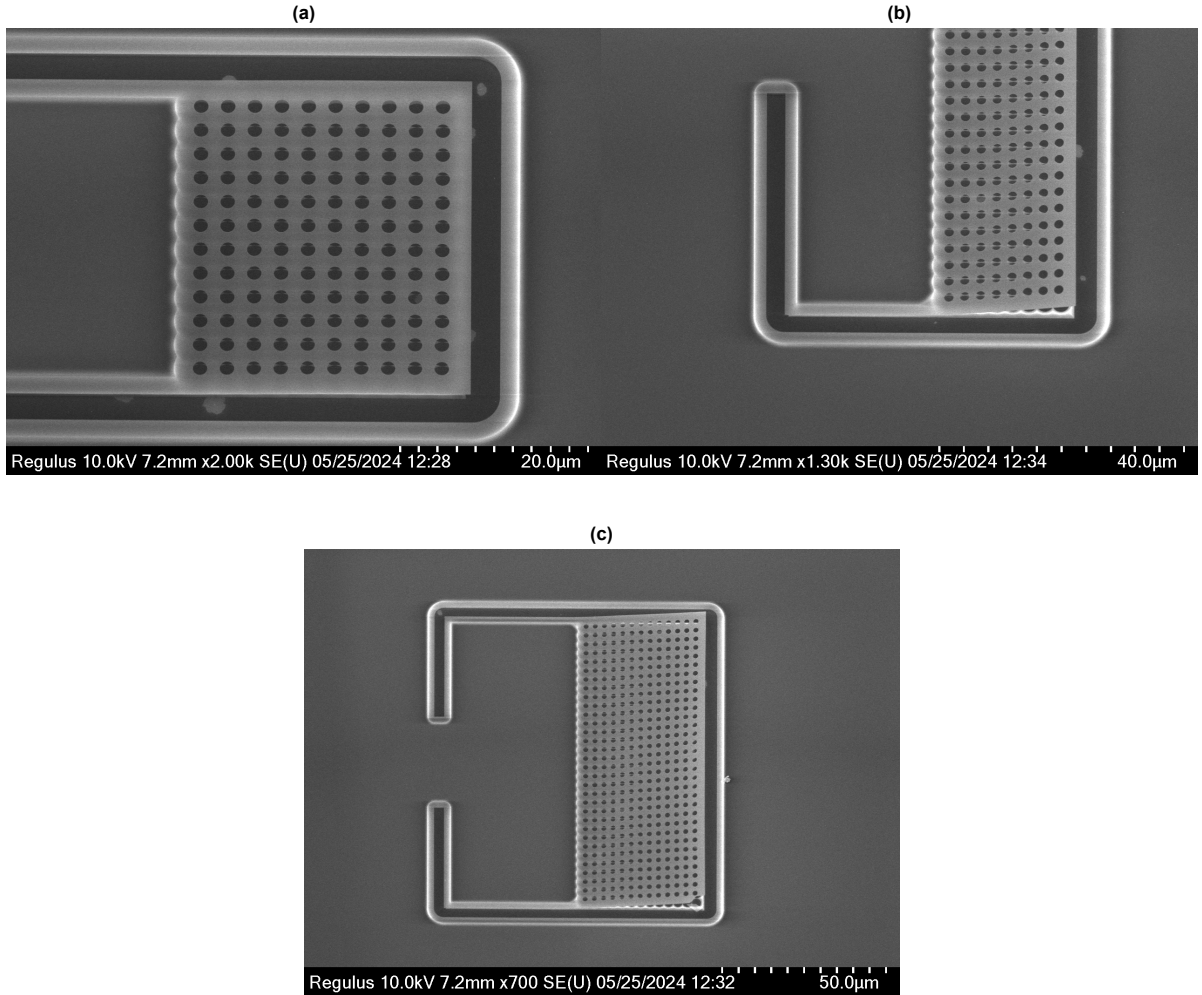


Figure 6.3: Top view SEM of single SiN cantilever beams of (a) $L_b = 32 \mu\text{m}$ and $w_b = 36 \mu\text{m}$, (b) $L_b = 24 \mu\text{m}$ and $w_b = 109 \mu\text{m}$, (c) $L_b = 40 \mu\text{m}$ and $w_b = 109 \mu\text{m}$.

The upward bending of the SiN cantilever beams could possibly be attributed to residual stress, defined as the internal forces developed in the material, present even when the external forces that induced them are absent, caused mainly by the fabrication process of the SiN thin film on a substrate [99,

100]. The residual stress results in residual strain based on the fundamental relation $\varepsilon = \sigma/E$, where σ is the stress. In the present case, the upward bending of the beam is a result of the residual strain gradient developed along the thickness of the beam, the bottom part of which experiences compressive, while the upper part experiences tensile stress leading to an expansion and a compression of the bottom and the upper surfaces of the beam respectively [99, 101]. The strain is directly proportional to the deflection of the cantilever which is a function of the beam length, justifying the bending variations as a function of L_b shown by the fabricated structures.

However, remarkably in the present case, the deformation shows a dependency on the beam width. Although based on Eq. (2.28) one would expect a larger beam width and a shorter beam length to stiffen the cantilever, Figures 6.3 show the opposite effect. To examine this effect the cantilever test structures of Figure 6.4a are deployed. The cantilever beams marked with the red rectangle have a length equal to $L_b = 40 \mu\text{m}$ and widths in the range $[0.5, 1, 1.5, 2, 4] \mu\text{m}$. Based on the strain gradient assumption and Figure 6.3c which depicts a cantilever of equal length, one would expect these cantilevers to be bending upwards. However, as clearly observed in Figure 6.4b the $40 \mu\text{m}$ -long cantilever beams show no bending, and thus no strain gradient, compared to the longer cantilevers seen in the same picture. Additionally, looking at the wider of these beams, a thin SiO_2 structure seems to have remained, observed by the color contrast on the beam, although in theory since $w_b = t_{\text{SiO}_2}$ the SiO_2 should have been completely etched away after the BOE step. Taking a closer look at this beam in Figure 6.4a, the SiO_2 seems to have been etched away up to a depth roughly equal to $1.6 \mu\text{m}$, instead of $2 \mu\text{m}$.

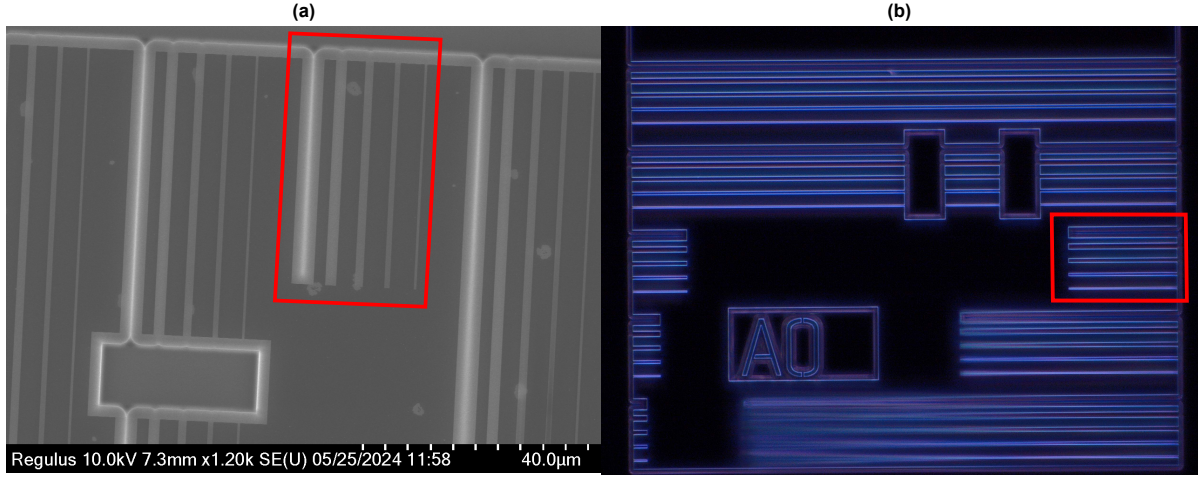


Figure 6.4: Partial top view (a) SEM, and (b) microscopy of the same single SiN cantilever beams, with the red rectangles marking beams of $L_b = 40 \mu\text{m}$ and widths in the range $[0.5, 1, 1.5, 2, 4] \mu\text{m}$.

The observation of the incomplete SiO_2 removal underneath areas wider than $3.2 \mu\text{m}$ indicates that there is most probably oxide remaining underneath some of the cantilevers. If residual SiO_2 remains attached to the SiN beam, the upward bending can be justified [102]. Taking into account that the distance between the holes has not been the same on all of the designed cantilevers, but was varied based on the beam width and beam length, to maintain a given hole radius, it is expected that the deformation effect will be more prominent for the cantilevers with a larger distance between the neighboring holes, as in this case SiO_2 is expected to be removed less effectively. Indeed the hole distance along the beam width in the cantilevers of Figure 6.3b and 6.3c is equal to $1.44 \mu\text{m}$, while the respective hole distance for the cantilever of Figure 6.3a is $1.26 \mu\text{m}$ providing support for the assumption that the upward bending can be attributed to the partial removal of the oxide. This assumption stands considering that the existence of remaining material attached to the partially released structure affects the strain properties of the SiN beam. However, considering that none of the designed distances between the holes exceeds $4 \mu\text{m}$ (not even $3.2 \mu\text{m}$), this assumption stands only considering that the BOE step has not been isotropic.

The above observation implies that the 27 min etching time is not enough for releasing the designed structures. Based on Figure 6.4a an increase by roughly 7 min would solve this issue. However, considering the HF flow rate may be low through the cantilever holes, either an even larger etching

time increase might be necessary, or the widening of the holes. The latter solution would additionally ease the development and lift-off challenges experienced in the fabrication of this device.

The same part of the layout contained the strain test structures seen in Figure 6.5 after SEM inspection. The original form of these structures is shown in Figure 5.8b. These structures, after being released with HF etching, provide an indication that allows for determining whether the SiN cantilevers are experiencing compressive or tensile stress, based on the rotating indicators. Specifically, compressive stress causes beams A and B to elongate causing the indicator beam C to rotate clockwise, while tensile stress causes beams A and B to contract and the indicator beam C to rotate counterclockwise [103, 104]. Based on this principle, from Figures 6.5a and 6.5b it becomes evident that the fabricated SiN structures undergo tensile stress. Increasing the length of the indicator beam C enhances the amplification, hence the sensitivity and readability of the deflection results [104]. Each of these strain test structures consists of identical indicators in different orientations to extract conclusions regarding how residual strain varies with orientation. However, many of them collapsed after the BOE step (specifically, the ones that do not look displaced with regards to the nominal orientation have collapsed).

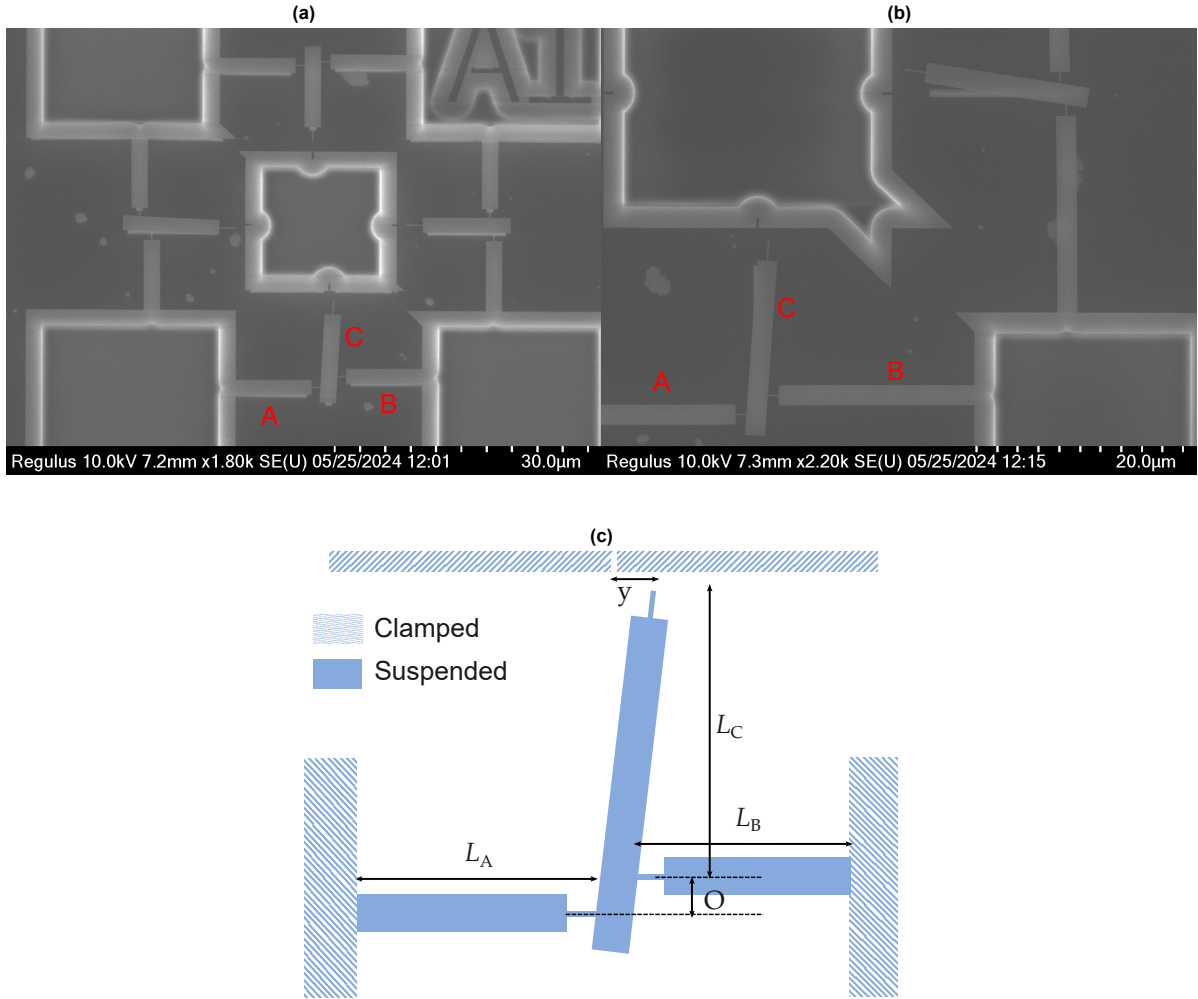


Figure 6.5: (a) Partial top view SEM of the strain test structures with an indicator beam C of $L_C = 10.5 \mu\text{m}$, and (b) $L_C = 15 \mu\text{m}$, and (c) top view schematic of the strain indicator with the relevant dimensions annotated (not in scale).

Based on the general schematic of the strain indicator shown in Figure 6.5c, the strain can be measured from the horizontal displacement y of the indicator using the following formula [103–105]:

$$\epsilon = \frac{Oy}{(L_A + L_B)(L_C + O/2)}, \quad (6.1)$$

where L_A , L_B and L_C the length of the beams A, B and C respectively, and O the offset between the spots at which beams A and B are attached to the indicator beam C.

Using Eq. (6.1) and the structures of Figures 6.5a and 6.5b the resulting residual strain is roughly estimated equal to $4.2 \cdot 10^{-3}$ and $5.4 \cdot 10^{-3}$ for the two suspended indicators (the annotated and the differently oriented one respectively) of Figure 6.5a and roughly equal to $3.6 \cdot 10^{-3}$, $6.9 \cdot 10^{-3}$, $7.2 \cdot 10^{-3}$, and $3.8 \cdot 10^{-3}$ for the indicators (mentioned counterclockwise, starting from the annotated one) of Figure 6.5b.

6.2.2. Metal on SiN cantilever beams

Indicative metal on SiN cantilever structures from the second part of the sample, are seen in Figure 6.6a and 6.6b, corresponding to a longer and collapsed and a shorter and suspended structure, respectively. The different strain properties, Young's modulus, and film geometries of different materials comprising a multilayer structure, potentially result in different deformations of the MEMS component [101, 106]. This results in differences in the deflection characteristics of the beams of Figure 6.6, compared to the monolayer structures of the previous subsection. To explain the behavior of the structures shown in Figure 6.6, which consist of Au deposited on top of SiN (and a thin Cr adhesion layer in between) all the properties and characteristics of the different layers should be taken into account. Young's modulus of Au ranges roughly between 80 and 100 GPa, while for SiN between 100 and 330 GPa, depending on several factors [107]. A quantitative analysis of how the properties of different layers impact the deflection of the cantilevers is beyond the scope of this project. However, based on the observation of the structures shown in Figure 6.6, certain qualitative conclusions can be drawn.

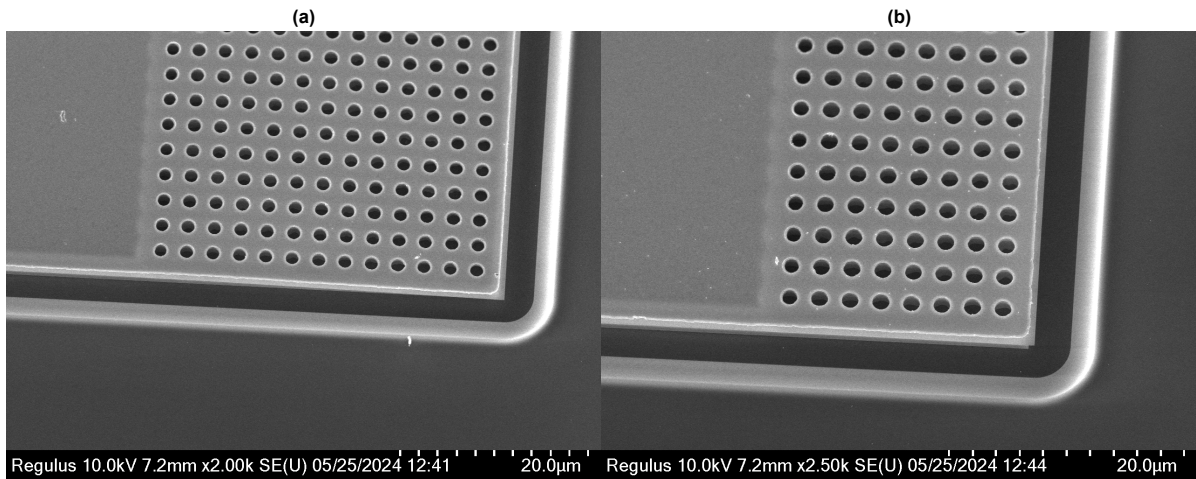


Figure 6.6: Partial top view SEM of metal on SiN cantilevers beams of (a) $L_b = 40 \mu\text{m}$, and (b) $L_b = 24 \mu\text{m}$.

Figure 6.6 indicates a relation between the collapsing of the cantilever beams and the beam length. The collapse of the longer structures could be attributed to large deformations (extreme downward bending) of the bilayer beam caused by the conflict of strain characteristics at the interface between the two materials. Based on the inspection of this sample under SEM, cantilevers of beam length $\leq 24 \mu\text{m}$ survived suspended, while the longer cantilever beams collapsed. This means that the fabrication of cantilever beams that can be theoretically actuated with a voltage equal to 31.1 V is already achieved. The corresponding footprint that would be obtained by integrating this cantilever in an optical MEMS switch would not reach higher than $101 \times 129 \mu\text{m} \times \mu\text{m}$.

Successfully fabricating even longer cantilever beams that could allow for lower actuation voltage requires more careful consideration of the strain model that describes this structure. Based on the strain model, the thickness of the Au layer can be optimized and the suitable geometries for maintaining suspended cantilever beams can be calculated.

6.3. Discussion

The first part of this chapter presented the successful fabrication of photonic directional couplers functioning as beamsplitters and switches. Specifically, with the current fabrication method, beamsplitters approaching the 50:50 power split with a deviation less than $\pm 2\%$ and a directional coupler length smaller than $100\text{ }\mu\text{m}$ were fabricated, achieving the corresponding set goals. Additionally, directional couplers capable of achieving an extinction ratio for the higher than 30 dB for the on-state and 15 dB for the off-state with a coupling length shorter than $150\text{ }\mu\text{m}$ were also fabricated. The simulation results of the displacement required for switching between the off and on-states of the switch were confirmed, opening the possibility for operation with actuation voltages lower than 5 V if the directional coupler is integrated with a comb-drive actuator scheme.

Continuing, this chapter introduced the fabrication of suspended cantilever beams suitable for integration with a cantilever-beam actuated optical MEMS switch. Specifically, cantilevers of length up to $24\text{ }\mu\text{m}$ were fabricated, promising operation with a voltage around 30 V fulfilling the project requirements and paving the way for the fabrication of even longer cantilever beams that can allow for lower actuation voltages. A significant contribution towards this goal is the establishment of the fabrication recipe presented in this report, the identification of the remaining fabrication challenges, and the observations related to the strain properties.

The results presented in this chapter indicate that there is clearly room for improvement. First of all, the fabrication of the photonic directional coupler with careful attention paid to the gap patterning, especially for gaps smaller than $0.2\text{ }\mu\text{m}$, will result in achieving the desired performance in terms of fabrication accuracy of the beamsplitter and the extinction ratio for the switch with devices of even smaller footprint. Regarding the optical MEMS switch fabrication, a careful study of the mechanical properties of the structure and the re-evaluation of the BOE etching time are expected to yield suspended structures of longer lengths, thus suitable for lower operation voltage.

7

Conclusion

7.1. Project summary

The general goal of this project was to design, fabricate, and characterize SiN photonic directional couplers optimized for beamsplitter and optical MEMS switch applications at visible wavelength. More specifically, this goal was broken down into establishing the photonic directional coupler design in terms of small footprint and low loss and studying the bandwidth and tolerance to potential fabrication errors. Particularly for the integration of the photonic directional coupler into an optical MEMS switch configuration, the goal expanded to additionally examining the extinction error and investigating device designs that can operate with low actuation voltage for CMOS compatibility. The ultimate aim of this project was to successfully fabricate photonic directional coupler devices and characterize them intending to evaluate whether the designed performance can be achieved. An additional aim of this project was to contribute to the fabrication of the optical MEMS switch by going through the fabrication of suspended MEMS structures.

To achieve the set goals, the project was organized into three parts: simulations, fabrication, and measurements. The simulations were performed to establish the directional coupler design and predict the corresponding performance. The fabrication part, that followed the simulations, aimed at manufacturing the simulated devices and concluding on the feasibility of the designs. After every fabrication run the devices were measured and characterized to assess the fabrication output and predict the performance.

The main challenges of this project were creating a design that could achieve the set performance goals at visible wavelength and establishing a fabrication process that could successfully replicate the designed devices. Specifically, regarding the optical MEMS switch design, the most intricate aspect was lowering the actuation voltage to values compatible with integration with CMOS electronics. For this purpose, the structure, the inherent trade-offs, and the advantages offered by two different optical MEMS switch configurations were studied in detail. Considering the directional coupler fabrication challenges, the small feature size required for achieving the desired performance at visible wavelengths complicated the fabrication process introducing aspect-ratio-dependent fabrication errors. Addressing these fabrication issues required extensive inspection of the fabricated samples and multiple repetitions of the fabrication and measurement cycles. The attempted fabrication of suspended components for the optical MEMS switch was also challenging considering the multidimensional nature of the device that demanded the integration of small and large feature sizes, photonic and mechanical parts, and suspended multilayer structures in one run.

The results obtained in this project were highly promising. Regarding fabrication, tackling the aspect-ratio-dependent fabrication issues yielded beamsplitters achieving a 50:50 with accuracy better than 99%. The same fabrication run produced directional couplers that confirmed the switching operation with displacements that require an actuation voltage lower than $5\text{ }\mu\text{m}$ with an extinction ratio for the on-state as high as 30 dB. Successfully fabricated directional couplers with a gap $g = 0.2\text{ }\mu\text{m}$ and a coupling length smaller than $100\text{ }\mu\text{m}$ were reported in this project. Finally, suspended cantilevers of beam length equal to $24\text{ }\mu\text{m}$, promising to support an actuation voltage around 30 V and an optical MEMS switch footprint smaller than $20.000\text{ }\mu\text{m}^2$ were fabricated. An additional contribution to the op-

tical MEMS switch fabrication was the results obtained from the single cantilever test structures that indicated the special considerations that need to be taken into account when fabricating such devices and showed the next steps for further increasing the fabrication yield. Regarding the loss simulations, the bend loss results align with the goal for insertion loss lower than 1 dB, however, mode mismatch losses were not accurately simulated to derive concrete results on the final insertion loss performance expected to be achieved by the designed devices.

In summary, all aspects of the photonic directional coupler design were examined, two different optical MEMS switch configurations were analysed and various versions of beamsplitters and directional coupler-switch configurations were successfully fabricated. The additional fabrication of suspended cantilevers was another step towards the realization of a cantilever-beam-actuated optical MEMS switch. The results derived from simulations and confirmed with fabrication and measurements show great promise for the potential of the designed devices and the established fabrication process. Further increasing the fabrication yield is possible and necessary for realizing devices of smaller feature sizes that can achieve even smaller device footprints, directional couplers of higher fabrication accuracy, and switch devices operating with low actuation voltage and high extinction ratio.

7.2. Future research

Although the results presented in this report and summarized above show great promise, they clearly indicate that there is room for improvement, as well as multiple aspects that need further investigation. The following ideas are expected to result in more complete analysis and improved performance of the devices studied in this report:

- Loss simulations of each one of the sources of mode-mismatch losses separately to examine their impact on the total insertion loss. Simulation of the sidewall roughness for propagation loss estimation would also be useful.
- Study of the mechanics of the actuation mechanisms that will result in more accurate prediction of the obtained performance and larger flexibility in design optimization. Additionally, a detailed strain analysis for the cantilever can help in a similar way.
- Optimization of the supporting anchors and cantilever size in terms of the mechanical stability of the structure. The supporting anchors should also be included in photonic simulations to study the leakage they induce.
- Optimization of the grating couplers for higher measurement accuracy.
- Attempting ICP SiN etching, and potentially ALE, for completely tackling ARDE.
- Investigation of more aggressive development methods and further investigation of development time after E-beam exposure.
- Performing both the SiN layer mask and metal layer mask exposure with E-beam to ensure uniform development and increase reliability and repeatability of the fabrication process.

This report presented a study of the directional coupler and directional coupler-based optical MEMS switch integrated with a cantilever beam actuator aiming to achieve the project goals. However, alternative structures rather than the implemented ones can be considered for reaching even higher performance. Some relevant ideas are the following:

- Study of different kinds of S-bends that could provide a better loss performance.
- Realization of the comb-drive actuator that promises lower actuation voltages. Investigation of advanced comb-drive designs that leverage the pre-strain properties of the bilayer structure for further lowering the actuation voltage.
- Replacement of the directional coupler with an adiabatic coupler for broadband operation and lower sensitivity to fabrication errors.
- Deployment of MEMS technology for realizing a tunable beamsplitter to correct potential fabrication errors and facilitate broadband operation.

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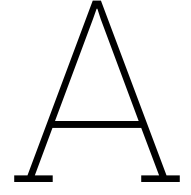
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Simulations

A.1. Background simulations

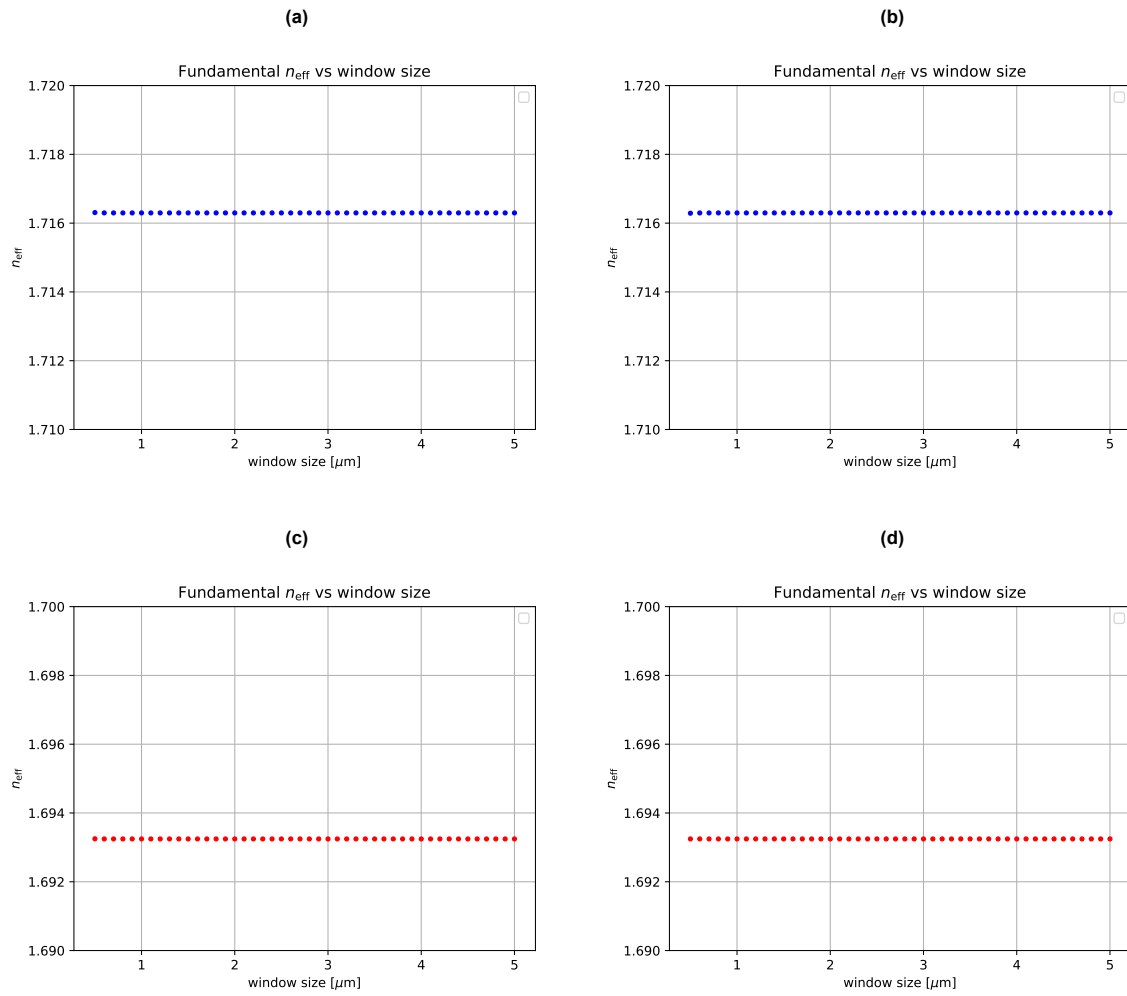


Figure A.1: Plot of effective refractive index n_{eff} of the fundamental mode as a function of the window margin size (a) along x -axis and (b) y -axis for SiO₂ substrate, (c) x -axis and (d) y -axis for air, for $g = 0.1 \mu\text{m}$.

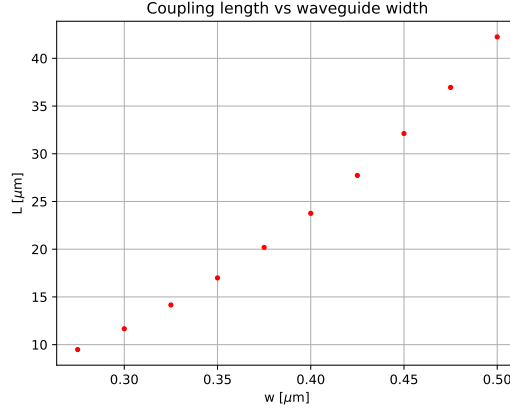


Figure A.2: Plot of length L of the directional coupler as a function of the waveguide width w , for $g = 0.15 \mu\text{m}$.

A.2. Insertion loss

The insertion loss is the total loss of the device that includes all the potential sources of loss. The simulation of insertion loss is performed with FDTD which models the light propagation in the device as a function of time and space. Considering the symmetry of the device, the propagation in the structure shown in Figure 3.12 is simulated and the loss between the planes z_1 and z_6 is calculated and doubled to refer to the full version of the device. For this purpose power monitors are placed at z_1 and z_6 in the simulation model and based on the extracted power data, the losses are calculated in dB using the following formula:

$$ILoss = -10 \log \left(\frac{P_{out}}{P_{in}} \right), \quad (\text{A.1})$$

where P_{in} and P_{out} the power at z_1 and z_6 , regarded as the input and output powers respectively. The derived results are shown in Figures A.3a and A.3b for SiO_2 and air set as substrates respectively.

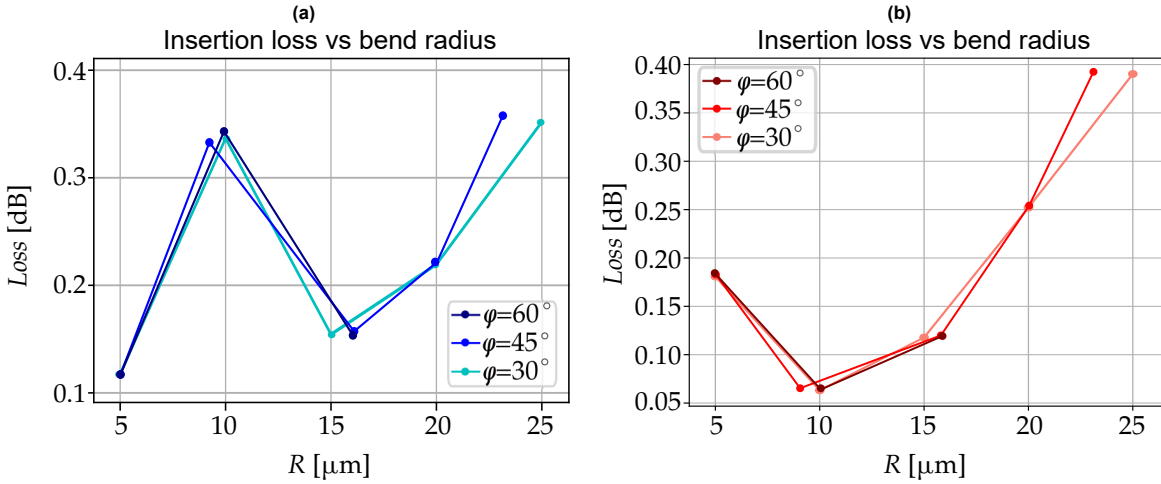


Figure A.3: Plot of total insertion loss $ILoss$ of the directional coupler as a function of the bend radius R for the bend angles $\varphi = \{30, 45, 60\} [^\circ]$ for (a) SiO_2 , and (b) air set as substrates.

Considering the negligible derived bend loss for $R \geq 5 \mu\text{m}$, the mode mismatch loss as a function of the bend radius and for the different examined bend angles is roughly similar to the insertion loss shown in Figure A.3, and therefore, these plots roughly correspond to the mode mismatch losses. However, the increase of the mode mismatch losses with an increasing bend radius, which is basically illustrated in Figure A.3 contradicts the intuition according to which bends of large bend radii approach more closely the straight waveguides. Therefore these results are not taken into account in the main

text of this report. Nevertheless, the methodology followed for extracting these results as well as some qualitative analysis of the results derived from independent structures are provided in the following subparagraph.

Mode mismatch losses

There are two kinds of spots on the structure shown in Figure 3.12 that could give rise to mode mismatch losses. These are specifically the interfaces between straight and curved waveguides z_1 - z_2 and z_5 - z_6 as well as the interfaces between oppositely curved waveguides z_3 - z_4 . These losses theoretically correspond to the reduction in transmittance caused by modes of different index profiles being supported by the two differently curved interfacing structures. In the present project, the calculation of this type of loss is based on the following simple relation: $MMLoss(R, \phi) = ILoss(R, \phi) - BLoss(R, \phi)$, considering that there is no other source of loss apart from bend and mode mismatch loss.

A qualitative assessment of the derived results for each structure independently is approached by monitoring the power at the planes shown in Figure 3.12 with FDTD method. In this context, the power at z_1 , z_3 , z_4 , z_5 and z_6 as a function of the propagation distance cT , is shown in Figures A.4a and A.4b. It is noted that at z_6 the power in both waveguides is monitored since z_6 already falls in the coupling region. The corresponding plot of power as a function of the propagation length is shown in Figure A.4c. The plots of Figure A.4 correspond to an example device with $R = 25 \mu\text{m}$ and $\varphi = 45^\circ$ on SiO_2 substrate. To make the observation more efficient a smooth curve was fitted through the data points of Figure A.4c using a non-parametric regression method. Specifically, the `sm.nonparametric.lowess()` fitting function from the `statsmodel` library in Python was applied which performs Locally Weighted Scatterplot Smoothing (LOWESS) without assuming a specific functional form, which was optimum for dealing with the non-uniformity of the extracted data.

Considering Figures A.4a and A.4b and looking at the power difference between z_5 and z_6 we observe the loss at the S-bend-shaped/straight waveguide transition region, which is non-negligible. The corresponding loss at the straight/S-bend-shaped waveguide transition region (marked by z_1 and z_2) is not shown but can be observed in Figure A.4c. Looking at monitors at z_3 and z_4 leads to the impression that no power is lost at the oppositely curved S-bend-shaped waveguide interface (with Figure A.4c pointing towards this conclusion as well). However, the larger power difference between the monitors z_3 , z_5 compared to the power difference between z_1 , z_3 , indicates that there is probably some power loss that should attributed to this interface (considering that the bends included in these regions are of identical R and φ). The reason why this is not reflected in the plots is probably related to the positions of the monitors or to the simulation setup in general which was proven to be problematic for these simulations.

It is noted that the example plots of Figure A.4 are similar to all the derived plots extracted from the examined devices, with minor differences in the power levels that do not prevent drawing general conclusions. It is also noted that the results derived from BPM are not reliable for large bend angles and are only used here in a complementary way, namely for the straight/S-bend-shaped waveguide transition region that is not affected by the bend angle of the structure.

The increase of the bend radii is expected to reduce both bend, as well as mode mismatch losses. However, although bend losses do show the expected trend as a function of the bend radii, the mode mismatch losses seem to have not been accurately simulated. Therefore no conclusions regarding the insertion loss are drawn in this report. The bend radius for the fabricated devices was selected equal to $25 \mu\text{m}$ to ensure low losses [25]. Based on the bend loss results this angle can be further reduced, however since mode mismatch losses were not calculated this was not attempted. In the footprint calculations in this report a bend radius equal to $10 \mu\text{m}$ is used.

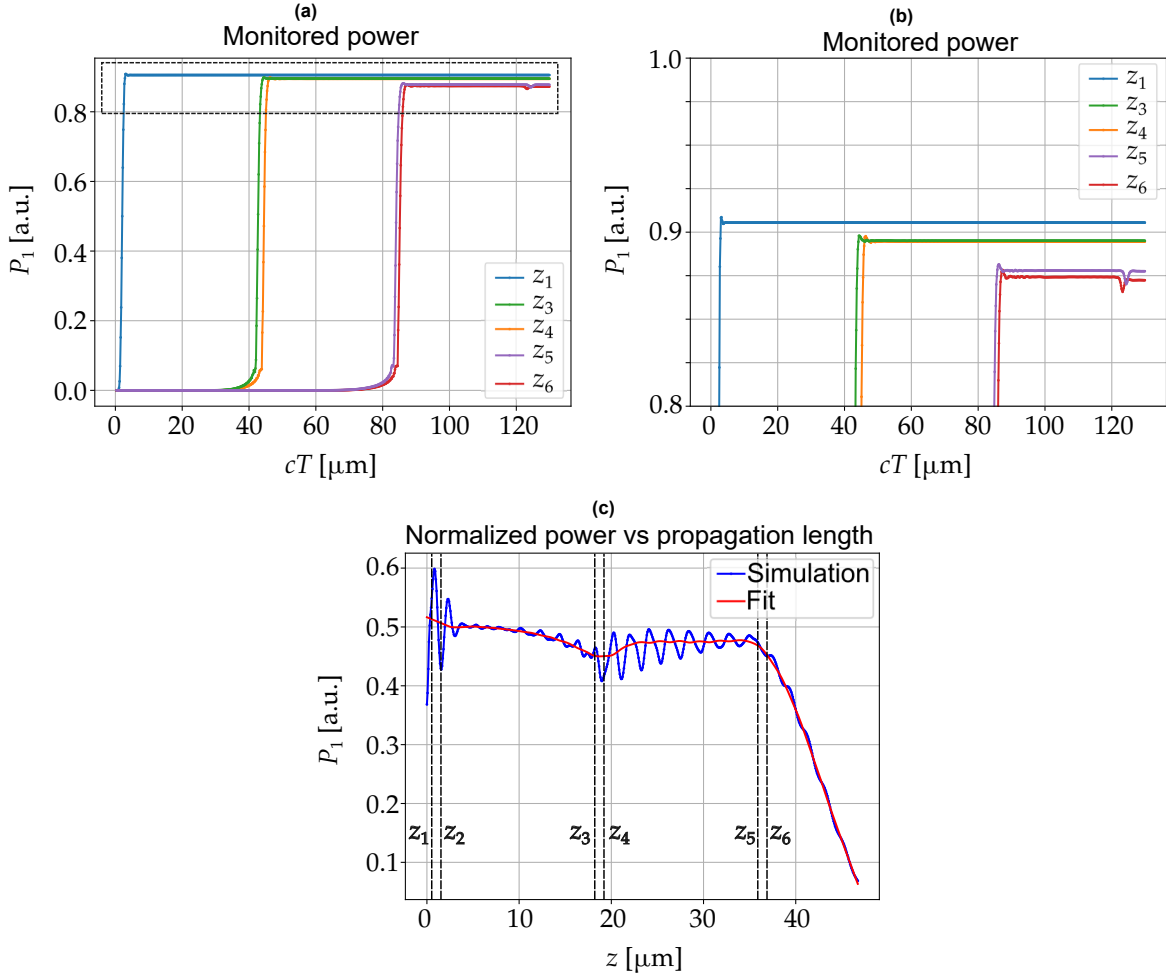


Figure A.4: Plot of the normalized power in the input waveguide as a function of the propagation distance extracted from (a) FDTD in full-scale, (b) FDTD in close view, and (c) BeamProp simulation for $R = 25 \mu\text{m}$, $\varphi = 45^\circ$ and SiO_2 substrate. The dotted lines mark the regions around the 'lossy' interfaces.

B

Device fabrication details and measurements

B.1. Photonic directional coupler

B.1.1. Design layout

The design is developed using the `gdshelpers` Python package. The design of an example device is shown in Figure B.1. The simulated part is marked by the red rectangle. The 90° -bends are of the same radius R as the S-bends. The grating couplers, marked by the black rectangle, represent the input and output ports of the device for the present case of a fiber-array measurement setup. The distance between two subsequent grating couplers is set at $127\ \mu\text{m}$, the standard value for the deployed measurement setup. The distances from Port 1 to Port 3 and Port 4 are kept the same for all designed structures to maintain efficiency during the measurements. To achieve this g was bounded to values that result in L shorter than $250\ \mu\text{m}$. It is noted that the design optimization of the grating couplers is beyond the scope of this project.

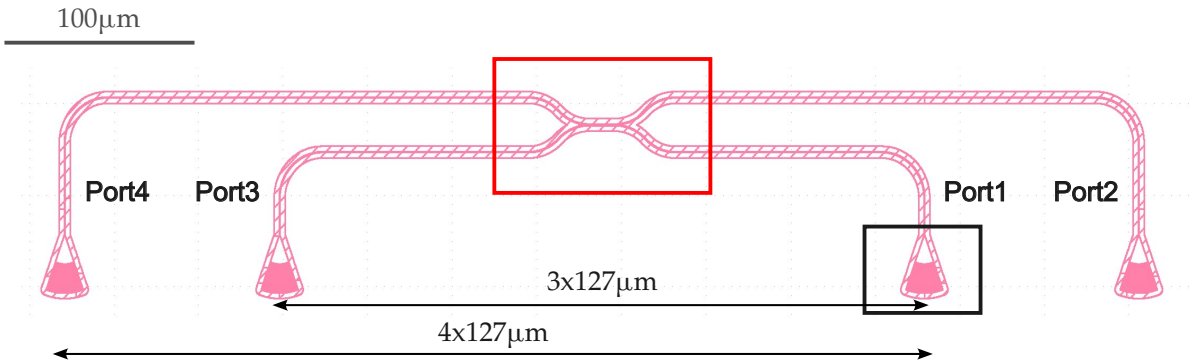


Figure B.1: Directional coupler layout. The pink-marked areas are exposed for patterning. The red rectangle marks the simulated part of the device, while the black rectangle marks one of the grating couplers.

Apart from the directional couplers, each layout contains a set of test structures used for drawing conclusions regarding the feature size that each fabrication run could resolve as well as some reference structures for keeping track of the variations related to the measurement setup, as shown in Figure B.2a. Spiral waveguide structures, like the one shown in Figure B.2b, are additionally included to perform propagation loss measurements. These are generated with the function `Spiral.make_at_port` for a given inner radius, gap between the waveguides and number of turns. The latter parameter is swept in the design to measure losses.

Measurement of the spiral structures with the SLD at $635\ \text{nm}$ produced the plot shown in Figure B.2b. Keeping track of the propagation loss of the fabricated waveguides comprising the couplers is necessary for the complete characterization of the fabricated devices. Knowing the propagation loss,

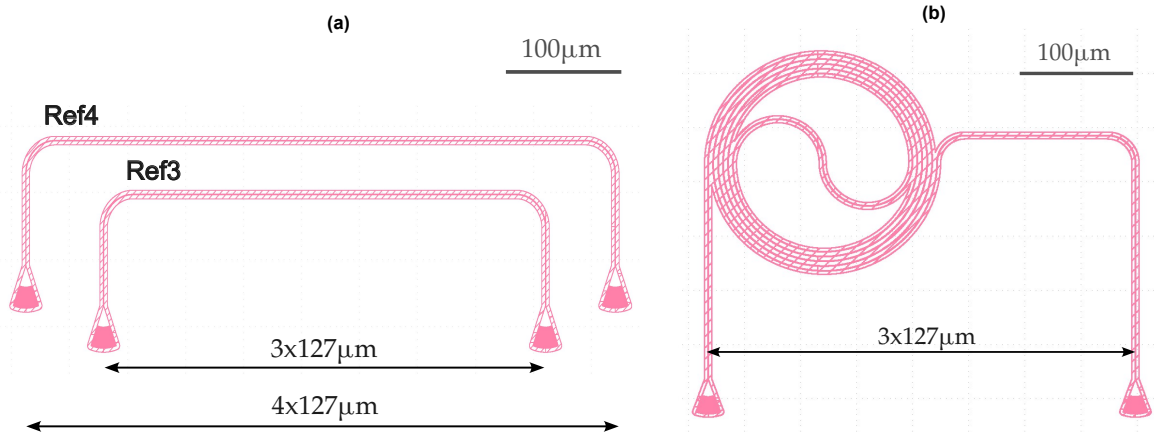


Figure B.2: Layout of (a) reference structures and (b) spiral waveguide with 5 turns. The pink-marked areas are exposed for patterning.

and thus being able to isolate it from the total losses of the device is the first step towards confirming the loss simulation results. Figure B.3 shows the measured transmission as a function of the propagation length.

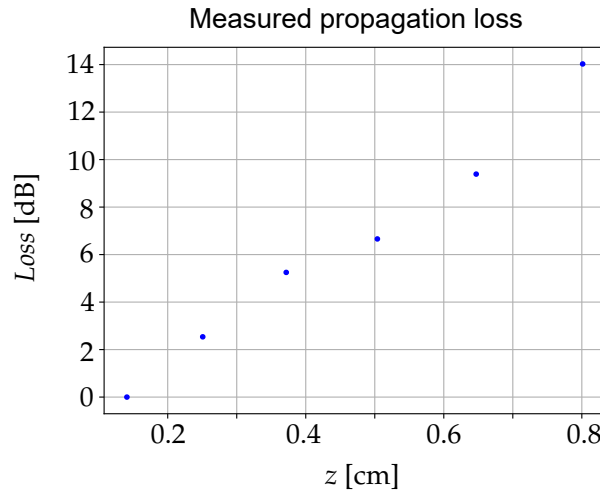


Figure B.3: Plot of the measured propagation loss as a function of the propagation length.

Figure B.3 shows that the propagation losses of the fabricated spiral structures reach up to 17.5 dB/cm, which is significantly high, compared to standard propagation losses below 3 dB reported for SiN waveguides at visible wavelengths [21]. For this reason and in order to isolate the effect of the propagation losses from the measurement data, the reference structures shown in Figure B.2a are fabricated and measured at the beginning of every measurement session. These reference structures resemble the measurement Port1/Port3 and Port1/Port4 in the sense that they have similar propagation lengths (only the S-bends are not included) with the corresponding directional couplers and most importantly they have light coupled in them through the same fiber array inputs and outputs. The latter property allows for isolating potential variations of the grating couplers and the measurement setup. This is performed by normalizing the output power data extracted from Port1/Port3 and Port1/Port4 measurements by the transmission measured from the reference structures Ref3 and Ref4 respectively.

Despite the fact that the measured propagation losses are high, the propagation loss experienced in the longest of the designed devices does not exceed 1.5 dB. The majority of the structures feature total losses (including bend, mode mismatch, and propagation losses) lower than 1 dB achieving the set goal even in the case that propagation loss is considered.

B.1.2. Process details

The samples used in the fabrication process are $10 \times 10 \text{ mm}^2$, parts of a cleaved wafer consisting of a 250 nm thin film of stoichiometric SiN, on a $2 \text{ }\mu\text{m}$ thick SiO_2 layer on Si substrate, provided by Rogue Valley Microdevices. The samples are prepared with a regular Acetone and IPA at a non-standard temperature for 5 min in an ultrasonic bath at maximum power, followed by oxygen-plasma clean with 600 sccm of O_2 at 600 W for 5 min. The fabrication of the photonic directional coupler was based on the following recipe:

1. Spin coating e-beam resist (AR-P 6200.09) at 2000 rpm and baking at 165°C for 2 min on a hotplate.
2. E-beam lithography with a dose of $340 \text{ }\mu\text{C}/\text{cm}^2$, a beam step size of 1.5 nm, a beam current equal to 0.16 nA, an aperture size of $200 \text{ }\mu\text{m}$ and an effective spot size equal to 4.8 nm
3. Development with Pentylacetate for 1.5 min, MIBK:IPA 1:1 solution for 1 min and IPA for 1 min.
4. Descum with oxygen plasma 300 sccm of O_2 at 200 W for 3 min
5. RIE with 25 sccm of Ar, 25 sccm of CHF_3 , at 60 W and 10 μbar , on Si carrier wafer for about 22 min (etching time is adjusted in each run based on the etching progress observed with the interferometer).
6. Resist stripping with PRS3000 overnight at 80°C in Au bain-Marie, followed by Acetone and IPA cleaning at maximum power in an ultrasonic bath.

Waveguide width variation

The descum step as described in the above fabrication recipe is intended to remove the e-beam resist residues left after development, smoothening the patterned resist sidewalls. However, the descum parameters mentioned in the fabrication recipe result in a narrowing down of the width of the patterned resist, thus in a narrowing down of the waveguides and a broadening of the gap between them, as shown in Figure 3.7a, by about 15 nm. Since this change is consistent for all the fabricated structures on the sample, the design rather than the fabrication recipe is adjusted to compensate for this variation. In this context, the waveguides are designed 15 nm wider, and the gap 15 nm narrower, resulting in fabricated devices with waveguide width and gap sizes within 5 nm accuracy with regards to the intended design. Based on Figure 3.9 this 5 nm width variation is within the fabrication accuracy goals set for this project, for structures of $m = 1/2$ and $m = 1$.

B.1.3. Broadband measurements

Broadband measurements were performed with the SLD for the last fabricated sample presented in Chapter 6. The results derived for the beamsplitter of $m = 3/2$ and $g = 0.15 \text{ }\mu\text{m}$ and the switch configuration of $m = 3$ and $g = 0.15 \text{ }\mu\text{m}$ are shown in Figures B.4a and B.4b respectively. The transmission at Port 3 is given for a displacement $d = 0.03 \text{ }\mu\text{m}$ in Figure B.4b. The results are normalized with the laser output spectrum but not normalized with the transmission of the reference structures Ref3 and Ref4, explaining why the intensity at Port 3 appears higher. It is additionally, noted that the spectrometer calibration has a maximum of $\pm 10 \text{ nm}$ inaccuracy.

From Figures B.4a and B.4b we observe that transmission at both ports peaks around 640 nm, shifted from 633 nm by an amount that is within the inaccuracy range of the spectrometer.

B.2. Optical MEMS switch

B.2.1. Design layout

The design layout of the optical MEMS switch is shown in Figure B.5. It is noted that the 90° -bends, the grating couplers, and the metal pads are not illustrated (since their design does not fall within the scope of this project) but are present in the actual design.

The design of the supporting anchors connecting the waveguides to the cantilever beams, as seen in Figure 5.6a is found in [25] and is not optimized in this project. The number of anchors and the distance d_{anchor} between them is set based on the beam width. These parameters are not optimized either but are set based on the considerations that the anchors should be enough to firmly attach the waveguides to the beam but not too many to preserve the guided mode and limit the coupling to higher-order modes in the tapered region which results in loss. The number of anchors is derived from the

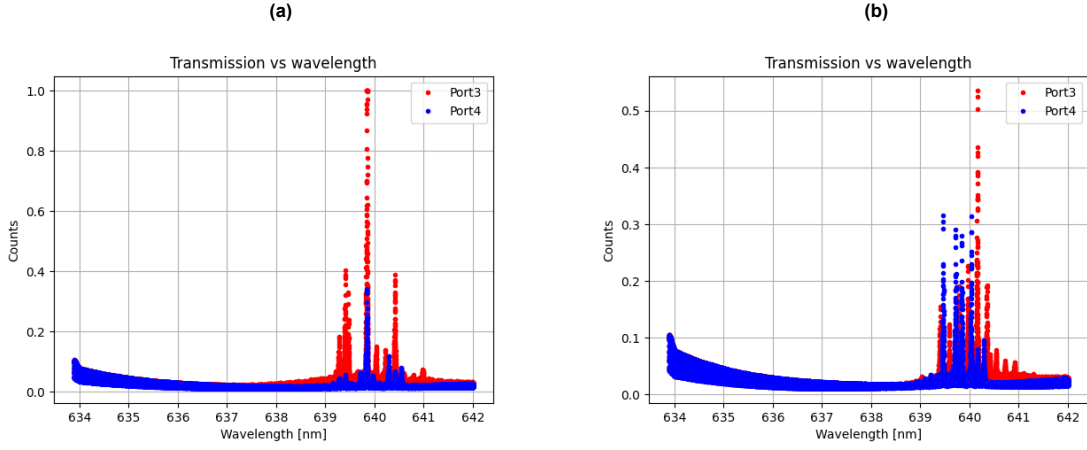


Figure B.4: Plot of the normalized transmission intensity given in counts in Ports 3 (red) and 4 (blue) as a function of the wavelength for (a) a beamsplitter of $m = 3/2$, and (b) a switch configuration of $m = 3$ and $g = 0.15 \mu\text{m}$. The transmission at Port 3 corresponds to a displacement $d = 0.03 \mu\text{m}$ in (b).

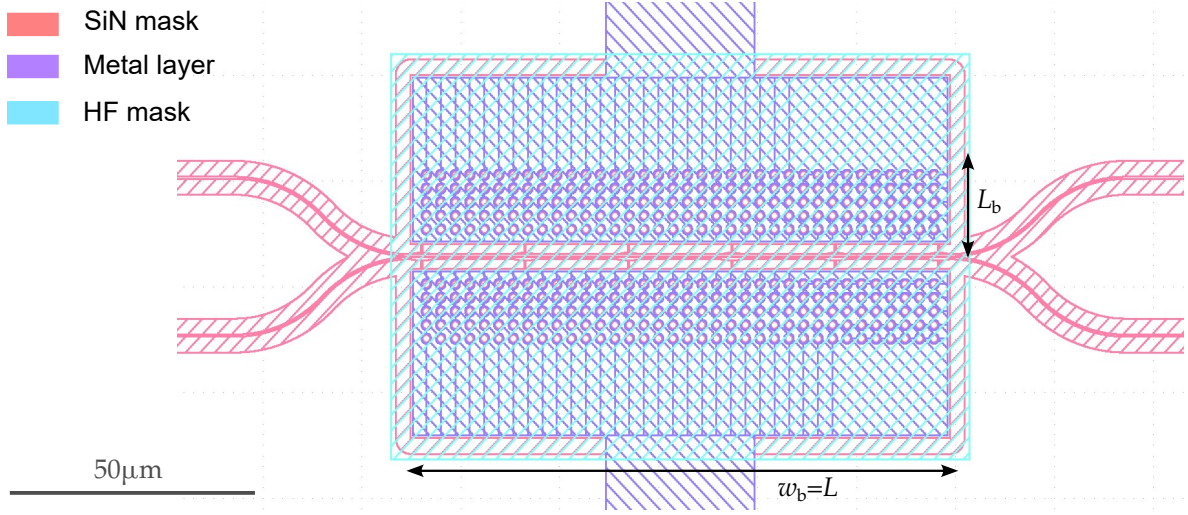


Figure B.5: Optical MEMS switch partial layout illustrating the cantilever beams of $L_b = 16 \mu\text{m}$ and $w_b = 109 \mu\text{m}$ and the directional coupler with $L = 109 \mu\text{m}$ and $g = 0.15 \mu\text{m}$. The metal pads and the grating couplers are omitted from the illustration.

following relation: $N_{\text{anchor}} = (w_b - 2L_{\text{taper}} - L_{\text{anchor}}) / (d_{\text{anchor}} + w_{\text{tip}})$, while d_{anchor} ranges in values larger than $25 \mu\text{m}$.

Apart from the design of the critical parameters affecting the fabrication process, other parameters are considered as well. The length of the fixed part of the cantilever is set equal to the length of the released part. The radius of the holes designed on the metal layer is $0.2 \mu\text{m}$ larger than the SiN holes to prevent the deposited metal from extending in the SiN hole hindering HF etching. The rectangle covering the main area of the structure, as seen in Figure B.5, represents the HF mask, used for limiting SiO_2 removal only in the region where motion takes place. The width of the beam is equal to the length of the directional coupler. The size of the metal pads is not of much significance in the context of this project since no electrical measurements were performed. The waveguide width and the gap of the directional coupler are designed accordingly to compensate for the variations induced by descum, as described previously. It is noted that the patterning of both the SiN and the metal layer is performed with positive resist, therefore the pink- and the purple-marked areas in Figures B.5, 5.6a and 5.6b are exposed.

B.2.2. Process details

$19 \times 19 \text{ mm}^2$ samples, parts of a cleaved wafer consisting of a 250 nm thin film of stoichiometric SiN, on a 2 μm thick SiO₂ layer on Si substrate, provided by Rogue Valley Microdevices are used. They are prepared with a regular Acetone and IPA at a non-standard temperature for 5 min in an ultrasonic bath at maximum power, followed by oxygen-plasma clean with 600 sccm of O₂ at 600 W for 5 min. The fabrication recipe used for the optical MEMS switch is detailed as follows:

1. Spin coating lift-off resist (PMGI SF7) at 4000 rpm and baking at 190°C for 1 min on a hotplate.
2. Spin coating photoresist (S1805) at 4000 rpm and baking at 115°C for 1 min on a hotplate.
3. UV lithography with a dose of 180 mJ/cm² and defoc equal to +4.
4. Development with MF21A for 30 s and water for 30 s.
5. Deposition of 10 nm of chromium (Cr) and 100 nm of gold (Au) thin films with Aja-QT.
6. Lift-off with NMP overnight at 80°C in Au bain-Marie with a stirring magnetic bar, followed by Acetone and IPA cleaning at $\geq 40^\circ\text{C}$ at maximum power in an ultrasonic bath.
7. Spin coating e-beam resist (AR-P 6200.09) at 2000 rpm and baking at 165°C for 2 min on a hotplate.
8. E-beam lithography with a dose of 340 $\mu\text{C}/\text{cm}^2$, a beam step size of 1.5 nm, a beam current equal to 0.16 nA, an aperture size of 200 μm and an effective spot size equal to 4.8 nm
9. Development with Pentylacetate for 1.5 min, MIBK:IPA 1:1 solution for 1 min and IPA for 1 min.
10. Descum with oxygen plasma 300 sccm of O₂ at 200 W for 3 min
11. RIE with 25 sccm of Ar, 25 sccm of CHF₃, at 60 W and 10 μbar , on Si carrier wafer for about 22 min (etching time is adjusted in each run based on the etching progress observed with the interferometer).
12. Resist stripping with PRS3000 overnight at 80°C in Au bain-Marie, followed by Acetone and IPA cleaning at maximum power in an ultrasonic bath.
13. Spin coating photoresist (S1813) at 4000 rpm and baking at 115°C for 1 min on a hotplate.
14. UV lithography.
15. Development with MF21A.
16. Wet-etching with BOE 7:1 for 27 min, followed by immersion in IPA and critical-point drying (CPD).

B.2.3. Patterning issues

Figures B.6a and B.6b illustrate the inconsistent patterning as a part of the procedure followed to investigate the defocus settings of the UV lithography.

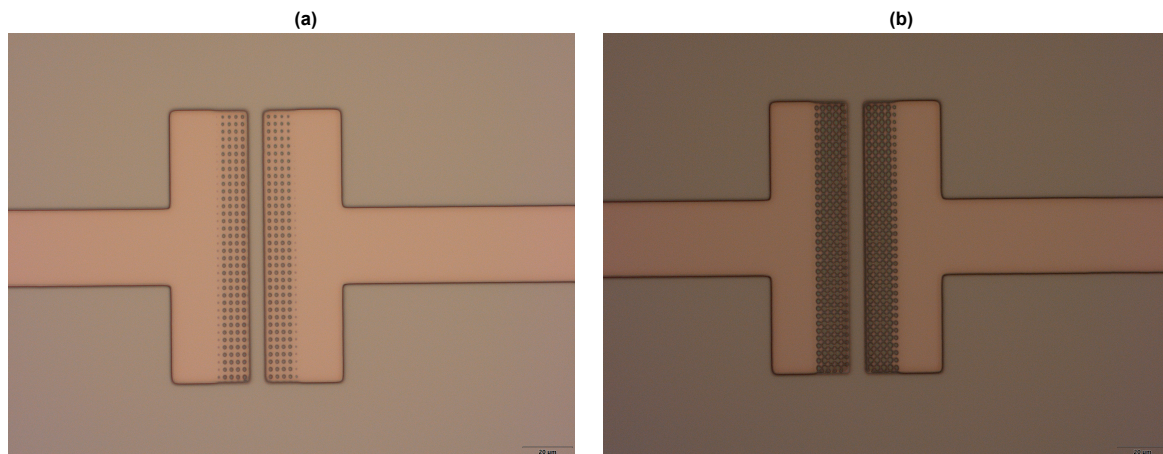


Figure B.6: Partial top-view microscope images of single MEMS cantilevers after UV lithography with (a) defocus 0, and (b) defocus 2 and development.

Figures B.7a and B.7b illustrate the inconsistent patterning of single MEMS cantilevers exposed with the same UV lithography settings and developed with the same development times. The pictures illustrate the effect of the hole size and the distance between the holes and the edges on development.

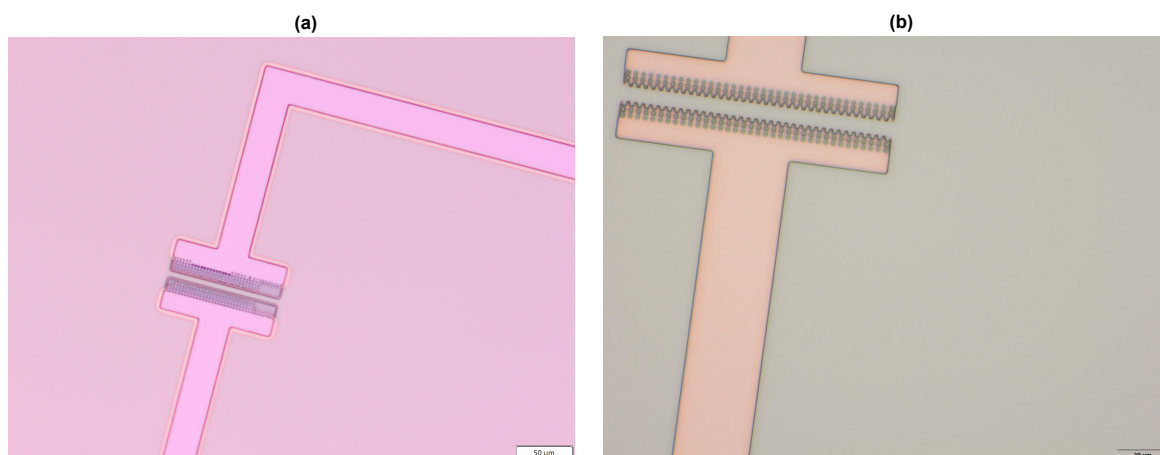


Figure B.7: Partial top-view microscope images of single MEMS cantilevers after UV lithography and development, indicating inconsistent patterning of the holes.

Figure B.8 illustrates an ineffective Au lift-off attempt, in which Au still covers some of the areas intended to be hole openings.

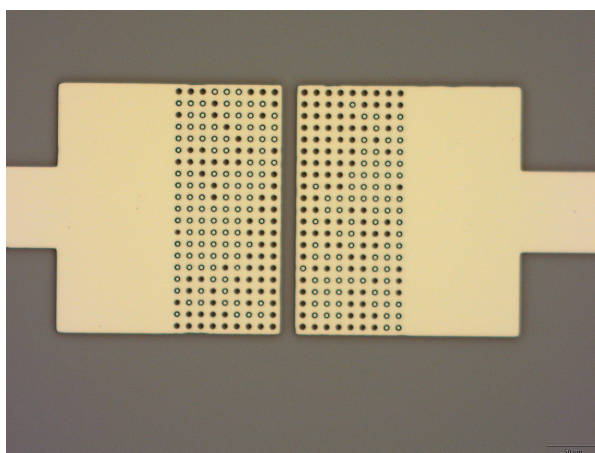


Figure B.8: Partial top-view microscope image of MEMS cantilevers after Au lift-off attempt.