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Enhanced sensivitivity of planar evanescent waveguide sensors: material and sensitivity

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ABSTRACT

This paper studies two different approaches for evanescent wave optical sensing: an horizontal one and a vertical one. In horizontal waveguides, the evanescent wave is distributed on the upper cladding. While in a vertical configuration, the evanescent wave is distributed on the left and right sides of the waveguide. In an horizontal configuration the evanescent wave can be also on both sides of the waveguide in order to increase the optical energy for sensing if the substrate under the waveguide is locally removed. However, in this configuration to achieve sensitive devices, the layers have to be free-standing and thin [1] limiting practical implementations of such approaches. Furthermore, very few materials can be defined as tall and thin in the case of a vertical configuration, as the deposition techniques often used (PECVD/LPCVD) are meant for films in the couple of micron range. In the following we will investigate the properties of the materials used but also the fabrication feasibility for both configurations.

Keywords: Evanescent waveguide sensing, Sensitivity, Waveguide materials

1. INTRODUCTION

Evanescent wave sensing has long been used in a free space configuration [2] whereby a free space wave impinges on a flat dielectric interface, and the totally reflected beam brings the information on the low index medium probed by the evanescent wave. More recently, since the advent of integrated optic technology [3], a number of sensor devices [4] have been proposed which use the evanescent field of a waveguide mode to either probe the absorption or the index change of the external medium. This guided wave configuration is attractive since it may lead to miniaturized and batch producible devices. In this paper, ridge waveguides are classified into two categories: horizontal waveguides and vertical waveguides. An horizontal waveguide has a cross section with a height-width ratio smaller than 1, while a vertical waveguide has a cross section with a height-width ratio larger than 1.

In horizontal waveguides, optical rays are mainly bounced on the upper and lower surfaces and evanescent wave is distributed on the upper cladding. Higher modes are mainly supported in horizontal direction. While in vertical ones, evanescent wave is distributed on the left and right sides of the waveguide and higher modes are supported in vertical direction. The evanescent wave distributions are shown in Figure 1 (a) (b).

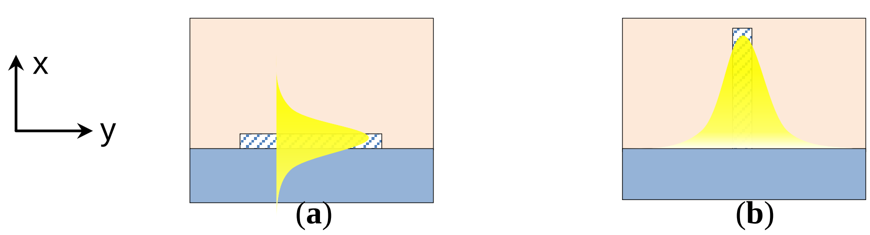

Figure 1. The evanescent wave distribution of: (a) Horizontal waveguide; (b) Vertical waveguide

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Sensitivity is an important criterion for waveguide based sensing systems. It is defined as the amount of change in sensor output resulting from a unit change on the sensor surface [5]. For evanescent wave sensing, sensitivity depends on the optical energy distribution in the cladding area interacting with the change in the cladding such as absorbed bio-targets. Therefore, achieving a waveguide with a high sensitivity depends on designing a structure that allows more optical energy to be distributed outside the waveguide core and reaching the furthest into the cladding. Accordingly, the cladding filling factor in the cover medium, which is the proportion of the optical energy distributed in the cladding, is used here as the criteria. The cladding filling factor in the cover medium is defined as [6]:

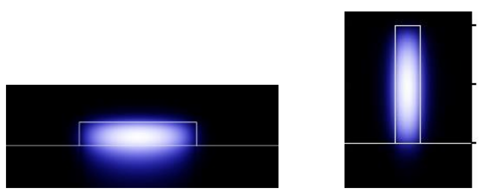
$$\Gamma_c = \frac{\iint_c |E(x,y)|^2 dxdy}{\iint_\infty |E(x,y)|^2 dxdy}, \tag{1}$$

where **E**(x,y) is the electric field vector and C is the cover medium area.

To compare the cladding filling factor of horizontal and vertical waveguides, simulations were performed to study these two structures with SOI waveguides. Silicon is here chosen as it has the highest possible refractive index. Two structures were set with reverse parameters, where the height of horizontal waveguide is the width of the vertical one, and vice versa. Results are shown in Table 1. In the horizontal SOI waveguide with parameter of H = 0.1 µm, W = 2 µm, the cladding filling factor in the left and right area is less than 0.0015% for the fundamental $TE_{0,0}$ mode, while that on the top is around 20%. In contrast, in a vertical SOI waveguide with parameters of H = 2 µm, W = 0.1 µm, the cladding filling factor in the left and right cladding is 46%, while that on the top is only 0.00127% for the fundamental $TM_{0,0}$ mode. The fundamental mode in waveguides is shown in Figure 2. This comparison shows that the vertical waveguide not only has a larger sensing area, but also a higher cladding filling factor, which indicates a potential higher sensitivity.

Table 1. Comparison of energy distribution of horizontal and vertical structures.

	Width	**Height**	**Cladding filling factor (on top)**	**Cladding filling factor (on sides)**
Horizontal	2 µm	0.1 µm	20%	0.0015%
Vertical	0.1 µm	2 µm	0.00127%	46%



(**a**) (**b**)

Figure 2. Fundamental mode in: (a) Horizontal waveguide; (b) Vertical waveguide.

Simulations on the cladding filling factor with different cladding refractive indices were performed to compare the optical sensitivity between horizontal and vertical sensors. The results are plotted in Figure 3a and show that the cladding filling factor increased with an increase in the refractive index of the claddings. Moreover, the vertical structure showed a higher sensitivity to the refractive index change in the cladding than the horizontal one. The sensitivity of the vertical one is found to be 2.38 /RIU, while that of the horizontal one was only 1.03 /RIU. Subsequently, three-dimensional (3D) models developed from the designed structure were built to further simulate the absorption sensitivity of these two structures. The concentration of chemical solution will have an influence on both the real component (n) and the imaginary component (k) of its optical constant. Here, the simulations were conducted by changing the refractive index of the cladding while the absorption rate of the cladding is kept constant. It simulated the situation of saline sensing, where the refractive index changes with different saline concentrations and the absorption rate is dominated by water [7,8]. The sensing length was set as 1 cm. The simulation results are shown in Figure 3b. It can be calculated that the sensitivity of the vertical waveguide is 5.2 dB/RIU while that of the horizontal waveguide is 2.6 dB/RIU, demonstrating that the vertical waveguide has a higher sensitivity than the horizontal one. This result is in agreement with the cladding filling factor predication presented in Table 1. However similar results can be achieved if the substrate in the case of an horizontal structure removed. In the following we will then focus at defining the most suited materials to achieve regardless of the sensor type the best sensitivity.

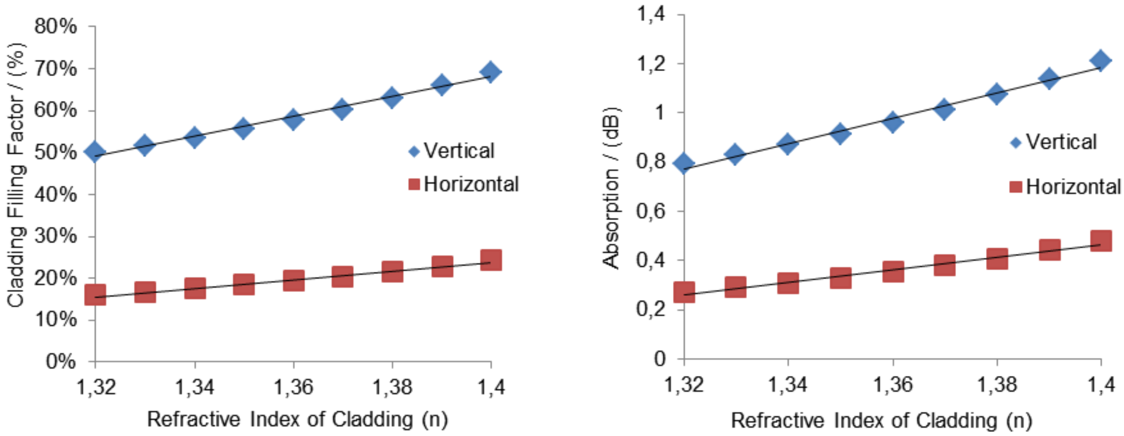


Figure 3. (a) Simulations on the optical sensitivity of horizontal and vertical waveguides; (b) Simulations on the absorption sensitivity of horizontal and vertical waveguides.

2. HORIZONTAL WAVEGUIDES

2.1 Material choice

High refractive index materials such as Si, GaAs, are single mode when very thin (<200nm) and therefore cannot be considered for free standings sensors as they will be too fragile (we assume of course here single mode waveguides as multimodal sensing requires much complex information retrieval). Of course supporting beams (figure 4 [9]) can be added to strengthen the devices but they will add to the overall losses. Evanescent wave sensors are often long (1 cm was considered in figure 3) and each beam will add losses. For application where detection at an early stage is required [10] a limited signal will be a problem.

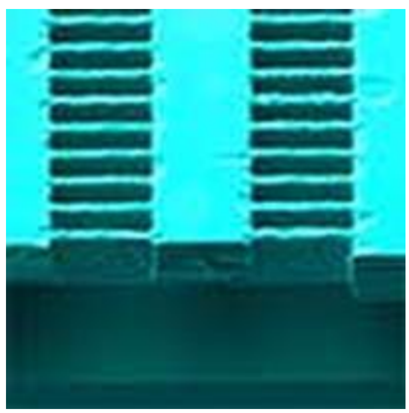


Figure 4. Long silicon waveguide with supporting beams (from [9]).

On the other end, low refractive index materials are also disregarded as they often yield not sensitive enough devices. Therefore the choice remains limited to materials with a refractive index between 2 and 3. Among the materials with indexes in this region TiO_2 has to be disregarded has its mechanical properties do not allow producing long and thin structures. They are for example for reinforcement placed on a supporting SiN membrane [11]. It is important to notice here that the way the waveguides are produced plays a key role. PECVD or ALD layers are not the best choice to consider as they often lead to compressive stresses and limit the fabrication of long and suspended structures. The stress

limitation can be overcome by annealing [12] but then the low temperature benefits of the deposition (CMOS compatibility, …) are lost.
On the end, LPCVD offers tensile stresses that are more favorable to define long and suspended structures. Among the layers showing a refractive index between 2 and 3, SiC and SiN are ideal candidates. Figure 5 shows however that even with similar mechanical performance SiC has an advantage in terms of sensitivity. Here the refractive index plays a key role and the higher the refractive index (for an optimized sensor) the better the performances

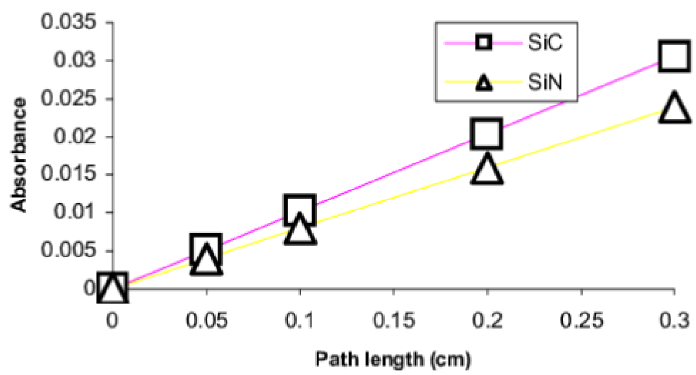
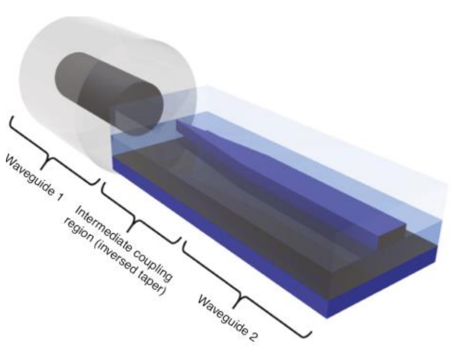


Figure 5. Absorption vs path length for an optimized SiC evanescent sensor compared to a SiN one.

2.2 Sensor interfacing

For both SiC and SiN the waveguide dimensions (if single mode) do not allow an easy coupling with standard optical fibers. The spot size is the range of 2 um and therefore do not match the one a fiber. One way to deal with the problem is to use inverted tapers but their fabrications rely on advanced lithographic tools as the tip of the taper has to be narrow (down to few nanometer) to match the mode profile of the fiber.



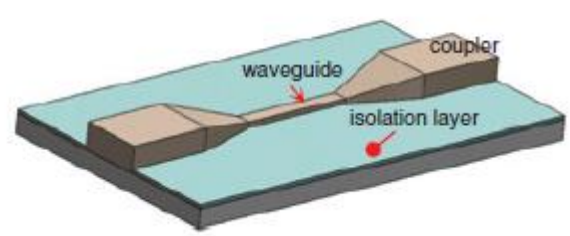


Figure 6. Inverted tapers as often implemented in SiN (left). Adiabatic tapers as recently implemented in SiC (right)

Alternatively recent progress in adiabatic tapers in SiC have shown that without the need of advance lithography efficient coupling can be achieved [13]. The technology rely on using a Si hard mask and the difference in etch rate between Si and SiC to achieves slopes in the 1 degree range (rule of thumb to design low loss adiabatic tapers).
LPCVD SiC showing better performance and being now able to be efficiently interfaced to standard fiber should be therefore the material of choice if an horizontal configuration for evanescent sensing is considered. Beside all the benefit listed above SiC as also a large advantage among all the other materials in harsh environment.

3. VERTICAL WAVEGUIDES

In the previous section we have been looking at defining the most suitable material for an horizontal evanescent wave sensor and found out that SiC is the best material. However even of the material as excellent mechanical properties making long free standing structures some applications might require more robust structures for example in applications in space or automotive were vibrations are part of the specifications. Therefore because they can achieve very good sensitivity vertical structures should also be considered.

3.1 Material choice

The structures as shown on figure 1 have to be thin (to deal with single mode waveguides) and tall (to have an increase interaction with the outside world. That limits the number of material that can be used. All the materials considered in section 2.1 are here disregarded as the deposition techniques employed often lead to layer in the µm range. Even PECVD that can generate layers in the tenth of µm. Indeed in this case the etching of the layer to produce the waveguide will be detrimental to get the losses required.

Polymers, as important materials for MOEMS applications, are also used in integrated optics due to their adjustable refractive indices, good mechanical properties, low cost, compatibility with semiconductor technology [14]. SU-8, as an epoxy photon-sensitive photoresist allows patterning by photolithography simplifying drastically fabrication processes. By avoiding dry etching, sidewall roughness is reduced and scattering loss is lowered. Further SU-8 can be fabricated by direct writing lithography such as E-beam lithography, allowing maskless processes, low-cost prototyping, fast and sub-micron fabrication with high precision [15].

We have fabricated SU8 evanescent waveguides to evaluate their performance. On a 3 µm thick SiO_2 was first thermally oxidized at 1100 °C on a silicon wafer as an isolation layer, acting as waveguide substrate and preventing light leakage into silicon underneath. Then a plasma treatment was conducted to improve the adhesion of SU-8 photoresist to the substrate. SU-8 3005 photoresist was then spin-coated on the SiO_2 layer for 5 µm thick with the following recipe: (1) spin at 500 rpm for 10 seconds with the acceleration of 100 rpm/sec and (2) spin at 3000 rpm for 30 seconds with acceleration of 300 rpm/sec. Afterwards, the wafer was prebaked with slow temperature ramping up and cooling down to prevent any potential induced stress and guarantee good adhesion. Then the whole wafer was processed by E-beam lithography using a Raith EBPG-5200. Post bake was also conducted with slow temperature ramping up and cooling down. Standard developing was continued to get rid of the un-crosslinked SU-8. Hard bake at 120 °C was performed consequently to stabilize the structure. The fabricated waveguide is shown in figure 7.

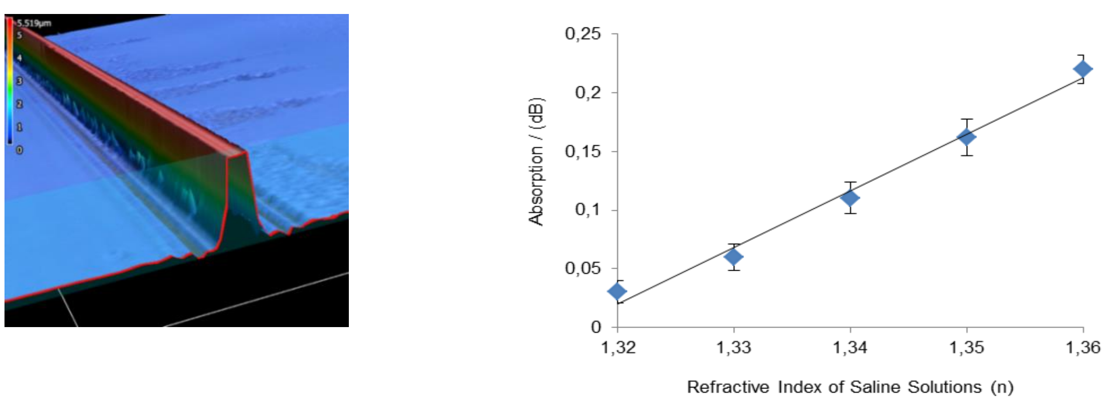


Figure 7. Fabricated SU8 vertical sensor (right) and its optical performance for different saline solutions [16].

Sensitivity experiments were performed using saline solutions with different concentrations. Different concentrations have different refractive indices. The refractive index changes with concentrations and can be referred to the research in [17]. Absorption rate is dominated by water, so the influence of saline concentration on cladding absorption rate can be neglected. However, the change in refractive index will influence the cladding filling factor and the optical distribution, which will further influence the total absorption of the waveguide. The sensitivity is calculated to be 5.2 dB/RIU (in agreement with the simulations presented in the introduction).

3.2 Sensor interfacing

Like for the horizontal case a good interface with a fiber is required in order to fabricate fully autonomous systems. However here the fact the waveguide is very tall makes the problem less complex as there is a matching in the vertical direction. For the other direction the waveguide is simply tapered out (figure 8).

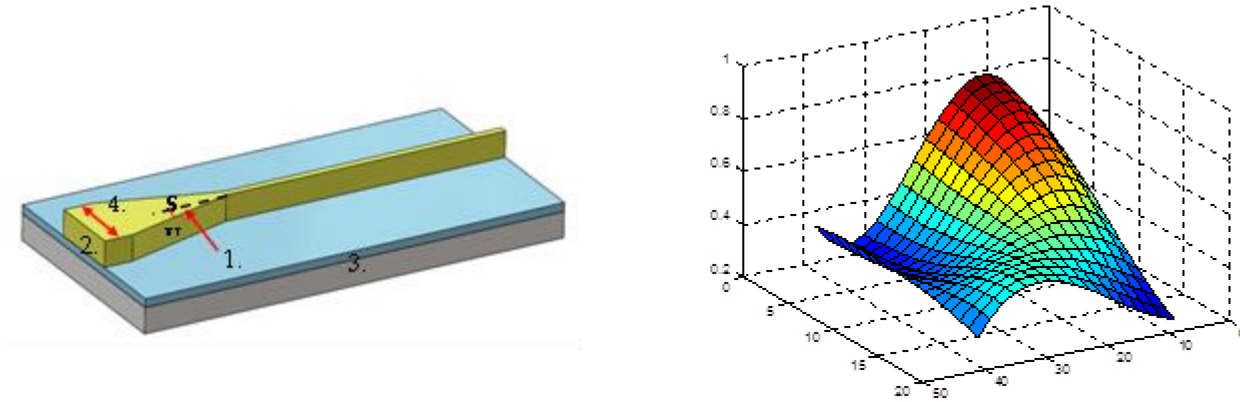


Figure 8. Taper fabricated in SU8 (right) and its optimized length (left)

4. CONCLUSION

Based on several considerations (sensitivity, interfacing, mechanical), SiC and SU-8 are found to be the most suitable materials for horizontal structure and vertical one respectively. SiC waveguide can be processed with standard LPCVD deposition to obtain precise layer thickness and dry-etched to define the structure. As for SU-8 waveguide, E beam lithography is an efficient fabrication method. However, adhesion problems occur when processing high-aspect-ratio SU-8 structures. Therefore the process needs optimization. Different parameters including pre-process of substrate, baking temperature, baking time, and development time were studied to deliver stable and tall waveguides

Furthermore, the sensitivities obtained for both configurations, for the horizontal configuration the best reported sensitivity using SiC and for the vertical one made of SU-8, were presented. Both designs have their own merits and can be advantageous under different conditions. For those applied in harsh environment , SiC waveguide could be a better choice considering the stability and chemical inertness of the material. For those applied in a plug-and-play system as a disposable component, the vertical SU-8 design is a suitable one. As it is cost effective and have a bigger alignment tolerance in vertical direction. It also guarantees the stability at the same time. Both waveguide sensors are biocompatible and can be surface-functionalized and can be broadened into biomedical sensing.

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