Universal tunable integrated mirror: the Sagnac Loop Interferometer

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ABSTRACT:

A reconfigurable Sagnac reflectometer to use as a tunable mirror has been modelled, designed and tested. It has been described mathematically for their ideal theoretical analysis and the Mach-Zehnder has been compared with Sagnac reflectometers. Furthermore, a photonic integrated circuit has been designed for the test of the different structures in a nitride platform. Some results have been obtained from the fabricated circuit, verifying with the theory the right operation of the active measurements.

Key words: Silicon nitride, photonic integrated circuits, integrated mirrors, reconfigurable integrated devices, linear optics, Sagnac loop interferometer

1.- Introduction

Photonics is the branch of physics that deals with the properties and applications of photons, especially for the transmission of information covering the entire spectrum from the ultraviolet to the infra-red. It started with the creation of a stable and coherent light source called laser. In the following developments, communications through the atmosphere were first attempted, and it was discovered that transmission was very sensitive to the changes in the environment. For this reason, guided optics solution was approached, in which a material conducive the light trough the medium is used for communication, analogously to electronics and, by extension, to microelectronics. The application of the same scale size of microelectronics applied to optics is named integrated optics. The term of integrated optics was coined in 1969 by [1] to describe all those integrated circuits that worked with the manipulation of photons. In this manipulation of the optics and integrate bulky optical systems, the spectrometers are one of the most promising applications. In the optical applications the spectra are acquired with costly off-chip bulky instruments (such as tunable lasers combined with photo-detectors, or broad band sources with optical spectrum analyzers). Hence, it is clear than bringing into the chip area a spectrometer will complement and suppose a significant progress over the current state of the art of photonic chip sensors, in the line of current trends on wearable chip sensors technologies. This project departs from the very recent research seed result, reported by the photonics research lab team on Reflective Arrayed Waveguide Gratings (R-AWG) [2]. The concept, theoretical description, and very first basic experimental demonstration of a Silicon-on-Insulator (SOI) R-AWG static spectrometer were reported for the telecom C-band (wavelength range of 1530-1565 nm). The AWG is a very well-known device, principally applied to wavelength division multi-/de-multiplexing in telecom networks. A R-AWG is half of a standard AWG, where mirrors are included half-way the arms, so it operates in reflective mode, leading to approximately half of the footprint. The mirrors in this concept are implemented via Sagnac Loop Reflectors (SLRs), whose response maybe adjusted by means of variable optical couplers. These couplers can be implemented for broadband operation and fabrication reproducibility, by means of Mach-Zehnder based broad-band, phase shift enabled.

2.- Modelling

Photonic devices can be studied as S-matrix networks like in microwave world [3]. A remarkable feature of S-matrix is the possibility to change to transfer matrix formalism to operate iteratively with mathematical programs to obtain the total response of the device. In integrated optics there are three port elements as Y-juntions or 1x2 MMIs. These elements have special treatment in dielectric waveguides because they don't have reflections, are reciprocal and unitary (lossless). There were some works trying to explain that is not possible to satisfy all the conditions [4]. This case is directly connected to the properties of optical waveguides that support different spatial modes. In summary, the approach to analyse these elements is to decompose the input modes between two modes, the symmetric and antisymmetric modes. So, these supermodes are propagated along the structure until to the output port. The interference among them obtains two solutions depending on the inputs, the first mode and the radiation mode of the output waveguide [5]. Thus, the 3-ports elements can be converted as 4-ports element with an extra port due to radiation mode and with this configuration the analysis is possible. Most of the elements in integrated optics can neglected the reflections due to this effect to couple to radiation modes.

Following the formulas, it is easy to obtain a generic formula of a MZI, independtly of the splitter used with 2 or 1 input ports.

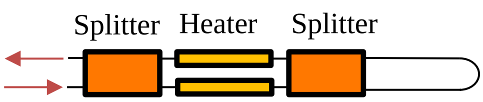


Fig. 1: Sagnac Loop Reflectors (SLR) schematic with one input and one output.

In the literature exists different types of reflectors as mirrors (based on total internal reflexion due to index contrast between two medias), bragg reflectors based on bragg theory of periodic slits) [6] and Sagnac reflector (based on one splitter with the output ports interconected) [7]. In each type there are different ways to tune the reflectivity of the device, but this work is focused in tunable Sagnac reflectors based on Mach-Zehnder interferometers. We have selected this device because does not require additional fabrication processes if compared with mirror-based devices (special metal deposition and trench) or Bragg gratings (high resolution lithography). The figure 1 shows the schematic of the a SLR. It can be obtained the formulas of the Sagnac Reflector cascading the transfer matrix of two Mach-Zehnders (MZI).

3.- Simulations

In this section, the response of a MZI and Sagnac loop reflector will be compared. Thanks to the transfer matrices, it is easier and faster to implement any parameter change in a mathematical program as MATLAB.

A Mach-Zehnder interferometer changes the optical output through the phase shift between arms. This phase shift can be achieved by introducing an extra length in one of the arms or with active dephase. There are a lot of effects that can be employed in integrated optics to obtain a phase shifter but it is possible to divide them in four categories: acoustic effect, electro-optical effect, plasma-displacement effect and thermal effect.

Acoustic, electro-optical and plasma-displacement effects need complex fabrication to control precisely the phase difference. On the other hand, the optical propagation constant can change with temperature. If higher temperature is used, more phase displacement is reached [8]. This change of the temperature could be obtained with a small electrical path on top of waveguide (heater). The resistance of a metallic material depends on their intrinsic sheet resistance (depends on the height and the material composition) and the dimensions (width and length). This heater warm up depending on the current flow applied. The disadvantages of this method are the velocity of the response, because temperature is a slow effect (milliseconds) and the power consumption, that it is too much for some applications. However, this phase shifter is the best to use it in all technologies because no extra complex processes are required.

Sagnac loop reflector could be simplified as two Mach-Zehnder connected. The power used to change between maximum and minimum is called P_π in a SLR this P_π is half of the P_π of a single MZI due to their configuration. The Mach-Zehnders and the Sagnac loop reflector are composed of two simple elements: waveguides, phase shifters and splitter. The main characteristics of the waveguides are the propagation losses and the length. The propagation losses of a specific geometry of waveguide depends on the material and the roughness of the side-walls of the waveguide that can introduce high scattering losses. The length of the waveguide modifies the total insertion losses of the waveguide section and the phase shift. The phase shifter also introduces a phase shift but with an external active signal. The insertion losses are comparable with a waveguide with the same length. Moreover, the splitters have two main parameters: excess loss and imbalance. The imbalance is the power distribution between the outputs of the splitter. The excess loss is the extra losses introduced by the splitter due to their configuration. In the next subsections a comparative analysis is made of these parameters between MZI and SLR.

3.3.- Amplitud and Phase responses

The response in the splitters will have an ideal configuration: excess loss ≈ 0, α, L≈ 0 and K ≈ 0.5. The amplitude and phase of the SLR and MZI depend on the phase difference in the phase shifters.

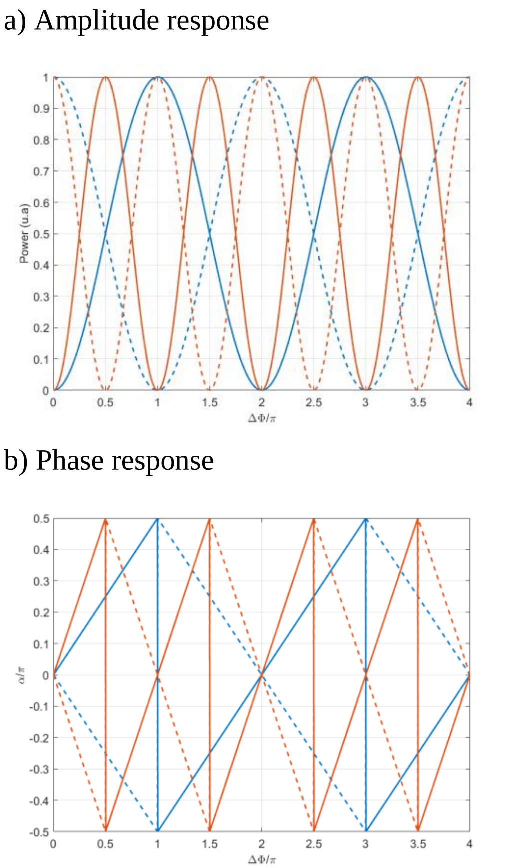


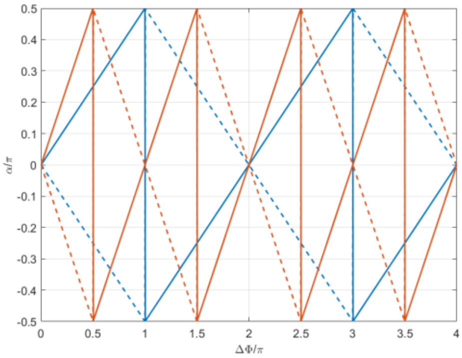
Fig. 2: Comparative figure between 2x2 MZI and SLR 2x2. Transmission of MZI in the cross-port (solid blue line), transmission of MZI in the direct-port (dots blue line), transmission of SLR (solid red line), reflection of SLR (dots red line).

The figure shows the improvement of SLR regarding of P_π as mentioned before.

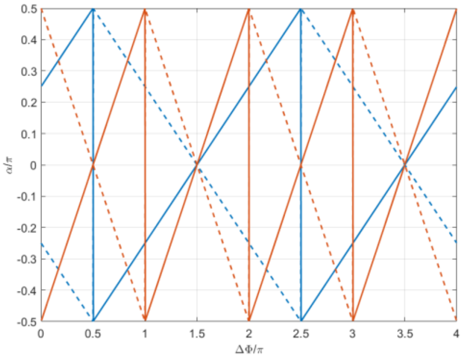
In a passive and ideal state of symmetric Mach-Zehnder interferometer 2x2, the formulas show that when input power is launched in the 1st input all the power goes to the cross port. Tuning the phase shift difference between arms to π we can switch the power completely to the opposite output. In contrast, the 2x2 SLR in π /2 state, all power goes to the same input waveguide. Moreover, in π state all power returns to the transmission port.

One interesting property of these devices are the control of the phase. If both phase shifters are modified at the same time, by changing the refractive index of both waveguides, the output amplitude distribution remains equal because it depends on the phase difference. However, the phase distribution of the both outputs changes with the change of both phase shifters.

a) 0 radian phase in both arms



b) π/4 radian phase in both arms



c) π/2 radian phase in both arms

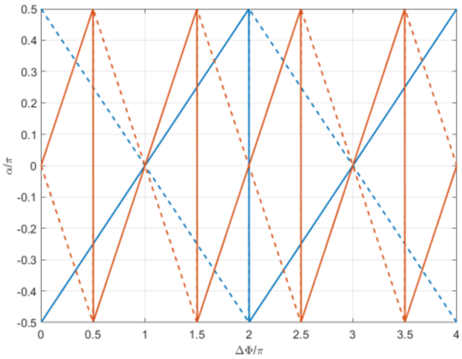


Fig. 3: Constant amplitude and phase response of 2x2 MZI and SLR 2x2. Transmission of MZI in the cross-port (solid blue line), transmission of MZI in the direct-port (dots blue line), transmission of SLR (solid red line), reflection of SLR (dots red line).

As shown the Fig. 3 the phase response of SLR 2x2 could be tuned by applying the same phase shift in both arms. This property is interesting as to correct the phase relations in Arrayed Waveguide Gratings (AWGs). The change in the phase allows you to adjust individually the phase response without change the amplitude response.

4.- Measurements and fabrication

To corroborate the results, the fabrication of these devices was made in the Centro nacional de Microelectronica (IMB-CNM). The process was developed with the collaboration of VLC Photonics [9] and it is based on silicon nitride material. Silicon Nitride based integration platforms are subject of attention due to the wide wavelength range over which the material is transparent (400-2400 nm) and inherently low-loss. This waveguide technology is based on a combination of silicon nitride as waveguide layers, filled by and encapsulated with silica (SiO2) as cladding layers grown on a silicon wafer. SiO2 and Si3N4 layers are fabricated with CMOS-compatible industrial standard chemical vapor deposition (both low pressures, LPCVD, and plasma enhanced, PECVD) techniques, that enable cost-effective volume production. The thickness is 300 nm and the monomode width for waveguides is ≈ 1 µm. There are processes to make metal on top for heaters, deep trenches and two levels of silicon nitride etching: 150 nm and 300 nm. Deep waveguides are 300 nm thick with rectangular shape. The shallow waveguides have a slab of 150 µm thick and the waveguide is defined in the next 150 µm. Shallow waveguides are useful because their geometry is less sensitive to the thickness variations and low loss compared with deep waveguides. However shallow waveguides are multimode, and they have higher bending losses. For these last reasons the deep waveguides are better to reduce the total size of the chip and to have monomode propagation.
The designs were fabricated in a multi-project wafer run (MPW) offered by IMB-CNM [10] within a 5x5 mm2 chip die.
The testing was made in the facilities of the research group [11]. An end-fire measurement setup is used with microscope objectives with MFD 2.5 µm and with polarizers, in order to inject and collect TE polarization. All structures include edge couplers at the input and at the outputs, each at one side of the chip. To measure the response an ASE

broadband source was employed, together with an OSA. All the measurements are normalized to the spectrum acquired without the chip, that is between the microscope objectives face to face. All measurements are with the polarizers set to allow TE to go through to/from the microscope objectives. Fiber collimators are employed, to allow fiber connections from the ASE source and to the OSA. The wafer exposition of the full reticle of the designs allow to obtain more than one copy of the die. In the same wafer, the thicknesses are not the same along the wafer and this condition also changes the definition of the waveguides. Furthermore, the foundry provides more than one wafer so there are a lot of dies to test the variability of a specific device.

The active measurements were carried out using electrical probes and electrical source to the electrical contacts inside the chip. Some of the chips were glued to a PCB board to use wire bonding, making easy the connection to the chip using standard connectors.

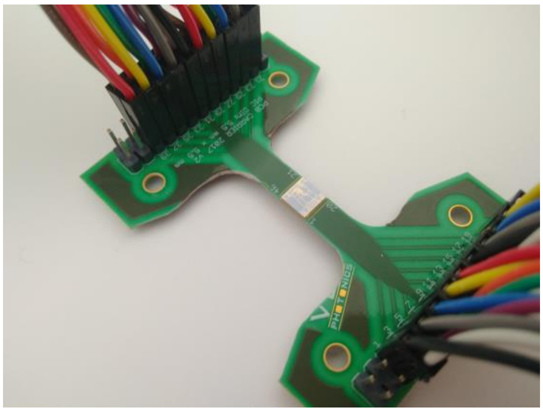


Fig. 4: Photonic integration chip on PCB

The measurements of the active elements follow the next steps:

1. Contact the electrical probes to the pads inside the chip.
2. Align the optical ports to obtain the maximum spectra.
3. Vary the electrical source.

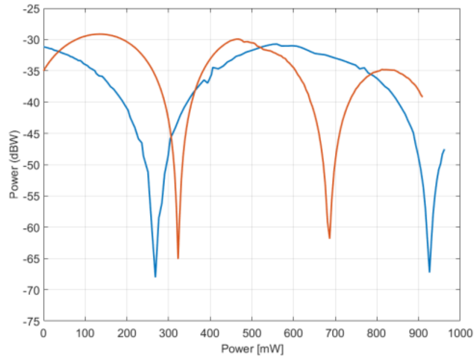


Fig. 5: Measurements of amplitude transmission of SLR (blue) and cross-port of the MZI varying the electrical power of one heater (red).

As shown the Mach-Zehnder reaches one peak meanwhile the SLR reaches two peaks. This is pretty like the theoretical estimations and corroborate that the K near to 50% could reach higher extinction ratios when a pi shift is applied. On the other hand, the measurements were strongly influenced by a thermal misalignment effect. From the experiments we can derive that the physical misalignment was only in the height position.

Reviewing the literature, this misalignment is produced by a mechanical variation of the stress due to the temperature of the chip [12]. This issue is related to the material composition of the layer stack and their expansion and compression factors depending on the temperature.

A theoretical model was developed feeding the measurements of the splitters and the phase shifters response. The model allows to fit the measurement response of the SLR.

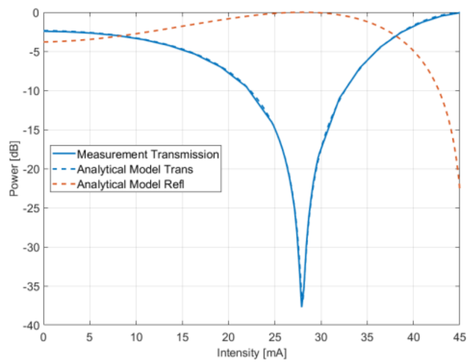


Fig. 6: Amplitude Transmission Measurement (solid blue), Analytical model Transmission (dots blue) and Analytical model Reflexion (dots red)of SLR

The model predicts perfectly the amplitude response of the SLR for different cases.
The phase measurements were made using optical frequency domain reflectometry (OFDR). Detecting the peaks of different temporal contribution due to the facets of the chip, the phase variation can be obtained.

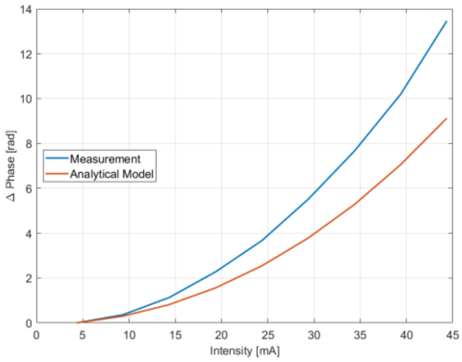


Fig. 7: Phase Measurements (blue) vs Analytical model (red) of the transmission of the SLR

As shown in the last figure, the model can predict the amplitude response however there is some deviation in the phase response. If the phase response is analyzed some fix contribution depending on the current applied is added. There is extra optical length (less than 10 microns according to calculations) that it is warming up in both arms of the SLR. The amplitude remains equal, but the phase response is higher than expected when the electrical power injected increases.

5.- Conclusions

A tunable reflector was described, studied, designed and tested, corroborating the analysis made. An analytic model was made that it predicts the amplitude and phase response of the tunable reflector. However, due to extra heat of some optical path, extra phase contribution was detected.
As a future work we foresee: try to use some methods proved in the literature to reduce the thermal expansion of the chip and the final goal is to include these structures in other bigger devices as array waveguide grating to tune the response.
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