Silicon Nitride Tunable Directional Coupler for programmable waveguide meshes

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ABSTRACT

Emerging programmable multifunctional integrated photonic circuits rely on different topologies of waveguide mesh arrangements of beamsplitters with additional phase shifting capabilities. The optimization of these basic units is essential to increase the versatility, performance and potential scalability of photonic signal processing structures. In this paper, we propose and experimentally demonstrate a thermally-tuned photonic directional coupler in a silicon nitride platform. The trade-offs of this approach and their potential impact is addressed.

Keywords: integrated photonics, programmable photonics, optical switches.

1. INTRODUCTION

During the last 30 years, photonic integrated circuits (PICs) have been shown for a wide range of applications. Most of the devices are specifically designed, manufactured and, in some cases, packaged to perform one single application. However, a new generation of programmable PICs proposes a paradigm shift where a common hardware structure is configured to enable multifunctional designs that potentially offer more versatile cost-effective solutions and reduce the time-to market [1]-[5]. Most of them are based on arrangements of 2x2 beamsplitters with additional phase shifting capabilities allowing either only-forward [2,3], or both forward and backward signal propagation and routing [1,4,5].

All the proposed demonstrators rely on using balanced Mach-Zehnder Interferometers (MZIs) closed by 3-dB couplers as their Tunable Basic Unit (TBU), offering wideband operation but limiting the scalability of the circuit due to the accumulated insertion losses (IL). Optimizing the TBU by miniaturizing the basic delay and the IL is essential to achieve high-frequency operation as well as reducing the footprint of the circuit. However, in principle, the time-step resolution of the mesh and the total accumulated losses are both related to a miniaturization of the TBU, since for MZI-based TBU, losses are dominated by the two 3-dB beamsplitters, [5].

Recently, standalone Tunable Directional Couplers (TDC) have been demonstrated in polymer materials [6] and in Silicon on Insulator [7], providing a reconfigurable splitting ratio by adding a propagation constant difference in the pair of waveguides with a thermal-tuner on top of one of the parallel waveguides. In this paper, we propose a Tunable Directional Coupler (TDC), which is able as a TBU providing both the beamsplitting and the additional phase shifting capabilities by inducing a differential and common phase shift, respectively. As a proof-of-concept, the thermally-tuned device is integrated in a silicon nitride platform and we analyse the potential benefits and weaknesses when acting in waveguide mesh arrangements.

2. PROGRAMMABLE WAVEGUIDE -MESH ARRANGEMENTS

In a similar way to the operating mode of electronic Field Programmable Gate Arrays, programmable photonic integrated circuits can be configured by discretising conventional circuits into a previously fabricated waveguide mesh arrangement of TBUs. By configuring each TBU, constructive, destructive or intermedium interference can be achieved at each complementary output port, leading to the routing of the signal and the definition of the circuit topology and design parameters. Figure 1 illustrates different combinations and waveguide mesh topologies that have been proposed in the literature for this purpose. A common feature is that their demonstrators have employed balanced MZIs to implement the TBUs, either using multimode interference or directional couplers for the two required 3-dB couplers. These, limit the miniaturization of the TBU and dominate the total accumulated insertion losses for a defined path. With this approach, a programmed waveguide length containing N TBUs will always have $2N\, IL_{coupler}$ additional losses compared to that of a standard waveguide in the same integration platform.

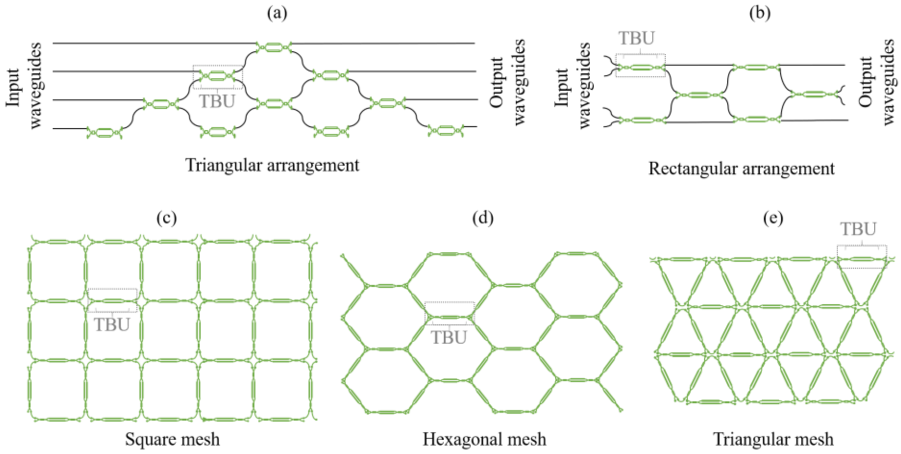

Figure 1. Different waveguide mesh arrangements of beamsplitters: (a)Triangular Feedforward [2], (b)Rectangular Feedforward [3], (c)Squared Feedforward/backward [4], (d)Hexagonal Feedforward/backward [1,5], (d) Triangular Feedforward/backward [1].

3. TUNABLE DIRECTIONAL COUPLER

The directional coupler is one of the most employed building block present at any PIC. The signal of one waveguide is transferred to a parallel waveguide if they are close enough to partially couple their signal field distribution. At a certain length, *Lc*, the signal is transferred totally from the first waveguide to the second one. However, this structure suffers from fabrication errors that change the designed wavelength of operation. As demonstrated in [6,7], a change in the propagation constant difference between waveguide 1 and 2 origins a change in the amplitude splitting ratio of the device (*K*), defined as the optical power ratio coupled to the cross port.

While by employing one phase shifter in one of the waveguides produces a differential phase shift that changes the amplitude splitting ratio, an additional common phase shift will keep constant the value of *K* while adding an independent common phase shift if required. This common phase shift is essential for implementing tunable optical filters, waveguide mesh arrangements and for correcting errors during fabrication. As an example, Figure 2a illustrates a possible implementation of a hexagonal waveguide mesh employing tunable directional couplers as their TBU. Figure 2b describes the structure topology and Figure 2c the different splitting ratios.

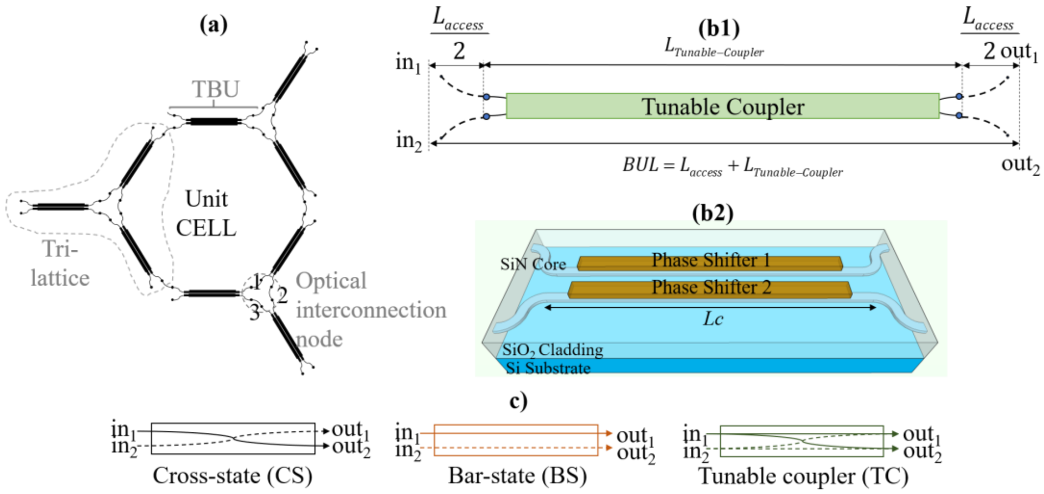

Figure 2. (a) Labelled Hexagonal waveguide-mesh cell, (b1) Tunable Basic Unit definition, (b2) Tunable Directional Coupler illustration, (c) modes of operation representing different splitting ratios.

For the experimental demonstration, we have designed and fabricated under a Multi Project Wafer (MPW) run offered by the Centro Nacional de Microelectronica (CNM) and VLC Photonics a standalone Tunable Directional Coupler in a silicon nitride platform. For the measurements we employed a tunable laser sweeping from 1520 to 1620 nm, followed by a polarization controller before accessing the chip by means of lensed fibres. The data was acquired by an optical spectrum analyser for each programmed electrical power value.

In this case, a single-mode waveguide of 1 µm width and 300 nm height was employed to propagate a TE field. As illustrated in Figure 3a (crossection inset), the gap between the waveguides (*g)* was set to 1.5 µm, leading to a

theoretical total coupling length of 717 µm. However, we decided to increase the final coupler length *L* to 1235 µm to increase the safety of the thermal tuners before proceeding to an optimization round. For the phase shifters, we exploited the thermo-optic effect. For the metal layer, a distance between heaters *(d)* of 2 µm was considered. The optical crosstalk was kept between 15-21 dB for the cross and bar operations while obtaining a bandwidth > 5 nm for a ±2% uniformity. The *total excess loss* was negligible and estimated to be under 0.1 dB. Figure 3b illustrates the change of *K* versus applied electrical current at four different wavelengths.
For this particular proof of concept device, the power consumption needed for the coupling factor reconfigurability from 1 to 0 is greater than in a MZI approach if a thermal tuning mechanism is employed (i.e we measured a power consumption of 270 mW for the MZI approach and 460 mW for the TDC approach in the same integration platform). The reason behind this is the proximity of the two waveguides and the resulting unoptimized thermal crosstalk that impacts more seriously the common rather than the differential phase shift. However, if the structure is optimized accordingly changing *d* and *g*, the electrical power consumption can be considerably reduced [6,7]. Moreover, this concept can be exploited with alternative tuning mechanisms like electromechanical, piezoelectrical or electrooptical effects. Furthermore, a lot of publications aims to increase the fabrication failure tolerance and bandwidth of directional couplers by optimizing the waveguides geometries. With the state-of-the-art, TDCs with phase shifting capabilities of less than 700 µm and 100 µm in silicon nitride and silicon on insulator platforms could be achieved, respectively, which represent more than a three-fold decrement with respect to the MZI-based TBU approaches.

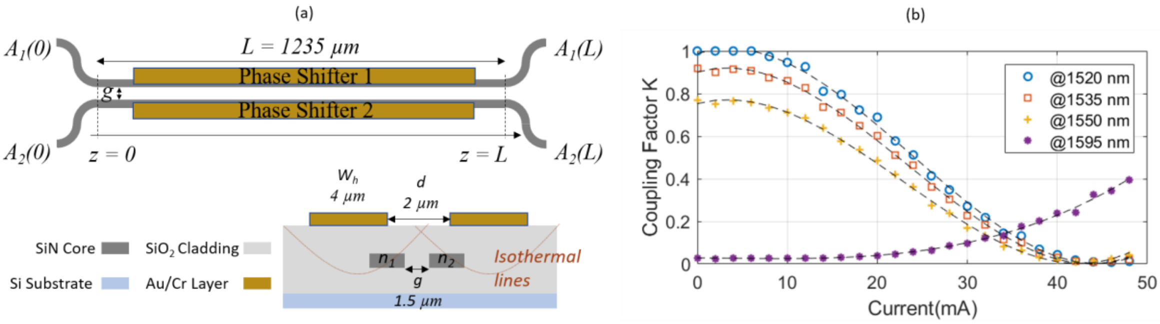

Figure 3. (a) Schematic topview of the fabricated tunable directional coupler and labelled crossection where d represents the distance between the metal layers and g the distance between the waveguides. (b) Experimental results of the tunable directional coupler coupling factor versus current applied to one of the phase shifters for different wavelengths. A cubic fitting is added for each trace (dashed).

4. CONCLUSIONS

We have proposed a new photonic 2x2 building block that allows both beam-splitting and phase shifting of light in a compact design, based on inferring a differential and common phase shift to each waveguide of conventional directional couplers. Once optimized, this component represents a promising TBU alternative for programmable waveguide meshes and for conventional PICs.

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