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Citation (APA)

Vanhamel, J., Dupont, S., & Saathof, R. (2025). Analysis and Design of an Integrated Compact RF Driving System for PIC-Based Hybrid AOM Phase Shifters for Free Space Optical Communication. In *Proceedings of the 2025 IEEE International Conference on Space Optical Systems and Applications, ICSOS 2025 IEEE*.
<https://doi.org/10.1109/ICSOS66026.2025.11443205>

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Analysis and Design of an Integrated Compact RF Driving System for PIC-Based Hybrid AOM Phase Shifters for Free Space Optical Communication

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Abstract— When using Radio Frequency aboard small satellites, for high data rates, this would need large antennas, violating constraints related to size, weight, and power. As an alternative, Free Space Optical Communication (FSOC) uses laser beams, operating in the optical and infrared frequency domain, in order to transmit data through the atmosphere between satellites and ground stations. However, implementing FSOC systems on (small) satellites remains challenging. In this paper, we investigate the role of phase shifting in FSOC systems. The functionality of these phase shifters is used for modulation, beam steering using optical phased arrays, and phase stabilization of the transmit and receive beams. This is where Photonic Integrated Circuit (PIC)-based platforms could offer a solution. Their extremely compact form factor makes them ideal for space applications. Phase shifters embedded within PIC-based platforms offer a known solution by allowing dynamic manipulation of the phase of light. A specific setup, namely the use of hybrid AOMs, looks promising as other phase shifting techniques can suffer from several issues, such as being thermal sensitive, having non-linear effects and possible material degradation in the long-term. As these devices come with their own challenges, this work identifies these shortcomings and focuses on the analysis and design of an efficient low-power miniaturized RF driving system, in combination with the design of an efficient hybrid AOM setup for phase shifting in a PIC environment.

Keywords—AOM, PIC, FSOC, RF driving, acousto-optics

I. INTRODUCTION

Radio Frequency (RF) communication has long been the baseline for satellite-based applications in multiple domains such as Earth observation and telecommunications. However, RF systems are now approaching their physical limits. Data transfer from satellites to ground stations can take hours, primarily due to scheduled downlinks and frequency congestion. Moreover, small satellites that require high data rates would need large antennas, which violate strict Size, Weight, and Power (SWaP) constraints. This is where Free Space Optical Communication (FSOC) offers an interesting alternative. FSOC uses laser beams, operating in optical and infrared frequencies, to transmit data through the atmosphere between satellites and ground stations. By leveraging narrow, high-frequency beams, FSOC increases capacity without relying on large ground infrastructure.

However, implementing FSOC systems on (small) satellites remains challenging due to stringent constraints on size, weight, and power. Also, due to the small divergence of the beam, the acquisition phase, and beam stability in the presence of satellite micro vibrations and atmospheric turbulence forms a known challenge. This is where Photonic Integrated Circuit (PIC)-based platforms could offer a solution. Their extremely compact form factor makes them ideal for space applications. By integrating complex optical functions such as modulation, demodulation, phase shifting and potentially beam steering onto a single compact chip, PICs could drastically reduce the size and power of the optical communications terminal. Especially, the role of phase shifting is important in FSOC systems. The functionality of these phase shifters is used for modulation, beam steering using optical phased arrays, and phase stabilization of the transmit and receive beams. Phase shifters embedded within PIC-based platforms offer a known solution by allowing dynamic manipulation of the phase of light.

For integrating phase shifters into such a platform, several techniques exist like Electro-Optic (EO) phase shifting (Pockels Effect) [1], Thermo-Optic (TO) phase shifting [2], carrier injection / depletion phase shifting [3], MEMS-based phase shifting [4], piezoelectric phase shifting [5] and nonlinear optical phase shifting [6]. Another promising technique is the use of a hybrid Acousto-Optic Modulator (AOM) [7]. In this framework, the use of hybrid AOMs looks interesting, as the other phase shifting techniques can suffer from several issues, such as being thermal sensitive [8], having non-linear effects [9] and possible material degradation in the long-term [10].



Fig. 1. Schematic view of the satellite to ground link. The satellite emits an optical beam, which contains the modulated signal. The optical ground receiver collects part of the light and relays it to the data detector. For satellites other than GEO satellites, the satellites carry speed, causing a doppler shift.

Hybrid AOMs are less prone to crosstalk [11], as well as less sensitive for non-linearities [12] and thermal variations [13]. The fact that AOMs can apply both phase modulation and frequency shifting [14] creates an additional advantage, for example to compensate doppler shifts due to satellite motion. Subsequently, the available RF driving system for Acousto-Optic devices in general consumes limited power [15], which is a necessity for efficient implementation in satellite applications. The driving system of AOMs relies on a RF signal, having a specific frequency and power level. AOMs are Acousto-Optic devices, relying on the interaction between sound and light. This interaction technique has the necessary heritage in space due to implementation in multiple ESA instruments like SOIR [16], NOMAD [17], ALTIUS [18] and SPICAV [19], as well as in missions like Chang'e-3 [20] and MicrOmega [21].

Of course, these devices come with their own challenges such as footprint and size, material integration and efficiency. This work identifies these shortcomings and focuses on the analysis and design of an efficient low-power miniaturized RF driving system, in combination with the design of an efficient hybrid AOM setup for phase shifting in a miniaturized system.

II. FREE SPACE OPTICAL COMMUNICATION SYSTEM

A. Architecture of a Laser Satellite Communications System

The schematic of the link from the satellite to the ground is shown in Figure 1 [22]. The typical wavelength used for laser satellite communications is 1550 nm. This is a compromise between atmospheric attenuation, wavefront errors and available equipment. Also, the motion of the satellite is depicted, because the large velocity of Low Earth Orbit (LEO) satellites cause a doppler shift. Figure 2 shows the schematic of the architecture of the optical bench of the optical communications terminal. Although the exact implementation in a satellite is different than the ground station, the main elements are the same. Notable is the tracking system, consisting of a tracking detector, tracking controller and the Fast Steering Mirror (FSM). The places where phase modulation in a laser satcom system are needed are the following:

Transmitter modulator: the signal needs to be modulated onto the carrier wave. Typical bandwidths for laser satcom are Gbps to 200 Gbps which have been demonstrated [22, 23] and Tbps for optical feederlinks [24]. For low bandwidth, amplitude modulation formats are used, such as On-and-Off Keying (OOK), or Pulse Position Modulation (PPM). The latter is an appealing modulation format for deep space missions, because the photon efficiency can be very low for

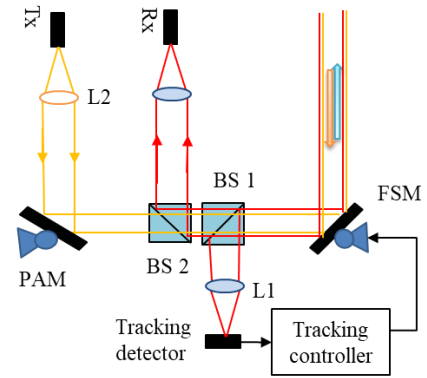


Fig. 2. Schematic of the optical bench, with a Fast Steering Mirror (FSM), to control the motion of the beam, two Beam Splitters (BS 1 and 2), to split the light to lenses L1 and L3 which focus the light on the receiver detector (Rx) and the tracking detector. Light from the transmitter Tx is collimated using L2 and, directed to the satellite using a Point Ahead Mirror (PAM).

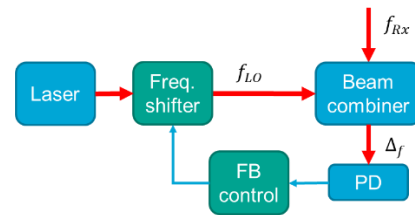


Fig. 3. Simplified schematic of a coherent detection system. The Rx laser the local oscillator are mixed using a beam combiner, resulting in an optical beat with $f_{LO} - f_{RX} = \Delta_f$. This beating frequency is tuned with a feedback loop, creating a Phase Locked Loop (PLL), using feedback control and a frequency shifter.

low bandwidths (e.g. less than 1 Gbps) [25]. A typical device to realize this type of modulation is a Mach-Zehnder modulator, where the destructive interference is the off state, and the constructive interference the on state. Coherent modulation formats, such as Binary Phase Shift Keying (BPSK), and Differential Phase Shift Keying (DPSK) make use of phase modulation. Higher order formats, such as Quadrature Phase Shift Keying (QPSK), or 16QAM make use amplitude and phase modulation, or IQ modulation. An IQ modulator comprises of two Mach Zehnder modulators. These modulators are also known as Electro-Optical Modulators (EOM) and are made from e.g. Lithium Niobate.

Receiver demodulator: for amplitude modulated signals, only a photodiode suffices as a detector, which records the on and off state of the incoming light, and the time lapse between two pulses for PPM. For DPSK, the carrier beam is split, one arm is delayed and mixed together again for self-interference. The demodulator that is needed in this case, is a simple delay line. For tuning of the delay line, a phase modulator can be used, for fine tuning of the phase. For BPSK and other higher order coherent communications, another laser – the local oscillator – is mixed into the received beam. The conventional approach is to create a Phase Locked Loop (PLL), to achieve heterodyning or homodyning, taking care that the frequency of the local oscillator and receive beam have a fixed frequency offset or have the same frequency respectively (Fig. 3). As using a PLL, this increases hardware complexity, and state of the art demodulators use a free running oscillator [26]. By this means, the complexity of the system is shifted from the hardware to the digital signal processing.

Beam steering: Beams in laser satellite need high accuracy steering. That is both for the receive beam, as well as for the transmit beam. In the receive path, the laser beam is focused onto a detector. When the detectors get smaller, e.g. when it is coupled into a single mode fiber, the beam need to be focused well on the single mode detector. For ground stations this means applying an Adaptive Optics (AO) system. The least complex variant of an AO system only has tip tilt correction, as shown in Figure 2. In this system, a tracking detector tracks the spot, and provides feedback to a FSM. As the transmit laser also runs over the FSM, this also provides movement to the transmit beam. Due to the reciprocity principle, this compensates the motion of the terminal and the beam wander. In other words, this pointing mechanism is providing the necessary pointing precision. Many steering mechanisms are mechanical of nature, such as a FSM, but also other mechanisms are under investigation, such as optical phased arrays [27].

The required accuracy of beam steering is determined by the divergence angle of the optical beam [28]. The irradiance of an optical beam is inversely proportional to the area of the spot. The diameter of the spot is proportional to the divergence angle θ_{div}^2 , so:

$$I_{sat} \sim 1/\theta_{div}^2 \quad (1)$$

This means that a smaller divergence is desirable. However, the pointing errors cause intensity fluctuations, for which a margin need to be taken into account. This margin is typically considered as a pointing loss [29]. The additional gain of the reduced divergence, and the additional losses by the pointing errors result in an optimum, where the standard deviation of the pointing jitter is five times smaller than the divergence of the optical beam [28]. This results in allowable pointing errors in the μrad regime. The bandwidth of the compensation mechanism, is related to the vibrations of the satellite [30] and the angle of arrival fluctuations caused by turbulence [31]. The bandwidth of the compensation is in the order of kHz. The range that the steering requires is related to the field of view of the telescope. For this reason FSMs have a range of one degree [32].

Doppler shift: Because of the velocity of the satellite, the optical beam gets a doppler shift [33]. The amount of doppler shift is dependent on the link type, for LEO satellites, this shift is around 5 GHz. Although this is only a very small shift – 4 pm compared to 1550 nm – This can be an issue for coherent communication systems [34].

B. Opportunities for Acousto-Optical Devices in Laser Satcom

Phase noise compensation: Besides the doppler shift, other phase noise is present in the laser beam. This can e.g. be caused by fluctuations in the laser and by turbulence. To compensate for the phase noise, it is beneficial to create a phase offset. A common way to do so is using an AOM, with e.g. few tenths of MHz phase offset. With this phase offset, it is easier to create a PLL, because it allows for a larger bandwidth of the loop filter.

Data modulation: Electro optical modulators are very well suited for data modulation. For data modulation a phase shift of maximum few waves is needed, and EOMs deal with that phase shift very well.

Beam steering: Acoustic optical devices can also be used for beam steering. This implies that the FSM in the system would be replaced by the acoustic optical device. The advantage of an acoustic optical device, is that it has no moving parts, or delicate mechanics that could buckle due to vibration forces at the launch of the spacecraft.

III. ACOUSTO-OPTICAL MODULATOR SETUP IN FSO

A. Acousto-Optic Principle and Applications

Acousto-optic device operation is based on the diffraction of light by a periodic refractive index grating induced within an elasto-optic material by an ultrasonic acoustic wave, both surface and bulk acoustic waves have been successfully employed. Such devices find applications for the modulation, deflection, filtering, and frequency shifting of laser beams in a various scientific and technological applications. In space applications, bulk acoustic wave devices have been employed in spectroscopic applications, pointing and hyperspectral imaging, whereas surface acoustic waves devices have been proposed for: spectroscopy, remote sensing and beam forming of linear array antennas, demultiplexing and phase/time delay applications [35 – 42]. In coherent optical communication systems, acousto-optic devices can bring useful functional specificities: it can act as a feedback actuator to compensate for phase offsets within optical coherent systems and it is also able to shift the frequency of the optical signals in Optical Phase Lock Loops (OPLL), the latter being is becoming a credible alternative to the traditional high speed datacenter interconnects [43].

B. Acousto-Optical Modulator

In acousto-optic devices, the intensity of the diffracted light is governed by the power of the ultrasonic wave, thereby providing an inherent modulation capability. The modulation speed is directly proportional to the diameter of the optical beam intersecting the acoustic column and inversely proportional to the velocity of the acoustic wave. Consequently, modulators generally employ longitudinal waves, which are typically faster than transverse ones. In the case of analog modulation, nonlinearities in the diffraction efficiency can be pre-compensated through appropriate adjustment of the driving electrical signals. The -3 dB modulation bandwidth, defined as the frequency at which the modulation index decreases by 50%, can reach values as high as 200 MHz in bulk-wave TeO_2 devices, while maintaining high diffraction efficiencies of up to 80%. Comparable performance can also be achieved with surface-wave devices. [44]. Recent developments focus on extending the operational bandwidth, though this improvement comes at the cost of significantly reduced efficiency [45]. Attaining optimal performance necessitates the use of an impedance-matching circuit, although the bandwidth over which effective matching can be achieved typically does not exceed one octave. This limitation arises from the inherent trade-offs between matching range and circuit complexity.

In high-speed coherent optical communication systems, one of the primary challenges lies in accurately determining the phase difference between two lasers operating in an optical frequency band. Precise phase detection is therefore of central importance. Among the available approaches, OPLL technology has emerged as a preferred solution. The

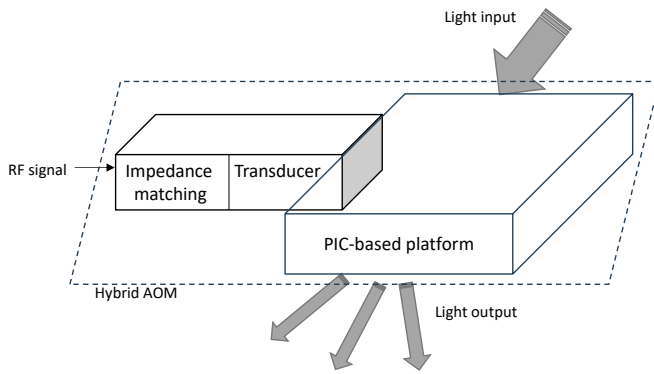


Fig. 4. The concept of the hybrid AOM for space applications.

performance of OPLLs is governed by loop gain and loop bandwidth, both of which are fundamentally constrained by loop delay. A dual-loop OPLL can achieve both higher loop gain and broader loop bandwidth, thereby enhancing dynamic coherence while simultaneously facilitating the lock-in process [46]. In more advanced triple-loop configurations, multiple control mechanisms are employed to stabilize the frequency and phase of the optical oscillator, typically involving temperature regulation, a piezoelectric actuator, and an Acousto-Optic Device (AOD). Owing to its rapid response, the AOD plays a crucial role in OPLL strategies, serving as the key component for high-speed phase and frequency control [47].

C. Conceptual Overview

The hybrid AOM applicable in space applications consists of multiple sub-blocks (Fig. 4). The core of the device is an Acousto-Optical interface, responsible for modulating the incoming optical beam. This interface can be implemented in a PIC-based platform, consisting of Silicon or Indium Phosphide [12, 48].

In order to activate the AOM, an RF signal is applied to the device. This signal first passes through an impedance network (Fig. 4). This electronic circuit is responsible for matching the acoustic and electrical impedance in the most efficient way for having a maximal energy transfer [49]. The impedance network is coupled to the transducer (Fig. 4). The latter is responsible for converting the RF energy into an acoustic wave, using a piezoelectric element [50]. The generated acoustic column creates a periodic modulation of the refractive index in the crystal, due to the photo elastic effect [51]. This acoustic column interacts with the incoming light in order to modulate the light beam.

D. RF Driving System

Acousto-Optical devices in general are operated using an RF signal, which requires a reliable RF driving system, capable of withstanding the harsh environment of space. The driving system consists of an RF generator and a RF amplifier as core-devices (Fig. 5). The RF generator produces an RF signal at a specific frequency and power level, depending on the requirements of the modulating light beam for the AOM. The RF signal should have a suppression of harmonics and spurs of -30 dBc as a baseline [15]. The generated RF signal produced by the RF generator needs amplification in an additional RF amplifier in order to reach the needed power levels. This power and frequency is applied to the impedance network and transducer, attached to the photonic platform (Fig. 4).

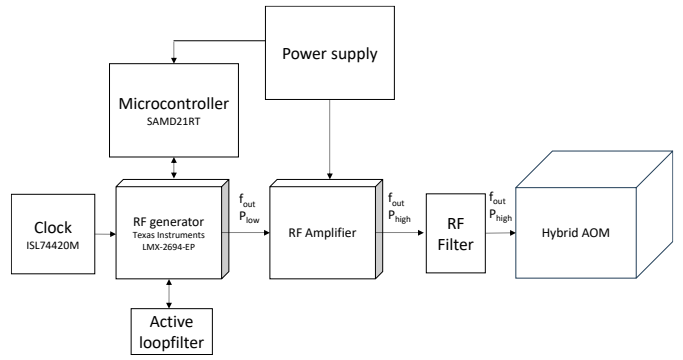


Fig. 5. The RF driving system for activating the hybrid AOM.

The RF generator consists of a space-grade LMX-2694-SEP PLL-chip of Texas Instruments [52]. The LMX-2694-EP [53], which is a commercial version, was tested as a standalone device and showed encouraging results to be used as a RF generator for Acousto-Optical devices [54]. The chip is able to generate an RF signal in the range between 39.3 MHz and 15.1 GHz, allowing a broad coverage. The chip uses a fractional N-PLL with a delta-sigma modulator and several selectable internal Voltage Controlled Oscillators (VCOs) in order to generate this broad frequency range. By using internal dividers, the frequency is downscaled. The chip runs on a single power supply of +3.3 V, which simplifies the power supply section [53].

The chip can be steered using a space-grade SAM21RT microcontroller of Microchip [55]. This device is responsible for selecting the appropriate frequency and power level.

The LMX-2694-EP PLL-chip needs a stable oscillating input signal. Therefore, a space-grade clock like the ISL74420M of Renesas can be used [56]. This device is responsible for generating a clock frequency which is used internally in the PLL-chip in order to generate the allocated frequencies. The LMX-2694-EP also needs an active loop filter for controlling the behavior of the loop by providing gain and flexibility [54].

As peripheral electronics, a power supply is needed to provide the necessary voltage and current levels to the microcontroller, the RF generator and amplifier. The latter is needed in order to increase the power level of the RF signal to an appropriate power level. Generally, the output power of the LMX-2694-EP PLL-chip is limited between 2.2 and 5 dBm [54] and needs further amplification to at least +30 dBm in order to drive a hybrid AOM [54]. The design of such an RF amplifier can be based on a class-E approach in order to increase the efficiency and lower the power consumption [57, 58]. The latter is especially useful in the frame of space applications.

The RF signal at the output of the RF amplifier still contains spurs and harmonics. These need to be removed using an appropriate filter in order to lower the levels below -30 dBc [15, 54] in order for the hybrid AOM to function appropriately.

Using this setup as shown in Figure 5, enables a compact, highly efficient and low-mass RF driving system, implementable in a space-based FSOC system. An estimation of the physical key-parameters for this RF chain is summarized in Table 1.

The total mass is estimated at 170 grams. The breakdown of this number contains the LMX-2694-EP PLL-chip

TABLE I
RF DRIVING SYSTEM PHYSICAL PARAMETER ESTIMATION OVERVIEW

Parameter	Value estimation
Printed Circuit Board area	100 mm x 70 mm
Total mass	170 gr
DC power consumption RF generator	1.2 W
DC power consumption RF amplifier	2.8 W
Total DC power consumption	4.5 W

including its peripherals at around 65 grams, the microcontroller and clock generator at around 20 grams, the power supply at around 35 grams, the PCB at about 20 grams and the RF amplifier section at around 30 grams.

Taking the sizes of all components into account funnels down to a needed PCB area of around 100 mm x 70 mm, which is highly compact for integration into a space-application setup.

For the DC power consumption of the RF generator, an estimate of around 1.2 W is taken [53]. Using a class E RF amplifier as the baseline for generating +30 dBm as an RF output signal, using an estimated practical efficiency of 85 % [58], needs a DC power of around 2.8 W. Taking the DC power consumption of all other electronics into account (estimate 0.5 W), this gives a total DC power consumption of around 4.5 W.

IV. CONCLUSION AND FUTURE WORK

In this paper, the concept of a hybrid AOM, embedded in a PIC-based platform was described in the frame of FSOC. It was shown that this hybrid AOM has the potential to serve as a device, usable in the harsh environment of space. The acousto-optical modulator implemented in a PIC-based platform, as well as the RF driving system was described and quantified to be applicable in the context of FSOC.

Future work is still needed in order to practically implement this concept into a PIC-based platform. Besides a clear view on how this hybrid AOM can be implemented aboard a FSOC system, experimental results need to be obtained to check the estimated RF driving system parameters, as well as the optical performance of such a hybrid AOM device.

ACKNOWLEDGMENT

The authors would like to thank the Space Systems Engineering section of the faculty of Aerospace Engineering at TU Delft, as well as the l'Université Polytechnique Hauts-de-France (UPHF) for their contribution to the performed work.

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