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HIGHLY INTEGRATED SILICON PHOTONICS DEVICES

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ITA
To my parents, my sister, my fiancée, and those who believed and trusted me.
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Abstract

This doctorate thesis has focused on the scientific and technological development of knowledge based on the long-standing challenges of Silicon Photonics technology. By means of design, fabrication, and characterization of entirely CMOS-compatible photonic devices, this thesis demonstrates new classes of highly integrated Silicon Photonics devices that enable particular functionalities, such as insensitivity to temperature, reconfigurability, low power consumption, and unidirectionality.

The photonic devices insensitive to temperature comprise two distinct designs, which are also considered reconfigurable devices. This thesis reports that two particular resonant structures are able to attain wideband optical properties, and such a characteristic can be exploited to reduce devices' sensitivity to temperature over a broad range of wavelength and temperature. Theoretical results show that a particular configuration is able to support up to 95 K of temperature variation for digital applications.

A third reconfigurable photonic device consists of a proof-of-concept for a new thermo-optic reconfigurable switch, based on a coupled ring resonator structure. Results show that a single optical device with compact footprint is capable of combining several functionalities, such as tunable filtering, non-blocking switching, and reconfigurability.

The fourth photonic device consists of a new tunable photonic crystal nanobeam cavity. Preliminary results show that a compact device (~20 µm²) with high Q-factor (~50,000) and integrated with a micro-heater atop, is able of tuning the resonant wavelength up to 15 nm with low power consumption (0.35 nm/mW), providing FSR higher than 100 nm, and attaining high modulation depth with only ~100 µW of electrical power consumption.

The last proof-of-concept photonic device reported in this thesis consists of the first unidirectional reflectionless passive Bragg grating photonic device, where the break of symmetry for light propagation is demonstrated by means of asymmetric reflection of 7.5 dB.
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LIST OF SYMBOLS

CMOS Complementary Metal-Oxide-Semiconductor
Si Silicon
SiO₂ Silicon Dioxide
LiNbO₃ Lithium Niobate
GaAs Gallium Arsenide
InP Indium Phosphide
FDTD Finite Difference Time Domain

\[ E_{i}^+ \] i-th input electric field
\[ E_{i}^- \] i-th output electric field
\[ \tau_i \] i-th transmission coefficient between ring resonator and bus waveguide
\[ \kappa_i \] i-th coupling coefficient between ring resonator and bus waveguide
\[ R_i \] i-th radius of the Ring Resonator
\[ L \] Length
\[ \phi_i \] i-th optical phase due to the propagation
\[ \lambda_0 \] Wavelength
\[ E_{in} \] Input electric field
\[ I_t(\lambda_0) \] Transmitted optical intensity as a function of wavelength
\[ I_r(\lambda_0) \] Reflected optical intensity as a function of wavelength
\[ n_{eff} \] Effective index of refraction
\[ \Delta n_{eff} \] Variation of effective index of refraction

GHz Gigahertz
dB Decibel
Nm Nanometer
K Kelvin
\[ \mathcal{PT} \] Parity-time
FSR Free Spectral Range
1 INTRODUCTION

Since the invention of the first transistor, in 1947, followed by the development of the first microprocessor, twenty-four years later, the microelectronics industry has committed a great deal of effort on the development of new devices and microprocessors, keeping up with the goal of reducing their footprint and increasing their overall performance [1, 2]. One clear example of such a pursuit is given by means of the Moore’s prediction, who empirically claimed, in 1965, that the number of transistors and other components in microprocessors would duplicate in every cycle of time of about two years. His prediction was so exact that many researchers have considered it as a law, named Moore’s Law, which is depicted in Figure 1.

![Figure 1: Moore's Law](http://software.intel.com/en-us/articles/de-mystifying-software-performance-optimization/)

Nowadays, almost fifty years late, the search for microprocessors with higher performance has been a permanent task, giving rise to the multi-core microprocessors for a continued increasing performance; on the other hand, the level of complexity in the
microprocessors has steadily increased, giving rise to the continued search of more compact
devices and narrower interconnections.

Thereby, inasmuch as the dimensions are shrunk and the number of components is
increased, the metal interconnection lines that provide the communication paths among the
internal components have become smaller and more closely spaced, what has the collateral
effect of limiting its speed performance [2] and rising power dissipation. This speed constraint
(called electronic bottleneck) turns into an increase of the propagation delay on the
interconnects among transistors of an integrated circuit, albeit the reduction of the gate delay
(switching speed of a transistor), as depicted in Figure 2.

![Figure 2: Trends in transistor gate delay (switching time) and interconnect delay with integrated circuit fabrication technology. Source: [2]](image)

Based on the continued demand for the increasing of the microprocessors process
capability, as well as the constant reduction of its dimensions, researchers have concluded that
substantial changes need to be made in the microprocessors architecture, in order for them to
keep up with the pace of the continued evolution of the desired requirements [2].
Thus, several researchers from microelectronics industry and renowned universities have discussed how the new generations of high performance microprocessors should be; they have concluded that a hybrid technology is likely to become the answer to several bottlenecks, being essential the synergic use of photonics and electronics in order to overcome the current technological limitations [2-4].

Photonics has been considered the most promising technology capable of replacing the traditional electrical interconnections; it is suitable for routing and processing signals among the most critical microprocessor blocks (i.e., the ones that require large-bandwidth performance), in order to avoid an on-chip communication electronic bottleneck [2, 3].

Thereby, researchers from IBM have presented a preliminary description on how the next generation of microprocessors could be; Figure 3 show a schematic representation divided in three layers. The first layer consists of a *Processor Layer*, which concentrates several cores; the second layer consists of the *Memory Layer*; and finally, the third layer is the *Photonic Network Layer*, as mentioned before, which is responsible for routing and interconnecting signals to the other layers, i.e., Memory Layer and Processor Layer.

Although being well known that silicon presents several intrinsic limitations when compared to other materials used in optoelectronics, such as LiNbO$_3$, GaAs and InP, silicon has been considered the most suitable material to overcome the challenges posed by the electronic bottleneck. This has been a consequence of the recent advances attained during the past few years and of the great variety of devices and functionalities demonstrated in Silicon Photonics platform. Amongst these special characteristics and advantages presented by silicon, it is noteworthy to point out a few of them:

- High index contrast, that makes it possible to produce waveguides with small cross-section (sub-micron) and small radius curves (few microns);
- Transparency for wavelengths commonly used in fiber-optic communication systems, between 1300 and 1600 nm, and beyond;
- Compatibility with CMOS process, which is of foremost importance and enables the use of already established and well-known fabrication processes used in the microelectronics industry, as well as its mature infrastructure.

The use of silicon as an optoelectronic material is within the broad area of Silicon Photonics, which has been considered a very promising technology for present and future applications, due to its potential scalability to the level of highly integrated photonic devices [3, 4].

### 1.1 Motivation

For the past few years, several active and passive devices have been proposed in order to overcome the challenges of building a *Photonic Network Layer* for high performance microprocessor, such as: electrooptic modulators [5], optical filters [6], electrooptic switches [7], optical reflectors [8], tunable lasers [9], all-optical switches [11], and all-optical modulators [11], amongst many others [12-24].
Although several silicon photonics devices have been proposed, analyzed, and demonstrated, there still are several challenges to be overcome by science and technology in order to bring this technology to the mass production commercial level. Among the main remaining challenges, it is noteworthy to point out reconfigurable devices with different functionalities to route the network, devices insensitive to temperature, integration of detectors and lasers, as well as devices presenting unidirectional characteristics.

Thus, the goals of this work consists on the design, fabrication and characterization of active and passive devices with distinct functionalities that present the relevant characteristic of being either insensitive to temperature, reconfigurable or unidirectional.

1.2 Thesis organization

This work is organized as follows. In the second section, the design of an electrooptic modulator, wideband and highly insensitive to temperature, is introduced; this structure is herein called Snowman modulator. In the third section, a new reconfigurable device, based on uncoupled ring resonators is theoretically proposed and experimentally demonstrated, this structure is called Persiana Structure. In the fourth section, a novel reconfigurable device based on a coupled Vernier ring resonator structure integrated with micro-heaters atop is theoretically and experimentally demonstrated. In the fifth section, the first thermo-optically tunable nanobeam cavity is demonstrated. In the sixth section, we theoretically and experimentally present the first demonstration of unidirectional reflectionless Bragg grating. Finally, we discuss the scientific and technical contributions achieved in this work.
2 SNOWMAN MODULATOR

In this chapter, an innovative approach for an electrooptic modulator is theoretically presented and analyzed; the device is based on a coupled ring resonator structure; such a device is herein called *Snowman modulator* due to its physical similarity.

2.1 Theoretical analysis of the device

The proposed device is schematically shown in Figure 4, consisting of two coupled ring resonators, which in turn are coupled to a bus waveguide; the proposed device works as an interferometer that can have its optical response tailored as a function of design parameters.

In our model, this structure was analyzed by means of scattering parameters, which have been used by several authors due to its excellent agreement with Finite – Difference Time – Domain (FDTD) simulations and experimental results [7, 8, 19-22].

In Figure 4 (a), there are three distinct coupling regions appropriately labeled, each coupling region consists of a directional coupler (Figure 4 (b)), which can be modeled as a four-port optical device. In this figure, the symbol $E^+_i$ corresponds to the $i$-th input electric field, representing the optical beam fed into the respective port, whereas $E^-_i$ relates to the $i$-th output electric field counterpart for the respective port; $\tau_j$ and $\kappa_j$ are, respectively, the transmission and the coupling coefficient between the major ring resonator and the bus waveguide; $\tau_2$ and $\kappa_2$ are, respectively, the transmission and the coupling coefficient between the minor ring resonator and the bus waveguide; $\tau_3$ and $\kappa_3$ are, respectively, the transmission and the coupling coefficient between the two ring resonators. $R_1$ is the radius of the major ring resonator, $R_2$ is the radius of the minor ring resonator, and $L$ is the length of the waveguide, which connects the coupled resonators.
Figure 4: (a) Schematic representation of a Snowman modulator and (b) schematic representation of a directional coupler, which represents each coupling region of the snowman modulator.

The scattering matrix which describes the output electric field components as a function of the input electric field counterparts is described by (1), the minus and plus signs represent, respectively, the optical beams exiting from and arriving at the coupling regions, as illustrated in Figure 4 (b).

\[
\begin{bmatrix}
E_1^+ \\
E_2^+ \\
E_3^+ \\
E_4^+ \\
E_5^+ \\
E_6^+ \\
E_7^+ \\
E_8^+ \\
E_9^+ \\
E_{10}^+ \\
E_{11}^+ \\
E_{12}^+
\end{bmatrix} = \begin{bmatrix}
0 & \tau_1 & -j\kappa_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\tau_1 & 0 & 0 & -j\kappa_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-j\kappa_1 & 0 & 0 & \tau_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -j\kappa_1 & \tau_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \tau_2 & 0 & 0 & -j\kappa_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -j\kappa_2 & 0 & 0 & \tau_2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -j\kappa_2 & \tau_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tau_3 & -j\kappa_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tau_3 & -j\kappa_3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tau_3 & -j\kappa_3 & 0
\end{bmatrix}
\begin{bmatrix}
E_1^- \\
E_2^- \\
E_3^- \\
E_4^- \\
E_5^- \\
E_6^- \\
E_7^- \\
E_8^- \\
E_9^- \\
E_{10}^- \\
E_{11}^- \\
E_{12}^-
\end{bmatrix} \tag{1}
\]

In order to account for the optical phase accumulation, one can notice that the \( E_i^- \) can also be written in terms of \( E_i^+ \), thereby \( E_i^+ \) are given by:
where $\phi_1$, $\phi_2$, and $\phi_3$ are the optical phases accumulated due to propagation inside ring resonator 1, ring resonator 2, and length $L$, respectively; $\phi_1$, $\phi_2$, and $\phi_3$ are given by:

\[ \phi_1 = \frac{2\pi}{\lambda_0} n_{\text{eff}} (2\pi R_1) \quad \phi_2 = \frac{2\pi}{\lambda_0} n_{\text{eff}} (2\pi R_2) \quad \phi_3 = \frac{2\pi}{\lambda_0} n_{\text{eff}} L \]

where $\lambda_0$ is the free space wavelength and $n_{\text{eff}}$ is the complex effective index of refraction for ring resonators and waveguides.

Considering the initial condition that the device is optically fed only in port 1, one can rename $E_{i}^{\text{in}}$ as $E_{i}$, in which $E_{i}$ is the input electric field that feed port 1. Thereby, multiplying (1) by (2), and rearranging accordingly, one can obtain a system of twelve coupled equations, which can be easily solved with the appropriate choice of boundary conditions; thereby, this system becomes:

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & -\tau e^{ik} & 0 & 0 & 0 & jK e^{ik/4} & 0 & 0 & 0 & \ldots & E_1 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_2 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_3 \\
0 & 0 & 0 & 1 & jK e^{ik} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_4 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_5 \\
0 & -\tau e^{ik} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_6 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_7 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_8 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_9 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_{10} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_{11} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & E_{12}
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
\tau E_1 \\
-j\tau E_2 \\
E_3 \\
E_4 \\
E_5 \\
E_6 \\
E_7 \\
E_8 \\
E_9 \\
E_{10} \\
E_{11} \\
E_{12}
\end{bmatrix}
\]
Among the set of coupled equations, special attention is given to $E_6$ and $E_1$, because these electric fields are the ones that describe the optical response of the device, i.e., they are the electric field components that leave the device; thereby, the optical response can be assessed by analyzing the optical intensity at the output ports 1 and 6. The transmitted and reflected optical intensity responses can be evaluated by $I_t(\lambda_0) = |E_6/E_{in}|^2$ and $I_r(\lambda_0) = |E_1/E_{in}|^2$, respectively. In this work, our attention is specially focused on $I_t(\lambda_0) = |E_6/E_{in}|^2$.

### 2.2 Theoretical results of the Snowman modulator

One of the greatest advantages of the proposed device is that its optical response can be tailored as a function of the design parameters, i.e., $\tau_1$, $\tau_2$, $\tau_3$, $\kappa_1$, $\kappa_2$, $\kappa_3$, $R_1$, $R_2$, $L$. Each combination of parameters produces a very distinct optical response, what makes the device present a complex behavior due to its multivariable nature. The proposed configuration is hereby analyzed considering the set of variables shown in Table 1, which were carefully chosen amongst typical values found in the literature for ring resonators, as well as an appropriate value for $L$, such that the device could attain the desirable optical response.

<table>
<thead>
<tr>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
<th>$\tau_3$</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$L$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.678</td>
<td>0.929</td>
<td>0.491</td>
<td>10 µm</td>
<td>4 µm</td>
<td>5π µm</td>
<td>150 m$^{-1}$</td>
<td>300 m$^{-1}$</td>
</tr>
</tbody>
</table>

In this model, the directional couplers are considered lossless; therefore, the coupling coefficients are related to the transmission coefficients by means of a simple equation that describes the principle of conservation of energy: $\kappa_i = (1-\tau_i^2)^{1/2}$, where $i = 1, 2, 3$. In addition, $\alpha_1$ and $\alpha_2$ are, respectively, the loss coefficient for ring resonators 1 and 2, due to the complex value for the effective index of refraction of curved waveguides.

The principle of operation consists of modifying the effective index of refraction of the major ring resonator, what can be done, for instance, by means of free-carrier injection [23]. In this model, we consider a modulation such as the one schematically shown in Figure
which helps illustrate both situations: modulated and not modulated; we considered $\Delta n_{\text{eff}} = -0.002$ inside the waveguide core of the major ring resonator.

Figure 5: Schematic representation of a Snowman modulator: (a) not modulated, (b) modulated.

In order to assess the optical response of the device, Figure 6 shows the normalized output intensity as a function of the wavelength, $I_t(\lambda_0)$, when the Snowman modulator is considered operating under two distinct conditions: modulated and not modulated. In Figure 6, we considered a waveguide with cross section 400 nm wide and 200 nm thin, as well as the optical losses due to free-carrier injection [23]; the polarization mode is the quasi-TM$_{00}$.

Figure 6: Normalized transmitted optical intensity response of the Snowman modulator.

An important observation should be made concerning Figure 6: the optical response is
only considered for quasi-TM$_{00}$ polarization mode and for the values shown in Table 1; if the quasi-TE$_{00}$ polarization was considered, the shape of the optical response would be slightly changed and the wavelength of operation would be slightly shifted. This occurs due to the distinct optical phase accumulated in each polarization state, which are directly related to the respective effective index of refraction [3].

In Figure 6, one can notice the periodic resonances in both situations, modulated and not modulated; some important characteristics can be observed at the highlighted region in Figure 6, which is inside the main telecommunication spectral window, and presents ultra-broadband operation, as well as a good extinction ratio between both conditions, modulated and not modulated. Therefore, in order to see more details at the highlighted region, Figure 7 shows a zoom-in at this region, as well as the transmittance of the device as a function of the change of effective index of refraction for a central resonance wavelength (1.5592 µm).

![Figure 7](image)

**Figure 7:** (a) normalized transmitted optical intensity response of the Snowman modulator and (b) its transmittance as a function of the change of refractive index.

Based on Figure 7, one can notice the high operation bandwidth of the device. In order to quantify the bandwidth of the device, we analyzed the extinction ratio of the modulator (*i.e.*, the ratio between transmission intensity in both cases, *i.e.*, when $\Delta n_{eff} = -0.002$ and when $\Delta n_{eff} = 0$) as a function of the wavelength; this result is shown in Figure 8.
One can observe the high and flat operation bandwidth of the device, which is approximately of 3 nm, thus around 370 GHz in frequency span, for an extinction ratio of 15 dB or higher. On the other hand, if the minimum extinction ratio can be tolerated to be of 10 dB, one can observe a bandwidth as wide as 6 nm, which is approximately 740 GHz in frequency span.

This result shows that this proposed compact structure can be used as a broadband modulator or as a broadband switch; nonetheless, a more important characteristic of the proposed device is its intrinsic property of very low temperature sensitivity, due to the broadband characteristic.

2.3 Temperature sensitivity analysis

The temperature dependence of the effective refractive index for silicon waveguides is one of the most critical characteristics that affect the overall optical response of such devices; this dependency varies with several parameters, such as: waveguide dimensions, optical polarization, and wavelength of operation [3, 4, 13].
The thermo-optical coefficient for silicon and silica, around a wavelength of 1.55 µm, are approximately \( \frac{dn_{Si}}{dT} = 1.86 \times 10^{-4} \, K^{-1} \) and \( \frac{dn_{SiO_2}}{dT} = 1.28 \times 10^{-5} \, K^{-1} \), respectively; therefore, the effective waveguide thermo-optical coefficient is highly affected by the level of optical confinement, and thus depends directly on the several parameters mentioned before [13].

Table 2 shows the effective index, as well as the effective thermo-optical coefficient as a function of the waveguide cross-section and polarization state. These data were obtained with commercial software from RSoft Design Group, for a wavelength of 1.5592 µm.

### Table 2. Thermo-optical coefficients as a function of the waveguide cross-section

<table>
<thead>
<tr>
<th>Dimension (nm)</th>
<th>Quasi-TE(_{00})</th>
<th>Quasi-TM(_{00})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n_{eff} )</td>
<td>( \frac{dn_{eff}}{dT} ) (K(^{-1}))</td>
</tr>
<tr>
<td>450x250</td>
<td>2.5026</td>
<td>2.008 \times 10^{-4}</td>
</tr>
<tr>
<td>400x250</td>
<td>2.3981</td>
<td>2.003 \times 10^{-4}</td>
</tr>
<tr>
<td>350x250</td>
<td>2.2540</td>
<td>1.962 \times 10^{-4}</td>
</tr>
<tr>
<td>450x200</td>
<td>2.3369</td>
<td>1.919 \times 10^{-4}</td>
</tr>
<tr>
<td>400x200</td>
<td>2.2356</td>
<td>1.894 \times 10^{-4}</td>
</tr>
<tr>
<td>350x200</td>
<td>2.0924</td>
<td>1.818 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Based on Table 2, one can notice that the thermo-optical coefficient for the quasi-TM\(_{00}\) polarization mode is lower than that for the quasi-TE\(_{00}\) counterpart; as a tradeoff, the quasi-TM\(_{00}\) mode inside the waveguide core is less confined, what can be assessed by its lower effective index, what means that it is more prone to optical bending losses. If the waveguide cross-section is chosen in such a way that the optical mode becomes more confined, the thermo-optical coefficient gets higher as well; therefore, an optimized cross-section and polarization state must be chosen, such that the waveguide presents low sensitivity both to temperature and bending losses.

According to the data presented in Table 2, one can conclude that a reasonable choice for the waveguide cross-section is 400 nm wide and 200 nm thin, for the Quasi-TM\(_{00}\) mode. Other cross-section parameters could provide lower temperature sensitivity; however, the
chosen ones correspond to a critical limit of optical confinement that still provide low bending losses.

Figure 9 shows the extinction ratio provided by the *Snowman modulator* as a function of the temperature variation, for both polarization states, at a wavelength of operation corresponding to the resonance center.

![Figure 9: Extinction ratio dependence on temperature.](image)

Figure 9 shows that the temperature sensitivity for the quasi-TE\(_{00}\) polarization is twice as much as the quasi-TM\(_{00}\) counterpart; this occurs due to the distinct effective thermo-optical coefficient, as shown in Table 2. Figure 9 also shows that the device performance remain completely unaltered under temperature variation of up to 24 K, for quasi-TM\(_{00}\), considering an extinction ratio of approximately 15 dB. Moreover, if an extinction ratio of 10 dB can be tolerated, the device supports up to 65 K of temperature variation.

On the other hand, if the quasi-TE\(_{00}\) polarization is chosen, the thermal insensitivity is reduced to half of the quasi-TM\(_{00}\) counterpart, *i.e.*, 12 K for an extinction ratio of 15 dB, and 32 K for an extinction ratio of 10 dB.
2.4 Fabrication tolerance analysis

In this section, the Snowman modulator is analyzed in terms of tolerance variation in fabrication parameters. Usually, during the fabrication process of structures like that, the waveguide’ widths tend to be slightly reduced or increased; it means that gaps in the coupling regions can be slightly increased and reduced, affecting \( \tau \). For example, 1 nm deviation in our analysis means around 0.4\% of variation on the transmission coefficient in our model.

Therefore, the three coupling regions are analyzed in four situations, i.e., we considered variations of \( \pm 0.01 \) and \( \pm 0.05 \) in \( \tau_1 \), \( \tau_2 \), and \( \tau_3 \) in order to observe how sensitive its figure-of-merit is to fabrication deviations.

All simulations are compared to the original simulations shown previously in Figure 7, Figure 8, and Figure 9, i.e., with the listed values in Table 1. Thereby, Figure 10 shows the first analysis, which consist of adding 0.01 to and subtracting 0.01 from the initial value of \( \tau_1 \), shown in Table 1.

![Figure 10](image)

Figure 10: Comparison between the (a) optical response modulated and not modulated, (b) extinction ratio as a function of temperature variation, and (c) extinction ratio as a function of wavelength when is considered \( \tau_1 \) and \( \tau_1 \pm 0.01 \).
One can notice that the shape of the optical response in Figure 10 (a) is almost not affected with variations of $\tau_1 \pm 0.01$. In addition, Figure 10 (b) and (c), in dB scale, show that the flat broadband characteristic is slightly reduced and the broadband characteristic and high insensitivity to temperature are similar to those for the ideal case.

Figure 11 shows the second analysis, which consist of adding 0.05 and subtracting 0.05 from $\tau_1$ shown in Table 1, this simulation shows how relevant this parameter is.

The shape of the optical response in Figure 11 (a) is not so much affected with variations of $\tau_1 \pm 0.05$. However, Figure 11 (b) and (c) show that the flat broadband characteristic is lost. Nonetheless, the broadband characteristic and high insensitivity to temperature are kept for 10 dB of extinction ratio. Figure 12 shows the third analysis, which consist of adding 0.01 to and subtracting 0.01 from $\tau_2$ shown in Table 1.
Figure 12: Comparison between the (a) optical response modulated and not modulated, (b) extinction ratio as a function of temperature variation, and (c) extinction ratio as a function of wavelength when is considered $\tau_2$ and $\tau_2 \pm 0.01$.

One can notice that the shape of the optical response in Figure 12 (a) is not so affected with variations of $\tau_2 \pm 0.01$; Figure 12 (b) and (c) show that the flat broadband characteristic is reduced. Nonetheless, the broadband characteristic and high insensitivity to temperature are kept for 10 dB of extinction ratio. Figure 13 shows the fourth analysis, which consist of adding 0.05 to and subtracting 0.05 from $\tau_2$ shown in Table 1.
Figure 13: comparison between the (a) optical response modulated and not modulated, (b) extinction ratio as a function of temperature variation, and (c) extinction ratio as a function of wavelength when is considered $\tau_2$ and $\tau_2 \pm 0.05$.

The shape of the optical response in Figure 13 (a) is completely affected by variations of $\tau_2 \pm 0.05$; the same occurs with Figure 13 (b) and (c), i.e., the device loses its extinction ratio, demonstrating that the device is highly dependent on this parameter. Figure 14 shows the fifth analysis, which consist of adding 0.01 to and subtracting 0.01 from $\tau_3$ shown in Table 1.
One can notice that the shape of the optical response in Figure 14 (a) is not so affected with variations of $\tau_2 \pm 0.01$; Figure 14 (b) and (c) show that the flat broadband characteristic is slightly reduced. However, the broadband characteristic and high insensitivity to temperature are kept for 10 dB of extinction ratio.

Figure 15 shows the sixth analysis, which consist of adding 0.05 to and subtracting 0.05 from $\tau_3$ shown in Table 1.
Figure 15: Comparison between the (a) optical response modulated and not modulated, (b) extinction ratio as a function of temperature variation, and (c) extinction ratio as a function of wavelength when is considered $\tau_3$ and $\tau_3 \pm 0.05$.

One can notice that the shape of the optical response in Figure 15 (a) is affected by variations of $\tau_3 \pm 0.05$, in the Figure 15 (b) and (c) is shown that the flat broadband characteristic is completely affected. However, the broadband characteristic and high insensitivity to temperature are slightly perturbed.

Based on the results shown in this section, the device may lose its flat response characteristics due to fabrication variation and the most sensitive parameter consists on the coupling coefficient between the minor ring resonator and the bus waveguide.

However, another situation should be considered; so far, it was considered the variation of only one of the parameters, i.e., or $\tau_1$, or $\tau_2$, or $\tau_3$; Figure 16 shows the analysis with small combined variations of the three coupling regions simultaneously. In Figure 16, it was considered the follow derivations $\tau_1 \pm 0.01$, $\tau_2 \pm 0.01$, and $\tau_3 \pm 0.01$ in order to observe how sensitive to combined variations the device is.
In Figure 16, one can notice that small combined fabrication errors can preserve the flat broadband characteristics, modifying only the level of modulation, i.e., the extinction ratio depth. In addition, the sensitivity to temperature remains low for 10 dB of extinction ratio.

2.5 Commentaries

Based on the results presented in this section, one can classify the silicon Snowman modulator as a promising integrated optical device, due to its characteristics of broadband operation, up to 740 GHz, and very low sensitivity to temperature, of up to 65 K, when it is tuned to the central resonance wavelength for the quasi-TM$_{00}$. In addition, it is worthy to mention the device's intrinsic characteristics of compactness and CMOS-compatibility.

Regarding fabrication parameter derivations, we conclude that the proposed device is relatively sensitive to it; in addition, one of the most critical parameters is the coupling region between the minor ring and the bus waveguide. However, the required level of fabrication accuracy in building the Snowman modulator has already been achieved by some researchers.
Therefore, the proposed device may open the door for novel structural configurations of silicon optical devices that are capable of mitigating one of the few remaining sources of criticism for widespread use of silicon photonics – the temperature sensitivity.
3 RECONFIGURABLE SILICON THERMO-OPTICAL DEVICE BASED ON SPECTRAL TUNING OF RING RESONATORS

Similarly to the Snowman modulator, the device proposed in this chapter, herein called Persiana Structure, is a device based on ring resonators that allows reconfigurability on chip, being an important building block to be useful in optical signal processing. In addition to that, if suitably designed and fabricated, it can present wideband characteristics and show high insensitivity to temperature; although they have similar properties, the principle of operation of the Persiana Structure is completely different from the Snowman modulator. The following sections describe the functionalities of this device by means of theoretical and experimental results.

3.1 Theoretical analysis of the device

The proposed device is schematically shown in Figure 17. It consists of ten uncoupled ring resonators, which in turn are coupled to a bus waveguide; in addition, there is one micro-heater atop of each ring resonator.

![Figure 17: Schematic representation of proposed device – the Persiana Structure](image)

The principle of operation of the device consists of using each ring resonator resonance, slightly and appropriately spaced, in order to develop a wideband resonator; each resonance is controlled by means of thermo-optic effect with a tailored heater configuration.

Before demonstrating its principle of operation, it is beneficial to show the mathematical approach used to design the device. In this work, the device was analytically
modeled by means of the scattering parameters method and numerically simulated by means of FDTD commercial tools from Rsoft Design Group; moreover, it is noteworthy to point out that several authors have shown the efficiency of both tools by means of the good agreement with experimental results [7, 8, 19-22].

A typical analytical mathematical approach for ring resonators and other structures based on ring resonators have been demonstrated by other works [26, 34], in which the approach of each ring resonator may be analyzed by means of scattering parameters, considering a directional coupler with one input port optically connected to the output port on the same side [27]. The mathematical approach for only one ring resonator is given by [26]:

\[
T(\lambda) = \left| \frac{\tau - \frac{\kappa e^{-j\phi}}{1 - \tau e^{-j\phi}}}{1 - \tau e^{-j\phi}} \right|^2,
\]

(5)

where \(\tau\) and \(\kappa\) are the electric field transmission and coupling coefficient between the ring resonator and the bus waveguide; \(\phi\) is the optical phase due to the propagation inside the ring resonator, which is given by:

\[
\phi = \frac{2\pi}{\lambda_0 n_{\text{eff}}} (2\pi R),
\]

(6)

where \(\lambda_0\) is the free space wavelength, \(n_{\text{eff}}\) is the complex effective index of refraction of the waveguide, and \(R\) is the radius of the ring resonator.

However, the proposed structure consists of a sequence of ten ring resonators; thus, one can obtain the complete optical response of the device by multiplying each ring resonator transmittance, it results in the following equation:

\[
T(\lambda) = \prod_{n=1}^{10} \left( \frac{\tau_n - \frac{\kappa_n e^{-j\phi_n}}{1 - \tau_n e^{-j\phi_n}}}{1 - \tau_n e^{-j\phi_n}} \right)^2,
\]

(7)

where the subscribe \(n\), in all parameters of the design, means the \(n\)-th ring resonator \((n = 1, 2, 3 \ldots 10)\).

Therefore, in order to demonstrate the principle of operation of the device, we have
selected the special design parameters specified on Table 3, where each one of them was carefully chosen based on typical results found in the literature [5, 11]:

Table 3: Parameters used on the design of the modulator

<table>
<thead>
<tr>
<th>Ring</th>
<th>τ</th>
<th>R (µm)</th>
<th>Width (µm)</th>
<th>Height (µm)</th>
<th>α (µm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>0.90</td>
<td>5.043</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 2</td>
<td>0.90</td>
<td>5.043</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 3</td>
<td>0.90</td>
<td>5.043</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 4</td>
<td>0.90</td>
<td>5.043</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 5</td>
<td>0.90</td>
<td>5.043</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 6</td>
<td>0.90</td>
<td>5.060</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 7</td>
<td>0.90</td>
<td>5.063</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 8</td>
<td>0.90</td>
<td>5.066</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 9</td>
<td>0.90</td>
<td>5.069</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
<tr>
<td>Ring 10</td>
<td>0.90</td>
<td>5.072</td>
<td>0.400</td>
<td>0.200</td>
<td>2.6 x 10⁻³</td>
</tr>
</tbody>
</table>

The coupling coefficient, κ, is related to the transmission coefficient by means of the principle of conservation of energy, i.e., \( κ = (1-τ^2)^{1/2} \).

Thereby, from the data showed on Table 3, one can assess the optical response of the device; it is shown in Figure 18 (a), which illustrates the optical response of the device without any bias voltage applied to the micro-heaters; in this figure, it is emphasized where the resonances are spectrally positioned under this condition, i.e., the resonance of the rings one, two, three, four, and five are spectrally positioned on the same wavelength, whereas the other resonances are slightly and periodically spaced. Thus, in order to create an overall broadband resonator, we consider a bias voltage applied to the micro-heaters, numbered from one to five, where such resonances become equally spaced, as shown in Figure 18 (b).

Figure 18: Optical response of the proposed device; a) without bias and b) with bias, (Quasi-TM₀₀ polarization).
The required change of effective refractive index, \( \Delta n_{\text{eff}} \), to switch from condition showed in Figure 18 (a) to condition showed in Figure 18 (b), is given on Table 4. It is noteworthy to point out that the ring status On means that a bias voltage is applied to the respective ring resonator heater, whereas Off means the opposite.

### Table 4: Established condition from Figure 18

<table>
<thead>
<tr>
<th>Ring</th>
<th>Fig.18(a)</th>
<th>Fig.18(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta n_{\text{eff}} ) (x10(^{-3}))</td>
<td>Ring Status</td>
</tr>
<tr>
<td>Ring 1</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 2</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 3</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 4</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 5</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 6</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 7</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 8</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 9</td>
<td>0.0</td>
<td>Off</td>
</tr>
<tr>
<td>Ring 10</td>
<td>0.0</td>
<td>Off</td>
</tr>
</tbody>
</table>

The condition shown on Figure 18 (b) is a configuration for a broadband filter or one level of modulation, which is defined in our analysis as level 0; on the other hand, our main purpose for this device is to demonstrate its capability of processing an optical signal, in such a way it can be used as a reconfigurable and tunable thermo-optical filter or modulator. Of course, the intrinsic speed limitation of the thermo-optic effect [31-33] implies that the device has to be used in processing speeds on the range of up to a few MHz [33], which is enough for several applications in the field of photonics [3].

The next stage to be showed is depicted in Figure 19, the so called Persiana Effect is demonstrated in this figure. Figure 19 (a) consists of the same condition showed in Figure 18 (b), Figure 19 (b) consists of our second level of operation, i.e., level 1, which is obtained by tuning the ring resonators resonances of resonators labeled six to ten. This is attained by means of a bias voltage applied to the respective ring resonator heaters, while the others resonances, labeled one to five, are just turned off, thus establishing a modulated and
processed signal.

Figure 19: Optical response of the device; (a) not-modulated (corresponds to the logic level 0), and (b) modulated (corresponds to the logic level 1), Quasi-TM00 Polarization.

In order to clarify the Persiana Effect, Figure 20 depicts the schematic representation of operation of the device and it emphasizes the scheme for the micro-heaters feeding, which establish the Levels 0 and 1, as well as its optical responses.

Figure 20: Optical response of the device (a) not-modulated and (b) modulated (Quasi-TM00 Polarization).

The required change of refractive index for the device to switch from condition shown in Figure 19 (a) into that in Figure 19 (b), which is the same requirement to that from Figure
20 (a) into Figure 20 (b), is given by Table 5.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Fig.20(a) Level 0</th>
<th>Fig.20(b) Level 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δneff (x10⁻³)</td>
<td>Ring Status</td>
</tr>
<tr>
<td>Ring 1</td>
<td>1.1 On</td>
<td>0.0 Off</td>
</tr>
<tr>
<td>Ring 2</td>
<td>2.1 On</td>
<td>0.0 Off</td>
</tr>
<tr>
<td>Ring 3</td>
<td>3.1 On</td>
<td>0.0 Off</td>
</tr>
<tr>
<td>Ring 4</td>
<td>4.1 On</td>
<td>0.0 Off</td>
</tr>
<tr>
<td>Ring 5</td>
<td>5.1 On</td>
<td>0.0 Off</td>
</tr>
<tr>
<td>Ring 6</td>
<td>0.0 Off</td>
<td>5.1 On</td>
</tr>
<tr>
<td>Ring 7</td>
<td>0.0 Off</td>
<td>4.1 On</td>
</tr>
<tr>
<td>Ring 8</td>
<td>0.0 Off</td>
<td>3.1 On</td>
</tr>
<tr>
<td>Ring 9</td>
<td>0.0 Off</td>
<td>2.1 On</td>
</tr>
<tr>
<td>Ring 10</td>
<td>0.0 Off</td>
<td>1.1 On</td>
</tr>
</tbody>
</table>

Figure 18, Figure 19, Figure 20, and Table 5, show the principle of operation of the proposed device, the Persiana Effect, and, as far as the authors know, this is the first time that it has been proposed and demonstrated in the technical literature.

Up to now, we have presented only the mathematical approach of the device with the help of analytical tools; however, we have also made simulations with analytical and FDTD methods, using a professional computational designing tool from R-Soft Design Group.

Our FDTD simulation consists of a 2D simulation of a structure that is equivalent to its 3D counterpart [31]; the simulation takes into account the material dispersion, waveguide dispersion, and losses in general; moreover, it is noteworthy to point out that our analytical method also takes into account the dispersion characteristics of the device. Thereby, in Figure 21, we show the sensitivity to the losses of the optical response of the device, as well as a comparison between our analytical results and our FDTD simulations; these results are, respectively, shown in Figure 21 (a) and (b).
Based on Figure 21 (b), one can notice the excellent agreement between our analytical methods and the FDTD simulations. In addition, Figure 21 helps us to clarify our choice for losses coefficient of $2.6 \times 10^{-3} \, \mu m^{-1}$.

Based on the results presented on this section, one can observe the wideband performance attained with this device; in addition, due to this intrinsic nature, one can use it to inhibit the natural temperature variations and keep a static characteristic of operation [35]. The relevant figure-of-merit to be observed is the extinction ratio, i.e., the ratio between the maximum and minimum value achieved on the two operating levels.

### 3.2 Bandwidth and temperature analyses

Based on the results presented in the last section, one can observe a large modulation depth, which establishes an excellent extinction ratio. For that reason, in this section, we analyzed the broadband nature of the device, as well as its intrinsic nature of insensitivity to temperature.

Therefore, in order to quantify how broadband the device is, Figure 22 shows the extinction ratio of the device as a function of the wavelength. Based on Figure 22, one can observe that the bandwidth of operation of the device is approximately of 4.78 nm, which translates into approximately 600 GHz in frequency span, for an extinction ratio of 20 dB.
However, if the minimum extinction ratio that can be tolerated is of only 10 dB, one can obtain a bandwidth as wide as 5.78 nm, which is approximately 710 GHz in frequency span.

Obviously, the device is considered a broadband device as compared with other typical devices, such as single ring resonators.

![Figure 22: Extinction ratio of the device as a function of the wavelength (Quasi-TM$_{00}$ polarization).](image_url)

In fact, the broadband nature of the device is an important characteristic; however, our main purpose with this particular feature is to demonstrate that, for a central wavelength of operation, the device can work under a large range of temperature.

Therefore, in order to demonstrate this advantage of the proposed device, Figure 23 shows the same analysis made in Figure 22 for three different values of temperature variations: -15 K, 0 K, and 10 K. Special attention has to be given to the central wavelength of resonance, around 1.550 µm.
Figure 23: Extinction ratio of the device as a function of the wavelength (Quasi-TM$_{00}$ polarization) for some values of temperature variation.

Based on the Figure 23 one can observe that, for the central wavelength of operation, the device preserves its extinction ratio and can be exposed to high temperature variations; thereby, in order to quantify how insensitive to temperature the device is, we have made an analysis of temperature sensitivity, which consists of selecting the central wavelength of working (around 1.550 µm) and assessing the extinction ratio as a function of temperature; this analysis is shown in Figure 24 for Quasi-TM$_{00}$ and Quasi-TE$_{00}$ polarization states.
Therefore, based on Figure 24, one can notice that the device can work with a temperature variation of up 96 K, keeping at least 10 dB of extinction ratio for Quasi-TM\textsubscript{00} polarization. On the other hand, if the Quasi-TE\textsubscript{00} polarization is chosen, the temperature variation is reduced to half of that. It occurs due to the different effective thermo-optical coefficients between Quasi-TE\textsubscript{00} and Quasi-TM\textsubscript{00}.

Although our work has demonstrated a theoretical prediction so far, it is worthy to point out that a previous work has experimentally reported up to 80K of insensitivity to temperature by means of a modified ring assisted Mach-Zehnder structure [6], being this result one of the best results reported in the literature. However, such structure requires a footprint in millimeter scale.

### 3.3 Fabrication tolerance analysis

On the previous sections, we have demonstrated the potentialities of the proposed device, where one can observe its important characteristics. In this section, we present a tolerance fabrication analysis in order to verify how sensitive to fabrication processes variations the device in fact is.
Our analysis consists of three different analyses; we assess the modulated and not-modulated optical response of the device, the broadband analysis, and the temperature sensitivity as a function of the transmission coefficient, covering the range from $\tau = 0.8$ to 1.

The first analysis is shown in Figure 25, where we analyze the normalized optical response of the device as a function of the wavelength and of the transmission coefficient for both levels, 0 and 1. Figure 25 (a) and (b) show the contour map and a perspective graphic of the optical response that corresponds to the Level 0, respectively; Figure 25 (c) and (d) show a similar analysis for the Level 1.

![Figure 25](image)

**Figure 25:** Normalized optical intensity as a function of the wavelength and transmission coefficient, (a) contour map and (b) perspective view of the optical response on Level 0, and (c) contour map and (d) perspective view of the optical response on Level 1.

An important observation should be done regarding the range of our analysis, in
particular when $\tau = 1$, which means that no optical field is coupled into the ring resonators; as a consequence, this condition makes the device work such as a straight waveguide and no resonant effects takes place. Indeed, this condition is completely undesirable, but it reveals what happens with high transmission coefficients, near $\tau = 1$. Moreover, based on Figure 25, one can observe that the device can work very well even with significant variations during the fabrication process; the range of transmission coefficients reveals that even for a 10% tolerance for this parameter, the device can still work satisfactorily. Obviously, these is a large fabrication variation, since researchers have achieved precision of up to 2 nm or less in some devices [25]; notice that a 1 nm deviation in our analysis means less than 0.4% of variation on the transmission coefficient in our model.

Another point deserves special attention, which is related to the amplitude response at the central wavelength as a function of the transmission coefficient; by selecting the central wavelength of resonance around 1.550 µm, Figure 25 (c) and (d), reveal that, as the transmission coefficient is reduced, its amplitude is reduced as well, because of different Q-factor values, which in turn is determined by the transmission coefficient. Thus, the level of the output amplitude may be decreased significantly if the coupling coefficient is increased. However, it does not mean that the extinction ratio will be totally hindered, since the amplitude of the level 0 is near of the transmission null; as a consequence, the behavior of the extinction ratio may assume different behaviors, because it is a ratio between a maximum and a minimum amplitude, and this is the main figure-of-merit to be analyzed; in addition, for several applications, a 10 dB extinction ratio is considered reasonably enough.

Therefore, in order to quantify how sensitive the extinction ratio is, the second analysis is presented on Figure 26, which shows the extinction ratio as a function of the wavelength and of the transmission coefficient. Figure 26 (a) shows the contour map, whereas Figure 26 (b) shows the same analysis in a perspective graphic.
In Figure 26 (a), the highlighted mark corresponds to the point of operation chosen in our model; however, one can observe that for $\tau = 0.915$, a high extinction ratio can be achieved, this is an excellent point and the extinction ratio may achieve up to 80 dB for a particular wavelength; this occurs for that particular value of $\tau$ because it establishes the critical coupling condition for all ring resonators [34]. On the other hand, one can notice that even with $\tau = 0.8$, a good extinction ratio is achieved. Therefore, at least 10 dB of extinction ratio is achieved for a broadband operation, even with relatively large variation of the parameter $\tau$.

Finally, Figure 27 shows the extinction ratio as a function of both temperature variation and transmission coefficient, for the central wavelength (1.550 µm).
Based on Figure 27, similarly to our previous analysis, one can observe that the device is able to keep the extinction ratio over 10 dB for a large temperature variation range, of almost 100 K; this characteristic is observed for a large range of values of the transmission coefficient, similarly to the broadband analysis.

Moreover, an important observation has to be made regarding the Quasi-TE\textsubscript{00} polarization mode; for that polarization, the sensitivity is reduced by a factor of a half. This happens due to the difference of effective thermo-optical coefficients between Quasi-TE\textsubscript{00} and Quasi-TM\textsubscript{00}; thereby, even for the fundamental mode for Quasi-TE\textsubscript{00} polarization, the device is able to present almost 50 K of temperature insensitivity.

### 3.4 Fabrication and characterization

Initially, we fabricated and measured the device with the dimensions showed in Table 3. However, we observed that the heaters were not able to support the required electrical power to provide the desired resonant shift. Thus, we decided to modify our design to increase the resonant shift but keeping the same working principle, \textit{i.e.}, tailoring the optical spectrum by means of the control of each resonance; thereby, we redesigned and fabricated the device using the conditions shown in Table 6.

<table>
<thead>
<tr>
<th>Ring</th>
<th>( \text{gap} (\mu\text{m}) )</th>
<th>( R (\mu\text{m}) )</th>
<th>Width (( \mu\text{m} ))</th>
<th>Height (( \mu\text{m} ))</th>
<th>Heater width (( \mu\text{m} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 2</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 3</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 4</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 5</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 6</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 7</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 8</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 9</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
<tr>
<td>Ring 10</td>
<td>0.25</td>
<td>10.00</td>
<td>0.400</td>
<td>0.220</td>
<td>2.500</td>
</tr>
</tbody>
</table>

The fabrication of our device is classified in two different layers: the optical layer and the metal layer. The optical layer was fabricated by means of direct e-beam lithography over silicon-on-insulator substrate with negative tone e-beam resist, followed by dry etching. A
thick layer of 1.5 µm of silicon dioxide was deposited by means of plasma-enhanced chemical vapor deposition (PECVD).

The metal level was built in two steps using aligned photolithography and positive photoresist with inversion process; the first step consists of photolithography of the micro-heaters, followed by 200-nm of Nichrome deposition and then lift-off; the second step consists of contact pads and feedline photolithography, followed by (5 nm / 270 nm) Ti/Au deposition and, finally, lift-off.

The fabricated device is shown in Figure 28, where Figure 28 (a) and (b), respectively, show a single ring resonator and a waveguide section after exposure and etch. Figure 28 (c) shows the finished device with all layers, i.e., after exposure and etch, as well as PECVD deposition and the two-step-metallization, Figure 28 (d) shows a zoom-in picture of one of the ring resonators with micro-heater atop.

![Figure 28: Micrograph of (a) single ring resonator and (b) waveguide section of the fabricated device, (c) final device passivized with silicon dioxide layer and integrated with micro-heater and pad contacts atop and (d) scaled region of the finished device.](image)
We analyzed the electrical properties of our heaters by means of a semiconductor analyzer and scanned the electric current versus voltage in order to measure the resistance of our heaters, which was found around 700 $\Omega$.

Optical measurements used nano-positioners to align polarization maintaining lensed optical fibers into the sample. An Agilent tunable laser model 81980A was used as light source, an Agilent fiber-coupled power meter model 81636B was used to measure transmitted signals. A Keithley precision current source model 2400 was used to control the electric current passing through the micro-heaters.

### 3.5 Experimental results

After designing and fabricating, we tested the device in order to demonstrate reconfigurability and ability to tailor a desired optical spectrum and use this device as an alternative solution as an equalizer filter and an efficient tool to be used in optical signal processing.

First, a single ring resonator was characterized in terms of extinction ratio, power consumption, and polarization dependence. For the quasi-TM$_{00}$ polarization state, it was observed a broad resonance (up to $\sim$0.8 nm) but poor extinction ratio ($\sim$4 dB); on the other hand, for the quasi-TE$_{00}$ polarization state, resonances showed extinction ratio higher than 10 dB but narrow band due to the high Q-factor. Therefore, in terms of demonstration of the *Persiana Effect*, the quasi-TE$_{00}$ polarization state was chosen due to the high extinction ratio.

We started our analysis characterizing a single ring resonator in terms of power consumption. Figure 29 (a) shows the optical response for a single ring resonator for different bias current values; Figure 29 (b) shows the resonant wavelength as a function of electric current and electrical power. Figure 29 (b) also shows that the ratio of resonant wavelength per electrical power is around 0.25 nm/mW. Furthermore, it is noteworthy to point out that
single ring resonator was able to shift the resonant wavelength up to 10 nm, being the heaters able so support up to 40 mW.

![Figure 29: (a) Optical response of a single ring resonator as a function of the electric current applied to the micro-heaters, (b) resonant wavelength as a function of the electrical power and electric current applied to the micro-heaters.](image)

In order to demonstrate the Persiana Effect, we measured the optical response of the device with no bias current applied to the micro-heaters; then, we tuned all resonances at the same wavelength, allowing us to control the red and blue shift of the resonant wavelengths. Figure 30 shows the optical response with no bias current applied and at the condition where the Level 0 is established.

![Figure 30: Optical response of the device under two conditions: no bias current applied and in such way that the Level 0 is established.](image)
Although Level 0 was demonstrated in Figure 30, Level 1 is still required to demonstrate the *Persiana Effect*. In order to establish Level 1, we tuned five resonances on one single wavelength and five on another wavelength. Figure 31(a) show the first demonstration of the *Persiana Effect* for quasi-TE$_{00}$ polarization state, Figure 31(b) shows the extinction ratio as a function of the wavelength.

**Figure 31**: Optical response of the device showing (a) both Level 0 and Level 1 conditions, and (b) the corresponding extinction ratio.

Based on the results showed in Figure 30 and Figure 31, one can observe that the optical spectrum can be reconfigurably tailored, allowing optical processing signal to demonstrate several characteristics, such as: filtering, optical signal processing, equalization, etc.

### 3.6 Commentaries

In this chapter, we have demonstrated a reconfigurable device that introduces on-chip functionalities enabling equalization filtering and optical signal processing, based on the control of the resonant wavelength of a cascade of ring resonators.

Based on the theoretical and experimental results, we could observe that the main characteristics regarding reconfigurability were demonstrated, showing that the *Persiana Effect* may open the doors for several applications regarding on-chip optical signal processing.
4 RECONFIGURABLE SILICON THERMO-OPTICAL RING RESONATOR SWITCH BASED ON VERNIER EFFECT CONTROL

Accessing a single communication channel without affecting others has been a long-standing challenge recently demonstrated by few researchers [45, 47]. In this chapter, we present a novel structure able to switch, filter and modulate an optical signal without affecting intermediate communication channels.

The device is schematically depicted in Figure 32 and consists of a reconfigurable thermo-optical switch based on Vernier effect [42-45] control, which is attained by means of a device structure that contains a pair of coupled ring resonators with micro-heaters atop.

The Vernier effect is an effective and well known approach to increase the free spectral range (FSR) of devices based on resonant cavities, leading to desirable characteristics in applications such as optical sensors and building blocks for communication systems [42-45]. In spite of the existence of several successful demonstrations [46], some researchers consider the mechanism difficult to be harnessed due to the precise optical phase matching between both ring resonators [40, 47].

In order to overcome the foreseen difficulties of phase matching, the principle of operation of the proposed device consists on individually controlling the optical length of each ring resonator. This is achieved by thermo-optical effect, imposed by electrically feeding
micro-heaters on top the ring resonators, allowing fine adjustments in phase matching between both ring resonators. To our knowledge, this is the first report in the literature concerning the asymmetrical use of micro-heaters so close to each other in order to try to control the optical phase difference between ring resonators.

4.1 Theoretical approach

Our modeling was based on a hybrid approach composed of 3D-FDTD simulations in the coupling regions, which were implemented on a commercial simulation tool from R-Soft Design Group, Inc., and the dispersive curves from 3D simulations were inserted in scattering matrix method to analyze the whole structure, similar to the approach adopted in our previous works [26, 27, 41]. The general scattering matrix which describes the optical behavior of the device is given by (1), which in turn obeys the schematic representation depicted in Figure 32.

\[
\begin{bmatrix}
E_{1}^- \\
E_{2}^- \\
E_{3}^- \\
E_{4}^- \\
E_{5}^- \\
E_{6}^- \\
E_{7}^- \\
E_{8}^- \\
E_{9}^- \\
E_{10}^-
\end{bmatrix} = \begin{bmatrix}
0 & 0 & \tau_1 & 0 & -j\kappa_1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \tau_2 & 0 & 0 & 0 & -j\kappa_2 & 0 & 0 \\
\tau_1 & 0 & 0 & 0 & 0 & 0 & -j\kappa_1 & 0 & 0 & 0 \\
0 & \tau_2 & 0 & 0 & 0 & 0 & 0 & \tau_2 & 0 & 0 \\
\tau_3 & 0 & 0 & 0 & 0 & 0 & 0 & -j\kappa_3 & 0 & 0 \\
-j\kappa_1 & 0 & 0 & 0 & 0 & 0 & \tau_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \tau_2 & 0 & -j\kappa_2 & 0 & 0 \\
0 & 0 & \tau_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -j\kappa_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \tau_3 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
E_{1}^+ \\
E_{2}^+ \\
E_{3}^+ \\
E_{4}^+ \\
E_{5}^+ \\
E_{6}^+ \\
E_{7}^+ \\
E_{8}^+ \\
E_{9}^+ \\
E_{10}^+
\end{bmatrix}
\]

(8)

In Fig. 1, the symbol \(E_i^+\) corresponds to the \(i\)-th output electric field for the respective output access, as depicted in Fig. 1, \(E_i^-\) corresponds to the \(i\)-th input electric field counterpart. \(\tau_1\) and \(\kappa_1\) are, respectively, the electric field transmission and coupling coefficient between the ring resonator 1 and the bus waveguide; \(\tau_2\) and \(\kappa_2\) are, respectively, the electric field transmission and coupling coefficient between the ring resonator 1 and ring resonator 2; \(\tau_3\) and \(\kappa_3\) are, respectively, the electric field transmission and the coupling coefficient between the ring resonator 2 and the add-drop bus waveguide.
Applying the initial condition that only port 1 is optically fed; the optical fields in each input access are given by:

\[
\begin{bmatrix}
E_1^- \\
E_2^- \\
E_3^- \\
E_4^- \\
E_{\phi}^+ \\
E_{\phi}^- \\
E_e^+ \\
E_e^- \\
E_f^+ \\
E_f^- \\
E_g^+ \\
E_g^- \\
E_h^+ \\
E_h^- \\
\end{bmatrix} =
\begin{bmatrix}
E_{in} \\
0 \\
0 \\
0 \\
E_{\phi} e^{-j\phi/2} \\
0 \\
E_{\phi} e^{-j\phi/2} \\
0 \\
E_{e} e^{-j\phi/2} \\
0 \\
E_{e} e^{-j\phi/2} \\
0 \\
E_{f} e^{-j\phi/2} \\
0 \\
E_{f} e^{-j\phi/2} \\
\end{bmatrix}.
\]

(9)

Thus, replacing (9) in (8), one can have the general system of equations which describes the electric fields at output ports of the device as a function of the electric field at input port:

\[
\begin{bmatrix}
E_1^- \\
E_2^- \\
E_3^- \\
E_4^- \\
E_{\phi}^+ \\
E_{\phi}^- \\
E_e^+ \\
E_e^- \\
E_f^+ \\
E_f^- \\
E_g^+ \\
E_g^- \\
E_h^+ \\
E_h^- \\
\end{bmatrix} =
\begin{bmatrix}
\tau_1 & 0 & -j\kappa_1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -j\kappa_1 & \tau_3 \\
-j\kappa_1 & 0 & \tau_1 & 0 & 0 & 0 \\
0 & \tau_2 & 0 & -j\kappa_2 & 0 & 0 \\
0 & 0 & 0 & \tau_3 & -j\kappa_3 & 0 \\
0 & -j\kappa_2 & 0 & \tau_2 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
E_{in} \\
E_{\phi} e^{-j\phi/2} \\
E_{e} e^{-j\phi/2} \\
E_{e} e^{-j\phi/2} \\
E_{f} e^{-j\phi/2} \\
E_{f} e^{-j\phi/2} \\
0 \\
\end{bmatrix}.
\]

(10)

\[\phi_1 = \frac{2\pi}{\lambda_0} n_{eff} (2\pi R_1), \quad \phi_2 = \frac{2\pi}{\lambda_0} n_{eff} (2\pi R_2).\]

(11)

\[\phi_1 \text{ and } \phi_2 \text{ are the accumulated optical phases due to the propagation inside ring resonators 1 and 2, respectively, given by:}\]

where \(\lambda_0\) is the free space wavelength, \(n_{eff}\) is the temperature sensitive complex effective refractive index for ring resonators and waveguides, and \(R_i (i = 1, 2)\) is the radius of the ring resonator.

The main output electric fields in our analysis are \(E_3^-\) and \(E_4^-\); they represent, respectively, the electric field at the through and drop output ports and the solution of the equations system described in (10) provides us the theoretical general optical behavior of this
device.

It is worth pointing out that other authors have developed a similar model to assess coupled ring resonator structure using similar approaches. In addition, some of those have used it to tailor a desired spectrum using the Vernier effect and providing a complete analysis regarding coupling/transmission ratio and Free Spectral Range – FSR [40, 42-46, 48, 49].

4.2 Fabrication and characterization

The fabrication process of our device is classified in two distinct layers: the optical layer and the metal layer. The optical layer was fabricated by means of direct e-beam lithography over silicon on insulator substrate with negative tone e-beam resist, followed by dry etching. A 150 nm low-stress silicon nitride layer \( n_{Si_{3}N_{4}} = \sim 1.9789 \) was deposited by low-pressure chemical vapor deposition (LPCVD) to \( \text{rise} \) the optical mode and controlling the coupling coefficient between the ring resonators, followed by one micrometer thick layer of silicon dioxide deposited by means of plasma-enhanced chemical vapor deposition (PECVD).

The metal level was built in two steps using aligned photolithography and positive photoresist; the first step consists of photolithography of the micro-heaters followed by 100-nm Nichrome deposition and then lift-off; the second step, consisted of contact pad and feedline photolithography, followed by \( (5 \text{ nm} / 300 \text{ nm}) \) Ti/Au deposition and, finally, lift-off. Table 7 shows the design parameters used on the fabrication of the device.

<table>
<thead>
<tr>
<th>Waveguide cross-section Width</th>
<th>Height</th>
</tr>
</thead>
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<td>450 nm</td>
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<table>
<thead>
<tr>
<th>Coupling regions Gap 1</th>
<th>Gap 2</th>
<th>Gap 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 nm</td>
<td>500 nm</td>
<td>200 nm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radii</th>
<th>( R_1 ) 10 µm</th>
<th>( R_2 ) 15 µm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Heaters Material</th>
<th>Thickness</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.5 µm</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Pad contacts Material</th>
<th>Thickness</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium/Gold</td>
<td>5 nm / 300 nm</td>
<td>30 µm</td>
</tr>
</tbody>
</table>

The Gap \( i (i = 1, 2, 3) \) directly affects the field transmission and coupling coefficients,
which in turn are related to each other by means of the principle of conservation of energy by
\[ \kappa_i^2 + \tau_i^2 = 1, \]
when losses are disregarded in the coupling regions.

The fabricated device is shown in Figure 33, where Figure 33 (a) shows the actual device’s image obtained by means of an optical microscope and Figure 33 (b) shows the micrograph taken by means of a Scanning Electron Microscope - SEM.

Our heaters were designed with a polygonal shape instead of a perfect circular shape in order to maximize the gap between heaters, allowing photolithography process, and still covering a considerable area on top of the ring resonators.

![Figure 33: (a) Device’s photograph taken from optical microscope; (b) Device’s micrograph taken from SEM.](image)

We analyzed the electrical properties of our heaters by means of a semiconductor analyzer and scanned the electric current versus voltage in order to measure the resistance of our heaters, which are 650 Ω for the major heater and 550 Ω for the minor one. In addition, the measured gap between heaters is approximately 2.5 μm as per the original design.

Optical measurements used nano-positioners to align polarization maintaining lensed optical fibers into the sample. An agilent tunable laser model 81980A with working band ranging from 1465 nm to 1575 nm was used as light source and an agilent fiber-coupled power meter model 81636B was used to measure transmitted signals. All optical transmission results in this manuscript were normalized to the maximum optical power obtained at the through port of the device. A temperature controller set to 20°C was used during all
measurements in order to reduce thermal drifts, and a Keithley precision current source model 2400 was used to control the electric current passing through the micro-heaters.

4.3 **Working principle and results**

So far, we have discussed just the theoretical approach and fabrication process used in our device; in this section, we discuss its functionalities and its working principle.

Figure 34 (a) and (c) show, respectively, the theoretical and experimental device’s optical response when no bias current is applied to the micro-heaters and when 8 mA are applied only to the micro-heater over the major ring resonator, which is defined as the ring with larger radius and pointed out in Figure 33 (a). One can observe in Figure 34 (a) the Vernier resonance at 1547.6 nm without any bias on heaters for the Quasi-TM polarization, which is fortuitous, but explained by the fact that the resonances for that polarization are broader; thus, it is easier to obtain the phase matching between them, and then demonstrate the Vernier effect. However, in general, it is difficult to achieve the precision required during the fabrication process to attain the Vernier resonance for Quasi-TE modes, since small deviation during the fabrication, either during e-beam lithography or the etching process, are enough to introduce phase mismatching between the optical modes; this is one of the reasons why the Vernier Effect is considered, for some researchers, not easy to be experimentally demonstrated [47].
Figure 34: (a) Theoretical and measured drop/through port optical response when no current is applied to the micro-heaters; (b) individual theoretical optical response of each ring resonator for the behavior observed in (a). (c) Theoretical and measured drop/through port optical response for 8 mA applied to the micro-heater on the major ring resonator. (d) Individual theoretical optical response of each ring resonator under the condition observed in (c). In (b) and (d), the dashed and solid lines correspond to the optical response for the major and minor ring resonators, respectively.

Figure 34 (b) and (d) show, individually and respectively, the theoretical behavior of each ring resonance when no bias current is applied and when 8 mA is applied to the major ring heater. A similar mathematical approach for each ring resonator was demonstrated in our previous works [26, 41].

Analyzing our device from the Vernier point of view, one can observe from Figure 34 (b) that the major ring resonator has five resonances in the spectral window that ranges from 1530 to 1565 nm, which are numbered from 1 to 5 on top of the Figure 34 (b). On the other hand, one can observe that the minor ring resonator has only three resonances for the same spectral window, which are numbered from 1’ to 3’ on bottom of Figure 34 (b). The condition showed in Figure 34 (a) and (b) shows the original condition in which our device was fabricated, without any electric current applied to micro-heaters, where one can observe that the device was fabricated to present a common resonance at the wavelength of 1547.6 nm,
which means that resonances number 3 and 2’ are in phase to each other, establishing a resulting resonance in this wavelength, as demonstrated in Figure 34 (a) by means of theoretical and experimental results, whereas the other individual resonances, which are not in phase to each other, are suppressed.

Figure 34 (c) and (d) show the device’s optical response of each ring resonator when electric current is applied to the major heater. In addition, this heating also increases the temperature of the minor ring as well, and one can observe that both the major and minor rings’ resonances are affected; however, the minor ring resonator is less affected. A new matching condition is found when the major heater is heated up with electric current of 8 mA, when resonances 3 and 2’ leave the phase matching condition and resonances 1 and 1’, as well as 4 and 3’, establish phase matching condition at a wavelength of 1539.6 nm and 1557.5 nm, respectively, as shown in Figure 34 (d).

In our model, all dispersive functions, such as field transmission coefficients, effective index of refraction for ring waveguides, and losses were fitted to the experimental results. Figure 34 shows the calculated transmission with the extracted parameters as well as the experimental results. Figure 35 summarizes the extracted parameters from the fitting process. Figure 35 (a) and (b) show electric field transmission as a function of wavelength used in our theoretical model for gaps of, respectively, 200 nm and 500 nm. Figure 35 (c) and (d) show, respectively, the effective refractive index for ring waveguides and the general power loss coefficient as a function of wavelength. It is worthy pointing out that the results showed in Figure 35 are possible mathematical solutions.
Our semi-analytical model allows us to insert the refractive index variation as a function of temperature. Figure 36 (a) shows the simulated theoretical effective refractive index for a straight waveguide as a function of wavelength and temperature. Figure 36 (b) shows the temperature sensitivity for three distinct wavelengths of interest. The results shown in Figure 36 were obtained with a 3D-mode solver from Rsoft Design Group, Inc., Sellmeier dispersions for both silicon and silicon dioxide were considered, as well as the dispersion for silicon nitride [50].
Comparing Figure 36 and Figure 35 (c), one can notice that there is a small discrepancy between the values for the effective index of refraction; this is because Figure 36 shows a straight waveguide simulation, and Figure 35 (c) is the extracted behavior of the effective refractive index for a bent waveguide. We considered a straight waveguide to assess the temperature sensitivity of our waveguide owing to the intrinsic limitations of our design tool to perform simulations of bent waveguides with small bending radius.

Based on numerical results shown in Figure 36, one can observe that the temperature sensitivity of straight waveguide is only slightly wavelength dependent; therefore, in order to simplify our analysis, we assumed that it was constant and took the value for 1550 nm, since our spectral analysis window provide a numerical maximum error of approximately 2%. These sensitivity values were used on the theoretical curve presented in Figure 35 (c), allowing us to predict the average influence of the heating profile in each ring resonator and the rate with which each one is affected by the heating profile.

Our semi-analytical model allows us to assess the behavior of the device based on the effective refractive index variation; thereby, in order to assess the influence of the thermal profile in each ring resonator, we developed a systematic algorithm to fit our semi-analytical model with experimental results.

We performed optical transmission measurements in two situations when applying electric current to the micro-heaters. First, driving only the major heater; secondly, driving simultaneously both heaters. The resonant peak shift was used by our algorithm to extract the average effective refractive index variation for each ring in both cases. The results are shown in Figure 37 (a). Figure 37 (b) shows the extracted effective refractive index variation as function of temperature, allowing the prediction of the average temperature in each ring resonator.
Figure 37: (a) Extracted behavior of the effective refractive index as a function of electric current, based on fitting of experimental measurements; (b) effective index of refraction variation as a function of temperature variation for 1550 nm.

Figure 37 (a) shows us that the average change on the effective refractive index as a function of the electric current obeys a ratio of 4.2:1 when only the major micro-heater current is set turned on, the major ring is 4.2 times more sensitive to heating than the minor ring. This is an indirect measure of the thermal crosstalk of the device.

On the other hand, when both micro-heaters are turned on by the same electric current amplitude, we observed that the shape of resonance is kept unaltered and the peak just shifts, providing the second condition observed in Figure 37 (a). This evidences that the average temperature is almost the same for both ring resonators, when both heaters are set turned on. In addition, under that working condition, one can observe that both heaters set turned on provide more heating to the major ring resonator, as compared to the previous case for the same electric current amplitude, which is due to the mutual thermal crosstalk behavior.

The effect of heating provides optical phase variations along ring resonators; therefore, based on Figure 37 (a) and (b), one can state that the average index of refraction variation along the ring resonators is approximately equivalent to an average temperature variation of 18.5 K ($\Delta n_{eff} = 2.5 \times 10^{-3}$) along the minor ring resonator, and 77.5 K ($\Delta n_{eff} = 10.5 \times 10^{-3}$) on major one, when 8 mA is applied to the major heater. This gives us a good
understanding of the thermal behavior of that structure, based only on our optical theoretical model.

In order to gain general understanding regarding the thermal behavior of our structure, we simulated its thermal behavior by means of simple 2D-Finite Elements method. Normalized thermal profiles are shown in Figure 38.

Figure 38 (a) shows temperature distribution in the case of a heater above a straight optical waveguide. Figure 38 (b) and (c) show the 2-D temperature distribution when electric current is applied to the major heater, and to both heaters, respectively. Figure 38 (d) and (e) show the thermal profile in the cross section of the coupling region between both ring resonators when electric current is applied to the major ring heater, and to both heaters, respectively.

The highlighted arrows in Figure 38 (b) and (c) indicate the position where the simulations shown in Figure 38 (a), (d), and (e) were performed. It is worth pointing out that Figure 38 (a), (d), and (e) are not cut views from Figure 38 (b) and (c); these are distinct 2D simulation considering the heater position atop, that is why there is a visual discrepancy between the thermal overlap among the cross section and the top view figures, since with simple 2D simulations one cannot take into account the whole behavior of the structure.
Figure 38: Normalized thermal profile behavior provided by NiCr heaters under following conditions: (a) waveguide cross section with micro-heater on top, (b) top view when just the major heater is submitted to electric current, (c) top view when both heaters are submitted to the same electric current amplitude. (d) waveguide cross section of the coupling region between ring resonators when the major ring is submitted to electric current and (e) when both are submitted to the same electric current amplitude.

The asymmetric heating provides an important physical design tool to demonstrate reconfigurability in such devices; as demonstrated in Figure 34 (a) and (c), it allows the use of this device as a multichannel reconfigurable switch or filter, independently processing wavelengths from only one structure. Figure 39 (a) shows the experimental measurements of the optical response at output drop port as a function of the electric current applied to the major heater. Figure 39 (b) shows the extracted behavior of each ring resonator’s resonance as a function of electric current based on the measured optical response and fitting with our semi-analytical model.
Amongst the characteristics observed in Figure 39 (a), it is evident that our device is able to optimize the phase matching between resonances, as one can observe from the increasing in optical intensity for currents ranging from 1 to 3 mA, establishing a fine tunable adjust of the Vernier effect of the coupled optical resonance.

Moreover, from 4 to 8 mA, one can observe that the coupled signal quickly reduces in amplitude. This is due to the transition which establishes the phase mismatching and decoupling at 1547.6 nm, followed by subsequent matching condition and coupling between resonances at the wavelengths 1539.6 nm and 1557.5 nm.

Finally, for electric currents ranging from 8 to 10 mA, the device goes through another coupling between resonances at 1548.6 nm and starts to regenerate its original shape.

In addition to the experimental results shown in Figure 39, we also investigated the device’s optical response when both heaters are submitted to an electric current of same amplitude. Figure 40 (a) shows the drop port optical response when the same amplitude of electric current is applied to both micro-heaters and Figure 40 (b) shows the extracted behavior of each ring’s resonance shift as a function of electric current based on the measured optical response and fitting with our semi-analytical model.
Figure 40: (a) Experimental device’s optical response (drop port) as a function of wavelength and electric current applied to both micro-heaters, (b) extracted behavior for each resonance shift as a function of electric current.

One can observe that the spectral behavior in Figure 40 (a) is quite different from what is shown in Figure 39 (a); in this case the optical response only shifts in wavelength. This is due to the fact that the heaters, when submitted to the same electric current, provide the same power density and hence the temperature variation on both ring resonators is almost the same. This in turn does not induce mismatch between the accumulated phase in both ring resonators, keeping the shape of the optical response, but shifting the transmitted peak wavelength.

Based on results presented in Figure 39 and Figure 40, one can observe that, depending on how electric current is fed into the heaters, the device may enable different spectral response shapes or just shift its wavelength; this allows implementing several interesting functionalities, such as tunable filtering/switching, multi-channel switching, non-blocking operation and reconfigurability, which can be useful in the optical signal processing in general, since we have precise control of the resonance’s position and amplitude. This behavior is expected to be similar for the quasi-TE case as well, even though it should be significantly more sensitive to the temperature or electric current fed into the micro-heaters. It is worthy to mention that the insight in the temperature distribution gained from characterizing the quasi-TM mode is very valuable for other polarization conditions.
In this device, the maximum extinction ratios for quasi-TM\textsubscript{00} mode was approximately 3 dB, on the resonance peaks; this is mainly due to the weak coupling condition, between both ring resonators, chosen in our design, which yields a high-Q for the resonances. It is worth pointing out that the electric field transmission coefficient is a relevant parameter to control some figures-of-merit of our device, such as: extinction ratio, the existence or absence of the double peak commonly observed by other authors [43, 48, 49]; and quality factor Q.

4.4 Commentaries

In summary, the proposed and experimentally demonstrated device allows for control of the optical length of individual ring resonators in a partially independent approach. We observed a relation of 4.2:1 for the heating, estimated from the agreement between our theoretical extracted behavior model and the experimental results. In addition, we have demonstrated that the proposed device allows a certain degree of reconfigurability, by independently enabling intensity and shifting control of its optical response. As such, it offers a potential solution to be used in reconfigurable solutions, such as equalization filters, switches and filters in general, allowing all these functionalities to be available in a single and compact device.

Moreover, the asymmetric and compact heating properties, demonstrated in this manuscript, may open the doors for a variety of novel devices, where reconfigurability and active compensation of fabrication deviations are relevant parameters.
COMPACT AND LOW POWER CONSUMPTION TUNABLE PHOTONIC CRYSTAL NANOBEAM CAVITY WITH BAND-STOP OPTICAL RESPONSE

Tunable resonators have been considered a class of devices of great relevance, since they have played an important role as a versatile building block, enabling the demonstration of feasibility of several specific devices and functionalities in Silicon Photonics platform, such as: tunable lasers [9], tunable filters [29], modulators [5], switches [54], reconfigurable devices [54, 41], and sensors [55, 56].

Amongst the resonators reported in the Silicon Photonics technical literature, the ring resonators and the photonic crystal nanobeam cavities are the most used structures, and have been widely used to demonstrate the feasibility of the devices and functionalities previously mentioned. These structures have distinct and complementary characteristics regarding their functionalities, depending on the application. Figure 41 schematically summarizes these functionalities, showing typical structures for both resonators and their respective optical responses, where the main differences regarding geometry, output optical response, and the Free Spectral Range – FSR can be observed [55-58].

![Figure 41: Schematic representation and optical response for a typical ring resonator and a conventional nanobeam cavity.](image-url)
Based on Figure 41, one can observe that nanobeam cavities can be designed to be ultra-compact and present high FSR and Q-factor on a wide spectral window [58], whereas ring resonators present limited FSR, which may be increased, up to a certain extent, by reducing its size [5, 27, 41]. However, reducing ring resonator size results in decreased Q-factor, which can make the device useless for several applications. Nanobeam cavities present a band-pass nature [56-58], whereas ring resonators present a band-stop behavior [5, 11, 26], making the ring resonator very attractive for several applications, such as Wavelength-Division Multiplexing – WDM and others [1-3].

In this chapter, we present a novel tunable and compact device by means of a special designed structure that is able to merge the characteristics of the ring resonators and nanobeam cavities in a single device, besides providing tunability of the resonant wavelength. The device is schematically depicted in Figure 42, which consists of a special designed nanobeam cavity coupled to a bus waveguide and integrated with micro-heater atop. This structure can provide large FSR, high Q-factor, band-stop behavior, low power consumption, and CMOS compatibility. To the authors’ knowledge, this is the first time that such a structure has been reported.

This chapter is organized as follows: in the second section, the design of the structure is assessed by means of Finite-Difference Time-Domain (FDTD) and Finite Element (FE)
simulations; in the third section, the fabricated device and fabrication process are discussed; in the fourth section, experimental results are presented and discussed; finally, we show our main conclusions.

5.1 Theoretical approach

Our modeling was based on 3D-FDTD simulations to design the optical layer, and on 2D-FE to design the micro-heater. Both layers were, respectively, simulated using professional design tools from R-Soft Design Group and from Comsol.

First, we designed the mirror section of the nanobeam cavity by launching an optical pulse into the periodic structure and observing the behavior of the transmitted and reflected light, finding out high reflectivity within a desired spectral window, similarly to our previous works [56].

On the mirror section, the width of the waveguide, the diameter of the holes, as well as the distance between them were suitably chosen in order to introduce high reflectivity within the spectral range from 1400 nm to 1700 nm. The separation distance and diameter of the holes are shown on Table 8 (mirror section). Figure 43(a) and (b) show, respectively, the calculated normalized transmission and reflection, as a function of the wavelength and number of holes.

![Figure 43. Mirror section (a) transmission and (b) reflection as a function of number of holes and wavelength.](image-url)
Based on Figure 43, one can observe that the periodic structure acts as a reflector within a wide bandwidth of approximately 300 nm, where one can notice that for particular spectral regions, which in turn depend on the number of holes, the reflectivity value varies between 60% and near 100%. One can also see, from the flatness of the transmission curves and from spectral oscillations, that the number of holes also plays a role on the device's optimization. This spectral behavior is assumed to be mostly associated with scattering losses due to the periodic nature of the structure, what can be inferred from the evidence that transmitted and reflected optical powers do not sum up to 100%.

The mirror section with nine holes was chosen in our design in order to guarantee that light would be highly reflected within the wavelength range of interest. In addition to that, we designed a tapered cavity length in order to smooth the reflected optical response, reducing the scattering and the modal volume of the resonant mode, as well as to provide a single resonance within a large spectral window of high reflectivity, in order to increase the Q-factor in this region.

The parameters used to design our cavity are shown in Table 8, where the mirror and taper sections were parameterized in terms of a length constant, $a$. It is worth pointing out that our cavity structure is symmetrical with respect to its center; therefore, both sections composed by one mirror and half of taper are symmetrically identical; thus, the taper section parameters are shown for half length of the cavity. The column “Distance between hole $T_n$ and previous” depicts the distance between the current hole in the taper section ($T_n$) and the previous one. $T_1$ is the first hole in the taper section, located near the mirror section, whereas $T_6$ is the hole in the center of the cavity.
Table 8: Design parameters

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Cavity width (nm)</th>
<th>Bus waveguide width (nm)</th>
<th>Coupling gap (nm)</th>
<th>Height (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>500</td>
<td>300</td>
<td>220</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mirror Section</th>
<th>Length constant ($a$)</th>
<th>Hole diameter ($a/2$)</th>
<th>Distance between hole $T_n$ and previous $T_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>453.2 nm</td>
<td>$a/2$</td>
<td>$(0.9)a$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Taper Section</th>
<th>Hole Diameter ($nm$)</th>
<th>Distance between hole $T_n$ and previous $T_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>$(a/2)(0.98)$</td>
<td>$(a)(0.9)(0.98)$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$(a/2)(0.92)$</td>
<td>$(a)(0.9)(0.92)$</td>
</tr>
<tr>
<td>$T_3$</td>
<td>$(a/2)(0.88)$</td>
<td>$(a)(0.9)(0.88)$</td>
</tr>
<tr>
<td>$T_4$</td>
<td>$(a/2)(0.84)$</td>
<td>$(a)(0.9)(0.84)$</td>
</tr>
<tr>
<td>$T_5$</td>
<td>$(a/2)(0.80)$</td>
<td>$(a)(0.9)(0.80)$</td>
</tr>
<tr>
<td>$T_6$</td>
<td>$(a/2)(0.76)$</td>
<td>$(a)(0.9)(0.76)$</td>
</tr>
</tbody>
</table>

Figure 44 shows 3D-FDTD simulations based on the data shown in Table 8. Figure 44 (a) shows the device's optical response in terms of transmission and reflection; the entire structure, nanobeam cavity coupled to the bus waveguide, is labeled as device. In addition to that, Figure 44 (a) also shows the transmission and reflection for half nanobeam cavity, i.e., one mirror section added to half tapered length, which is labeled taper + mirror. One can observe that a suitably designed taper section smoothies up the reflection and can match the resonant wavelength with the reflection peak. It results in a nanobeam cavity with high Q-factor and high FSR, as shown in Figure 44 (b).

In addition to the optical response of the device, we also performed 3D-FDTD simulations to assess how the optical response and the resonant mode, under the original
resonant wavelength, are affected by temperature variation. We considered the well-known thermo-optic coefficient for silicon and for silicon dioxide [13, 35, 41] and performed simulations to assess the optical response of the structure under different temperature variations ($\Delta T$), as well as the resonant mode profile, relative to the initial resonant wavelength, under four thermal conditions, $\Delta T = 30, 60, 90$ and 120 K.

The optical response and the resonant mode profiles as a function of temperature variation are shown in Figure 45. Figure 45 (a) and (b) show, respectively, the normalized transmission at the output port of the device and its back-reflection for different temperature variations; Figure 45 (c) shows the theoretical resonant optical mode for the initial resonance wavelength, i.e., $\Delta T = 0$, and the transition from the resonant to the off-resonant condition, as temperature increases.

![Figure 45](image)

**Figure 45:** Normalized (a) transmission and (b) back reflection optical response for different temperature variations and (c) behavior of the resonant mode as a function of the temperature variation.

Figure 45 (a), Figure 45 (b) were normalized regarding input optical power and Figure 45 (c) regarding the peak of electric field inside the structure. One can observe the resonant condition in Figure 45 (c) (top plot), where almost no energy is transmitted, being mostly
back-reflected. As temperature increases, the resonant mode runs off the resonant condition; only few degrees of temperature variation are enough to turn off the resonance, owing to the high Q-factor.

In order to find out a suitable top cladding thickness to avoid a non-negligible overlap between the optical mode and the micro-heater, but still keeping the heater close enough to ensure that the thermal profile will significantly overlap with the optical waveguides, we developed a simplified model by means of two different analyses.

First, we simulated, by means of a mode solver from RSoft Design Group, the optical mode profile for a single waveguide, considering a wavelength of 1653.2 nm, which is 30 nm longer than the one used in Figure 45 (c). The results are shown in Figure 46 (a) and Figure 46 (b). Figure 46 (b) shows that the optical mode requires a top cladding of at least 1 µm to symmetrically confine the optical mode, being negligible the electric field amplitude beyond 1 µm of silicon dioxide top cladding.

Considering the fabrication process using silicon-on-insulator platform, the required thickness to clad the silicon waveguide (220 nm) has also to be taken into account. Therefore, in order to guarantee that the optical mode will be uniformly confined and to prevent from small intrinsic deviations along the fabrication process, we chose a cladding thickness of 1.5 µm to ensure that the optical mode is not affected by the proximity of the micro-heater, as seen in Figure 46 (a).

On the other hand, in order to design the heater and its thermal profile, our design was based on 2D-FE method. The heater was designed with Nichrome and its dimensions are 2.5-µm wide, and 200-nm thick. Figure 46 (c) shows the simulated thermal behavior provided by the designed heater overlapping silicon waveguides. Figure 46 (d) shows the linear sensitivity of the resonant shift as a function of the temperature variation, which was obtained from simulations showed in Figure 45 (a) and Figure 45 (b). Based on Figure 46 (d), one can
observe that the theoretical shift of the resonant wavelength obeys a linear ratio of 0.07 nm/K; this result is similar to that presented in our previous work [54].

Figure 46: Theoretical optical mode profile: (a) cross-section profile and (b) 3D profile. (c) Theoretical thermal profile for the device’s cross section overlapping silicon waveguides and (d) theoretical resonant shift as a function of the temperature variation.

Therefore, based on this simplified and independent model, one can estimate a top cladding thickness to ensure that the thermal profile will significantly overlap the optical waveguide, whereas but the optical mode will only negligibly overlap the heater.

5.2 Fabrication and characterization

The fabrication of our device is divided in two distinct layers: the optical layer and the metal layer. The optical layer was fabricated by means of direct e-beam lithography over silicon-on-insulator substrate with negative tone e-beam resist, followed by dry etching. A thick layer of 1.5 µm of silicon dioxide was deposited by means of plasma-enhanced chemical vapor deposition (PECVD).

The metal layer was built in two steps using aligned photolithography and positive photoresist with inversion process; the first step consisted of photolithography of the micro-
heater, followed by 200-nm Nichrome deposition and then lift-off; the second step consisted of contact pads and feedline photolithography, followed by (5 nm / 270 nm) Ti/Au deposition and, finally, lift-off.

The fabricated device is shown in Figure 47, where Figure 47 (a) and Figure 47 (b) show scanning electron microscopy (SEM) images of the fabricated device after exposed and etched for two distinct magnifications, Figure 47 (c) shows the finished device with all layers.

![Figure 47: (a) and (b) device’s SEM micrographs, showing the device after dry etching process step, (c) final device passivated with silicon dioxide layer and integrated with micro-heater and pad contacts atop.](image)

We analyzed the electrical properties of the micro-heater by means of a semiconductor analyzer and scanned the electric current versus voltage in order to measure the resistance of our heater, which was found to be around 400 Ω.

Optical measurements made use of nano-positioners to align polarization maintaining lensed optical fibers onto the sample. An Agilent tunable laser model 81980A was used as light source, an Agilent fiber-coupled power meter model 81636B was used to measure transmitted signals. A Keithley precision current source model 2400 was used to control the electric current passing through the micro-heater.

### 5.3 Experimental results

The device was carefully measured in order to assess its figures-of-merit: extinction ratio, Q-factor, FSR, resonant shift and electrooptical efficiency. Figure 48 (a) shows the device’s optical response as a function of the wavelength for three different values of...
electrical power applied to the heater, where one can observe high extinction ratio, around 10 dB.

The resonant wavelength without any bias current applied to the heater was found at 1570.38 nm and this is the only resonance wavelength observed within a spectral window that comprises our measurement capability, which is of 100 nm, as per our original design. In addition to that, we observed a loaded Q-factor of approximately 50,000, which was estimated by means of fitting a Gaussian curve on the resonance and extracting its full width at half maximum (FWHM), which is only 31 pm, and then calculating the Q-factor by means of $\lambda/\Delta\lambda$ [58, 59].

Figure 48 (b) shows the modulation depth as a function of the electrical power applied to the heater, where one can observe that a high extinction ratio can be achieved within a small range of electrical power of 100 $\mu$W.

It is worth pointing out that none of the traditional wet processes to reduce roughness sidewall and increase the Q-factor [52, 62] was used in the device's fabrication, what evidences the good quality of our present fabrication process, as well as demonstrates a potential for further quality improvements of the device's performance.

In order to assess the resonance’s behavior as a function of the electrical power, we
experimentally measured the resonant shift as a function of the electric current applied to the micro-heater, and thus the resonance shift as a function of the electrical power.

First, we used an electric current source ranging from 0 to 9 mA, corresponding to approximately an electrical power ranging from 0 to 30 mW, since the resistance of our heater is around 400 $\Omega$. Figure 49 (a) shows the resonance shift as a function of the electric current and Figure 49 (b) shows the resonance shift as a function of the electrical power.

![Figure 49: Resonance shift as a function of the (a) electric current applied to micro-heater and (b) electrical power.](image)

Based on Figure 49 (b), one can observe an almost linear dependence of the resonance shift with electrical power, where we observed a ratio of approximately 0.35 nm/mW.

All measurements were carefully performed to preserve the device and not damage the heater; however, we pushed the limits to determine the maximum allowed resonance shift that the heater would be able to provide. We observed that it was able to support a maximum current of approximately 10.5 mA, i.e., approximately 45 mW; providing a maximum resonance shift of approximately 15 nm.

Taking into account the theoretical analysis showed in Figure 46 (d), where it was noticed that the resonance shift as a function of the temperature variation obeys a linear ratio of approximately 0.07 nm/K, we can theoretically infer that the maximum temperature variation that our heater is capable to provide to the silicon waveguides, before melting down,
is around 215 K, since we observed that the maximum allowed shift is around 15 nm.

In order to assess how fast our device can switch from/to the resonance wavelength, we applied a square-time-domain electrical power waveform on the micro-heater, by means of a function generator, and detected the modulated optical signal to obtain the rise/fall time. Figure 50 shows the results.

![Figure 50: Modulated and detected signal, (a) interval from 0 to 500 \( \mu s \), and (b) from 0 to 100\( \mu s \).](image)

Figure 50 (b) shows that the rise and fall time are approximately 15 \( \mu s \), being primarily limited by the heat diffusion speed into the silicon dioxide cladding layer.

In addition to the time response, we also investigated the nonlinear characteristics in our device. It is well-known that nanobeam cavities with high Q-factor and low modal volume can concentrate high optical energy, resulting in non-negligible two-photon absorption, which in turn causes heating by means of the relaxation of the nonlinearly photo-generated carriers [62, 63]. This heating can red-shift the device’s resonant wavelength as the input power increases, resulting in optical bistability depending on the optical power. This property has been investigated for several researchers, promising to be attractive for several applications [63].

Hence, we assessed the optical response of our device for different input optical powers and observed an induced spectral broadening and a sharp drop as the optical power is increased. These results are shown in Figure 51 (a), where the broadening and the sharp drop indicates a strong evidence for optical bistability, which is explained by the resonance locking due to the simultaneously combined effect of the laser sweeping direction (from shorter to
longer wavelengths) and the thermo-optical resonance red-shift; the behavior shown in Figure 51 (a) is a well-known fingerprint of thermo-optical effect on microcavities [62].

On chip optical bistability has been demonstrated in our past work [64], and other researchers demonstrated how to make this nonlinearity appear with ultra-low optical power [63]; here, once the bistable resonance is excited, we demonstrated that we can tune this bistable behavior without increasing the optical power, and then tune its spectral position. Figure 51 (b) shows the tuning of bistable resonance for different values of electric current, keeping the same level of input optical power required to excite the optical bistable resonance.

![Figure 51: (a) Device’s optical response for different input optical power showing the transition between linear and nonlinear behavior; (b) tunable devices optical response under nonlinear regime for different values of electric current.](image)

Control and tuning of the bistable resonance is a unique characteristic that our device has demonstrated, promising to help overcoming challenges of using optical bistability in several applications. We emphasize that, to the authors’ knowledge, this is the first time that tunable optical bistable resonance is thermally (by means of an external micro-heater) tuned on chip, showing unique characteristics that may open the door for several devices and applications [62, 63].

5.4 Commentaries

In summary, we have theoretically and experimentally demonstrated a tunable photonic crystal nanobeam cavity with high extinction ratio, high Q-factor and single
resonance mode within a wide spectral range. We have also demonstrated the capability of shifting the resonant wavelength up to 15 nm with a band-stop optical response. Additionally, we have demonstrated that the rise/fall time can be as fast as 15 µs.

We also reported the nonlinear characteristics of our device and showed that bistable resonances can be thermally tuned, keeping the same input optical power. Thereby, the proposed device presents special characteristics that may open the doors for several applications and a new variety of devices to find use in telecommunications, spectroscopy and sensors in general.
6 UNIDIRECTIONAL REFLECTIONLESS BRAGG GRATING: ONE-WAY ROAD FOR LIGHT

With the emergence and progress of Silicon Photonics, unidirectional devices have become one of the toughest challenges to be overcome by researchers. For the past decade, a significant theoretical effort has been made in order to provide enough tools to build this class of devices and breaking the symmetry of wave propagation, trying to attain asymmetrical and nonreciprocal devices [65-83].

Researchers in quantum theory have identified a combination of Parity symmetry ($P$) and Time Reversal symmetry ($T$), originating the $PT$– symmetry, creating a novel physical concept of quantum field theories and opening discussions in various areas, ranging from nonlinear optics to quantum field theory [65-83].

Such a theory has been exploited in quantum optics and theoretically predicted that under special conditions, combining losses and gain in periodic structures, the symmetry of electromagnetic wave propagation in devices can be broken; thus providing unidirectional characteristics that are not intuitive from the point of view of the classic electromagnetic theory [65-83, 88-97]. This complex theory has been remarkably exploited and translated in terms of classical models by few exceptional works [84, 87], providing insights from the point of view of coupled mode theory and electromagnetic optics (i.e., photonics).

However, the experimental demonstration of this concept has been a longstanding challenge during the past decade, owing to the high complexity of the required structure to demonstrate such effect, which requires special designed materials in periodic structures; which are not easily integrated or found in nature [93-95].

In this chapter, we propose and analyze an equivalent $PT$ structure based on the elementary structure used by previous works [84, 87]; however, we do so with no use of gain materials; we have adopted an alternative approach to make this structure experimentally
feasible. We have also developed the required theory in terms of classical model and, unlike the previous works, we have experimentally demonstrated this effect by means of purely compatible CMOS materials. The elementary structure, an ideal integrated unidirectional Bragg grating, is schematically shown in Figure 52.

\[ \Delta \varepsilon = \cos[q(z-z_0)] - j\delta \sin[q(z-z_0)] \]

Figure 52: Schematic representation of an ideal integrated unidirectional Bragg grating.

The variation of the dielectric permittivity \( \varepsilon \) in our structure is given by:

\[ \Delta \varepsilon = \cos(qz) - j\delta \sin(qz), \]  \hspace{1cm} (12)

where \( q = 2k_{\text{eff}}, 4n\pi/q + \pi/q \leq z \leq 4n\pi/q + \pi/q \), and \( k_{\text{eff}} \) is the guided wave vector, given by:

\[ k_{\text{eff}} = \frac{2\pi}{\lambda_0} n_{\text{eff}}, \]  \hspace{1cm} (13)

where \( \lambda_0 \) is the free space wavelength, \( n_{\text{eff}} \) is the complex effective refractive index of the waveguide.

This chapter is divided as following: in the second section, coupled mode theory formalism is discussed, followed by a special design using Transfer Matrix Method – TMM and by the full analysis by means of FDTD; the third section shows the fabricated device followed by the experimental results; finally, we present our conclusions.

6.1 Theoretical approach and design

6.1.1 Coupled mode theory approach with FDTD validation

In our approach, we consider a waveguide 800 nm wide and 220 nm thick, in which the fundamental mode supports a wave vector of \( k_{\text{eff}} \approx 2.69k_0 \) at the wavelength of 1550 nm.

A perturbation of the dielectric permittivity of \( \Delta \varepsilon = \cos(qz) - j\delta \sin(qz) \) is added to the
waveguide, where \( q = 2k_{\text{eff}} \) and \( 4n\pi/q + \pi/q \leq z \leq 4n\pi/q + 2\pi/q \), defining a perturbation length of \( \pi/q \). The Bragg grating period is chosen to be \( 4\pi/q \), corresponding to the 1st Bragg order. In the periodic sections, the electric field can be written as

\[
E(x, y, z) = A(z)E(x, y)e^{jk_{\text{eff}}z} + B(z)E(x, y)e^{-jk_{\text{eff}}z},
\]

where \( A(z) \) and \( B(z) \) are the amplitudes of forward and backward fundamental modes, respectively. Therefore, with slowly varying approximation, the coupled-mode equations can be derived as:

\[
\begin{align*}
\frac{dA(z)}{dz} &= -\delta - \frac{\alpha}{2\pi} A(z) + j\frac{1 - \delta}{8} \kappa B(z) \\
\frac{dB(z)}{dz} &= -j\frac{1 + \delta}{8} \kappa A(z) + \frac{\delta}{2\pi} \alpha B(z)
\end{align*}
\]

where \( \alpha \) and \( \kappa \) denote attenuation and mode coupling between forward and backward fundamental modes. The transfer matrix for the optical perturbation from \( z = 0 \) to \( z = L \) can be written as:

\[
\begin{pmatrix}
A(L) \\
B(L)
\end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A(0) \\
B(0) \end{pmatrix},
\]

where

\[
\begin{align*}
M_{11} &= \cosh(\gamma L) - \frac{\delta}{2\pi} \frac{\alpha}{\gamma} \sinh(\gamma L), \\
M_{12} &= j\frac{1 - \delta}{8} \frac{\kappa}{\gamma} \sinh(\gamma L), \\
M_{21} &= -j\frac{1 + \delta}{8} \frac{\kappa}{\gamma} \sinh(\gamma L), \\
M_{22} &= \cosh(\gamma L) + \frac{\delta}{2\pi} \frac{\alpha}{\gamma} \sinh(\gamma L),
\end{align*}
\]

and

\[
\gamma = \sqrt{(\delta\alpha/2\pi)^2 + (1 - \delta^2)\kappa^2/64}.
\]

The corresponding reflection coefficients of the Bragg grating for forward and backward directions are, respectively,

\[
R_f = \left| \frac{M_{21}}{M_{22}} \right|^2, \quad R_b = \left| \frac{M_{12}}{M_{22}} \right|^2.
\]
Based on equations (15) through (20), one can observe that the transmittance and reflectance are directly related to $\alpha$, $\kappa$, $\delta$, and $L$. Assuming values for $\alpha$ and $\kappa$, one can assess the forward and backward reflectance as a function of $\delta$ and $L$, which are shown in Figure 53 for three distinct values of $\delta$.

![Figure 53](image)

**Figure 53:** (a) Forward and (b) backward reflectance as a function of wavelength and some values of $\delta$.

Based on Figure 53, one can notice that for $\delta = 0$, which means that the amplitude of the imaginary part of the dielectric permittivity is null, the reflectance is the same in both directions (classical Bragg grating case). However, if $\delta \neq 0$, the break of symmetry in light propagation takes place and the reflectance intensity depends on the direction that light is launched into the structure. Assessing the asymmetry contrast ($C$) as a function of $\delta$, which is given by:

$$C = \left| \frac{R_f - R_b}{R_f + R_b} \right| = \frac{2\delta}{1 + \delta^2},$$

one can attain the condition where the asymmetry of reflection is maximum. Figure 54 (a), shows the contrast ratio as a function of $\delta$, where one can observe that the maximum contrast ratio takes place when $\delta = 1$, which means that the reflection asymmetry is maximized when the amplitudes of the real and imaginary part of the dielectric permittivity are equal.
This condition of maximum reflection asymmetry is equivalent to the exceptional point observed in Quantum theory and it allows re-writing the coupled mode equations as:

\[
\begin{align*}
\frac{dA(z)}{dz} &= -\frac{\alpha}{2\pi} A(z), \\
\frac{dB(z)}{dz} &= -j\frac{\kappa}{4} A(z) + \frac{\alpha}{2\pi} B(z). 
\end{align*}
\] (23)

Under that condition, \(\delta = 1\), these equations show a remarkable and clear understanding of the effect involved by means of the coupled mode theory. Under the presence of losses, periodically and suitably designed, both forward and backward transmitted amplitudes are attenuated; however, one of them allows the coupling between modes, whereas the other only attenuates, breaking the propagation symmetry of the structure.

Therefore, when \(\delta = 1\), the corresponding transmittance and reflectance can be written as:

\[
T = \exp\left( -\frac{\alpha L}{\pi} \right), \quad R_f = \frac{\pi^2 \kappa^2}{4\alpha^2} \sinh^2\left( \frac{\alpha L}{2\pi} \right) \exp\left( -\frac{\alpha L}{\pi} \right), \quad R_b = 0. 
\]

Assuming values for \(\alpha\) and \(\kappa\), one can assess the transmittance and reflectance as a function of the length of the periodic structure.

Therefore, in order to validate the analytical model by means of a powerful design tool, we assumed a waveguide 800-nm wide and 220-nm thick, and simulated the transmittance and reflectance as a function of the length of the periodic structure by means of...
FDTD (Lumerical design, Inc.) and compared with the analytical results provided by coupled mode theory. Figure 55 (a) shows this comparison; our analytical model assumed $\kappa = 0.49 \mu m^{-1}$ and $\alpha = 0.61 \mu m^{-1}$, which was based on fitting extracted data from FDTD simulation, in order to make the analysis representative of the numerical simulation. Figure 55 (b) shows 3D-FDTD simulations presented as mappings of light propagation inside the waveguide at the wavelength of 1550 nm, where for forward propagating light and its reflection form strong interference pattern, whereas reflection in the backward direction is close to 0. Therefore, one can clearly observe the break of reflection symmetry.

![Figure 55: (a) Numerically calculated transmission (red) and reflection (blue) spectra with different perturbation lengths of periodic structure at its exceptional point. Blue and red curves denote the corresponding fittings with the derived analytical formulas, (b) mapping of light in the waveguides for forward and backward conditions.](image)

In order to assess the structure in terms of optical response as a function of the wavelength, FDTD was used by means of launching a pulse into the structure of 25 periods (each period is $4\pi/q \approx 575.5$ nm). Figure 56 (a), shows the reflection spectra for both directions: forward and backward. The resonance peak in the forward direction is located around 1550 nm, whereas reflection in the backward direction is almost null within the entire analyzed range of wavelengths, from 1520 to 1580 nm. It clearly shows the expected unidirectional reflectionless phenomenon corresponding to the exceptional point, as the calculated contrast ratio, shown in Figure 56 (b), is always close to 1 for this spectral region.
Figure 56: (a) Simulated reflectance of the unidirectional Bragg grating in both directions and (b) the corresponding contrast ratio from 1520 to 1580 nm.

6.1.2 Transfer Matrix Method approach design and FDTD validation.

Designing the dielectric permittivity in such a way that \( \Delta \varepsilon = \cos(qz) - j\delta\sin(qz) \) is possible; however, it is not practical to implement due to its complexity, making it challenging to fabricate. Therefore, in order to attain a real implementation to show a practical device, we re-designed the structure and used an optical space transformation, displacing the real part of \( \Delta \varepsilon \) of \( 5\pi/2q \) in the \( z \) direction to become a positive sinusoidal perturbation \( (\Delta \varepsilon_{\text{real}} = \cos(qz) = \sin(qz - 5\pi/2)) \), whereas the imaginary perturbation part remains at the same location \( (\Delta \varepsilon_{\text{imag}} = -j\sin(qz) = j\sin(qz)) \), as depicted in Figure 57.

Figure 57: Equivalent designed structure with separate real and imaginary part optical perturbations.

Owing to the in-phase shift of the real part perturbation, the modulated phase and amplitude of guided light, accumulated from both real and imaginary part perturbations, remain the same after propagating through an entire unit cell.

To validate our strategy and evaluate the performance of our proposed structure, we
used the well-known Transfer Matrix Method (TMM) to analyze the equivalent structure. Each period of the structure can be assessed by the depicted structure shown in Figure 58, which consists of a structure with four layers, with perturbation in the real and imaginary part of the refractive index profile.

Using the TMM, one can represent each period of the periodic structure in a matrix form and obtain the reflectance and transmittance as a function of wavelength and number of periods. Considering the original structure, waveguide 800-nm wide and 220-nm thick, the effective refractive index is approximately 2.69 for a wavelength of 1550 nm. In our analysis, we assume small amplitude of the periodic region that would allow designing the effective refractive index under real conditions, therefore the effective refractive index perturbation in its Real and Complex components are given by:

\[
\begin{align*}
    n_{\text{Real}}(\Delta z) &= 2.69 + 0.15 \sin(q\Delta z) \\
    n_{\text{Complex}}(\Delta z) &= 2.69 - j0.15 \sin(q\Delta z) , 0 \leq \Delta z \leq \frac{\pi}{q}
\end{align*}
\]  

(24)

Figure 59 (a) and (b) shows the real and imaginary part of, respectively, the real and complex effective refractive index as a function of the position, \(\Delta z\).
Based on Figure 58, one can represent each period of the structure by a matrix. Layer $A$ can be expressed as:

$$
[M_A] = \begin{bmatrix}
\cos\left(\frac{2\pi}{\lambda_0} n_{eff} d_A\right) & j \sin\left(\frac{2\pi}{\lambda_0} n_{eff} d_A\right) \\
j n_{eff} \sin\left(\frac{2\pi}{\lambda_0} n_{eff} d_A\right) & \cos\left(\frac{2\pi}{\lambda_0} n_{eff} d_A\right)
\end{bmatrix},
$$

where $n_{eff}$ is the effective refractive index of the waveguide with no perturbation, i.e., $n_{eff} = 2.69$, $d_A$ is the length of the layer $A$, and $\lambda_0$ is the wavelength in vacuum. Layer $B$ can be represented by:

$$
[M_B] = \begin{bmatrix}
\cos\left(\frac{2\pi}{\lambda_0} n_{eff} d_B\right) & j \sin\left(\frac{2\pi}{\lambda_0} n_{eff} d_B\right) \\
j n_{eff} \sin\left(\frac{2\pi}{\lambda_0} n_{eff} d_B\right) & \cos\left(\frac{2\pi}{\lambda_0} n_{eff} d_B\right)
\end{bmatrix},
$$

where $d_B$ is the length of the layer $B$.

Layers *Complex* and *Real* consist of special layers where the refractive index is a function of position. Therefore, they cannot be represented similarly to the discrete Layers $A$ and $B$; a discretization is required in order to use TMM. To represent these layers, we used a productory of matrices that represents the whole period. The *Complex* layer is represented by:
where $n(\Delta z, \varsigma)$ is the complex refractive index, which is dependent of $\Delta z$ and the resolution, $\varsigma$, which in turn represents the step resolution of the discretized sinusoidal length of the layer. The intervals goes from 0 to $(\pi/q) (1/\varsigma)$, where $(\pi/q)$ represents the total length of the layer and $(1/\varsigma)$ is related to the resolution.

Similarly, the Real layer is obtained by:

\[
\begin{bmatrix}
\cos\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Real}} \varsigma\right) \\
\sin\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Real}} \varsigma\right)
\end{bmatrix} \begin{bmatrix}
j \sin\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Real}} \varsigma\right) \\
\cos\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Real}} \varsigma\right)
\end{bmatrix}
\]

where $n(\Delta z, \varsigma)_{\text{Real}}$ is the refractive index, position and resolution dependent of the Real layer.

Therefore, the period in the forward and backward directions can be expressed, respectively, by:

\[
[M_{\text{Forward}}] = \prod_{\Delta z=0}^{\pi/q}(\varsigma) \begin{bmatrix}
\cos\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Forward}} \varsigma\right) \\
\sin\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Forward}} \varsigma\right)
\end{bmatrix} \begin{bmatrix}
j \sin\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Forward}} \varsigma\right) \\
\cos\left(\frac{2\pi}{\lambda_0} n(\Delta z, \varsigma)_{\text{Forward}} \varsigma\right)
\end{bmatrix},
\]

\[
[M_{\text{Backward}}] = [M_{\text{Forward}}]^{-1}.
\]

Thus, the forward and backward matrixes as a function of the periods are given by:

\[
[M_{\text{Forward}}]^{N} \text{ and } [M_{\text{Backward}}]^{N}.
\]

These matrices represent all layers in their respective propagation direction; thereby, the electric field transmission and reflection coefficients for Forward and Backward propagation can be obtained by means of a matrix $Q$, given by:

\[
[Q_{\text{Forward}}] = \begin{bmatrix} 1 & 1 \\ n_{\text{eff}} & -n_{\text{eff}} \end{bmatrix}^{-1} [M_{\text{Forward}}]^{N} \begin{bmatrix} 1 & 1 \\ n_{\text{eff}} & -n_{\text{eff}} \end{bmatrix}
\]
\[
\mathbf{Q}_{\text{Forward}} = \begin{bmatrix} Q_{\text{Forward}}^{11} & Q_{\text{Forward}}^{12} \\ Q_{\text{Forward}}^{21} & Q_{\text{Forward}}^{22} \end{bmatrix}
\] (33)

\[
\mathbf{Q}_{\text{Backward}} = \begin{bmatrix} 1 & 1 \\ n_{\text{eff}} & -n_{\text{eff}} \end{bmatrix}^{-1} \mathbf{M}_{\text{Backward}} \begin{bmatrix} 1 & 1 \\ n_{\text{eff}} & -n_{\text{eff}} \end{bmatrix}
\] (34)

\[
\mathbf{Q}_{\text{Backward}} = \begin{bmatrix} Q_{\text{Backward}}^{11} & Q_{\text{Backward}}^{12} \\ Q_{\text{Backward}}^{21} & Q_{\text{Backward}}^{22} \end{bmatrix}
\] (35)

Therefore, the forward transmittance \((T_{\text{Forward}})\) and reflectance \((R_{\text{Forward}})\), as well as the backward transmittance \((T_{\text{Backward}})\) and reflectance \((R_{\text{Backward}})\), can be expressed by:

\[
T_{\text{Forward}} = \left| \frac{1}{Q_{\text{Forward}}^{11}(\lambda)} \right|^2
\] (36)

\[
R_{\text{Forward}} = \left| \frac{Q_{\text{Forward}}^{21}(\lambda)}{Q_{\text{Forward}}^{11}(\lambda)} \right|^2
\] (37)

\[
T_{\text{Backward}} = \left| \frac{1}{Q_{\text{Backward}}^{11}(\lambda)} \right|^2
\] (38)

\[
R_{\text{Backward}} = \left| \frac{Q_{\text{Backward}}^{21}(\lambda)}{Q_{\text{Backward}}^{11}(\lambda)} \right|^2
\] (39)

Assuming design parameters, one can assess both transmittances and reflectances as a function of wavelength and number of periods. In our design, we assumed the design parameters showed in Table 9.

**Table 9: Design parameters for the unidirectional Bragg Grating**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Refractive index</th>
<th>Length</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex</td>
<td>(2.69 - 0.15\sin(q\Delta z))</td>
<td>(d_{\text{complex}} = 144) nm</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>(A)</td>
<td>2.69</td>
<td>(d_A = 216) nm</td>
<td>-</td>
</tr>
<tr>
<td>(Real)</td>
<td>(2.69 + 0.15\sin(q\Delta z))</td>
<td>(d_{\text{real}} = 144) nm</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>(B)</td>
<td>2.69</td>
<td>(d_B = 71) nm</td>
<td>-</td>
</tr>
</tbody>
</table>

Using the design parameters showed in Table 9 and the equations (36) through (39), one can obtain the forward and backward transmittance and reflectance as a function of the wavelength and number of periods, which are shown in Figure 60.
Based upon the results shown in Figure 60, one can observe, in Figure 60 (b) and (d), that transmittance in both directions present similar behavior, they decay in intensity as a function of the number of periods. On the other hand, Figure 60 (a) and (c) show the break of symmetry in terms of reflection, showing high values in the forward reflectance and absence of the backward reflectance.

Figure 60 (a) shows that, after a certain number of periods, the forward reflectance reaches an asymptotic value, whereas Figure 60 (b) shows that transmitted energy continuously decays as number of periods increases, with energy partially coupled to the reflected mode and absorbed by losses. On the other hand, Figure 60 (c) shows that no energy was coupled to the contra-propagating mode and that energy decreases as the number of period increases, similarly to the demonstration shown using the coupled mode theory.

Therefore, this in-phase arranged periodic structure creates an equivalent unidirectional reflectance, similar to the structure in Figure 52. Unlike the balanced
perturbation in the real part in the case of Figure 56 (a), the only-positive real part perturbation here results in a red-shift of the resonance peak to the wavelength around 1560 nm (shown in Figure 60 (a)), which is also validated by means of FDTD and is shown in Figure 61 (a). However, the corresponding contrast ratio close to unity value still manifests the expected unidirectional optical property over the studied range of wavelengths from 1520 to 1580 nm, this result is shown in Figure 61 (b).

This breaking of symmetry at this exceptional point is also visualized at Figure 61 (c) by means of the mappings of light propagating inside the waveguide at the wavelength of 1560 nm: forward propagating light and its reflection forms strong constructive interference, whereas reflection in the backward direction is close to 0.

Figure 61: (a) Reflectance of the designed equivalent unidirectional Bragg Grating with spatially separated real and imaginary parts of the optical perturbations in both directions, (b) and its corresponding contrast ratio from 1520 to 1580 nm. (c) Simulated electric field amplitude distribution of light in the designed equivalent unidirectional Bragg grating.
It is noteworthy to point out the good agreement between both methods, showing good consistency with three design tools that complement each other regarding the complex understanding of this structure. The only discrepancy observed is the amplitude of the forward reflectance, which can be directly attributed to the completeness of FDTD regarding scattering losses, coupling to radiation modes and waveguide dispersion, which are not considered in our analytical model based on TMM.

6.1.3 Finite-Domain Time-Domain realistic design.

Coupled Mode Theory and Transfer Matrix Method are analytical tools that allow understanding the involved physical concepts and obtain quick analysis to make preliminary designs. Results obtained in the last section showed that 25 periods of the structure showed in Figure 58 are enough to provide high unidirectional reflectance and still provide some transmission. TMM shows that our equivalent structure is capable of obtaining the same effect shown in the original structure by means of a special optical transformation, making an equivalent structure to reduce the complexity of the original structure.

However, the structure shown at the TMM design is still not straightforward to obtain in terms of materials. Therefore, a special design is required to demonstrate an effective perturbation in the real and imaginary part of the refractive index, as shown in Eq. (24), which is reproduced in the following equation:

\[
\begin{align*}
&n_{\text{Real}}(\Delta z) = 2.69 + 0.15 \sin (q\Delta z), 0 \leq \Delta z \leq \frac{\pi}{q}, \\
&n_{\text{Complex}}(\Delta z) = 2.69 - i0.15 \sin (q\Delta z)
\end{align*}
\]

(40)

In order to design this structure, pure FDTD simulations were used to obtain the sinusoidal behavior of the real and complex effective refractive index. To achieve these sinusoidal-function modulated optical potentials using microscopically homogeneous materials, sinusoidal shaped combo structures (combination of a sinusoidal shaped structure and its mirror image along the transverse direction) are adopted on top of the Si waveguide.
Our design showed that the real effective refractive index perturbation can be obtained by means of sinusoidal shaped structure and its mirror image along the transverse direction made of 53 nm of silicon. Similarly, a bilayer of 14 nm of germanium and 24 nm of chrome structure on top of silicon waveguide is consistent with the real and imaginary part of the effective complex refractive index. Figure 62 (a) and (b) show the effective real refractive index and effective complex refractive index and their shapes compounded by their materials, respectively.

Based on Figure 62, one can observe that the designed periodic structure shows similar behavior to the one shown in Figure 59. However, there is a small discrepancy in index profiles, although it is quite close to the ideal required shape.

The equivalent FDTD designed structure with the real and complex sinusoidal structures are shown in Figure 63. It consists of a silicon waveguide 800-nm wide 220-nm thick, as well as additional sinusoidal structures composed of 51 nm of silicon and a combo bilayer made of 14 nm of germanium and 24 nm of chrome. Both sinusoidal structures are 800-nm wide and 143.9-nm long, aligned on the center of the waveguides.

Figure 62: (a) Effective real refractive index and its equivalent designed structure. (b) Effective imaginary refractive index and its equivalent designed structure
Figure 63: Periodically arranged sinusoidal shaped combo structures on top of Si waveguide embedded inside SiO₂, in which imaginary part perturbation is implemented with 14 nm Ge and 24 nm Cr bilayer structures and the real part perturbation comprises 51 nm Si layers.

The final designed structure is composed by 25 periods. To validate our designed unidirectional Bragg grating based on the final combo periods, we simulated the full structure (with 25 periods) by means of 3D-FDTD simulations and assessed the forward and backward reflectance, the contrast ratio as a function of the wavelength, as well as the mappings of light propagating inside the waveguide for the high reflective wavelength. These results are shown in Figure 64 (a), (b), and (c), respectively.

Figure 64: Simulated forward and backward reflectance of the designed structure as a function of the wavelength. (b) Contrast ratio as a function of the wavelength. (c) Forward and backward propagation mapping of light.
The forward and backward reflectances are significantly distinct in both directions with about 11 dB of extinction ratio in the studied wavelength range from 1520 to 1580 nm, showing the equivalence of our designed structure with the original ideal one.

Based on Figure 64, one can observe that the forward propagating light and its reflection forms strong a constructive interference pattern, whereas backward reflection is barely seen within backward incidence. It is thus evident that the designed on-chip waveguide system successfully mimics the unidirectional effect inherently associated with the exceptional point of breaking of symmetry, as it was pointed out in our first theoretical structure (Figure 52).

In experiments, however, measuring in-line reflection would require use of external components such as optical circulators or directional couplers, which in turn would increase the insertion losses and the noise level in the measurements, turning it into a difficult task to perform. Therefore, we propose an alternative approach, using on-chip waveguide directional couplers to measure the corresponding reflection coefficients in a way similar to the transmission measurement, as shown in Figure 65.

Figure 65: Schematic representation of the device with periodic structure and directional coupler to measure the reflected light.
To design the 3dB directional coupler, 3D finite difference beam propagation method (R-Soft Design Group, Inc.) was used. Our analysis showed that two 400-nm wide and 220-nm thick Si waveguides with a gap of 414 nm between them, and interaction length of 40 µm, is enough to obtain a 3 dB directional coupler, as shown in Figure 66.

![Simulated light coupling in the designed waveguide coupler, showing evolution of electric field envelopes (left) and intensities (right) in two waveguides as light propagates in the z direction.](image)

**Figure 66: Simulated light coupling in the designed waveguide coupler, showing evolution of electric field envelopes (left) and intensities (right) in two waveguides as light propagates in the z direction.**

### 6.2 Fabrication and experimental results

The previous sections, theoretically and conceptually, showed that the final designed structure is capable of providing evidence of unidirectional reflectionless.

Therefore, the sample was fabricated using the following process: two layers of periodically arranged sinusoidal shaped combo structures are first patterned in polymethyl methacrylate (PMMA) by means of two steps of electron beam lithography with accurate alignment, followed by electron beam evaporation of Ge/Cr and Si, and by lift-off in acetone. Then, the Si waveguide is defined by a third step of aligned e-beam lithography using hydrogen silsesquioxane (HSQ), followed by dry etching. Since the developed HSQ becomes porous SiO₂ and its refractive index is similar to SiO₂, it remains on top of the waveguide and
then plasma enhanced chemical vapour deposition with mixed gases of SiH₄ and N₂O is used
to clad SiO₂ on the entire wafer to increase the light coupling efficiency from tapered fibers to
waveguides. Figure 67 (a) and (b) show the structure before the SiO₂ deposition in two
different scales, where the pointed out region in Figure 67 (b) delimits a single period of the
periodic structure.

![Figure 67: Fabricated passive unidirectional reflectionless Bragg grating (a) entire periodic structure and
(b) zoom-in view, where the boxed area indicates a unit cell. The remaining HSQ resist can be seen on top
of the waveguide, as well as two kinds of sinusoidal combos.](image)

The reflection spectra of the fabricated unidirectional reflectionless Bragg grating have
been measured for both forward and backward directions, as shown in Figure 68 (a),
respectively. Consistently with simulations, red-shifts of the resonance peaks are also
observed in experimental measurements for both directions. The measured reflection spectra
also show significantly distinguished characteristics in reflection: the reflectance in the
forward direction is approximately 7.5 dB stronger than that in the backward direction,
indicating asymmetric optical properties, owing to our special design. The corresponding high
contrast ratios over a broad band of telecom wavelengths is shown in Figure 68 (b), thus
confirming the asymmetrical-reflection unidirectional Bragg grating associated with the
exceptional point of symmetry breaking attained in our design.
Figure 68: (a) Measured reflected spectra of the device through the waveguide coupler for both directions over a broad band of telecom wavelengths from 1520 nm to 1580 nm. Red and blue curves are Gaussian fits of raw data in forward (black) and backward (yellow) directions, respectively. (b) Spectrum of contrast ratio of reflectivity obtained from the fitting data in (a).

6.3 Commentaries

It is therefore evident that the presented on-chip designed unidirectional Bragg grating can successfully show breaking of symmetry by means of a special CMOS compatible design, showing clear asymmetrical characteristics in terms of light propagation, where the use of losses, suitably designed, enables unidirectional photonic characteristics.

The designed structure is a concept demonstration that may open the doors for a new generation of photonic devices, showing evidences that one of longstanding challenges in Silicon Photonics - the unidirectionality, can be overcome by purely CMOS materials cleverly arranged on a special designed.
7 CONCLUSION

On the second chapter we showed that a particular configuration of an electrooptic modulator, the so-called Snowman modulator, can attain reconfigurability and provide wideband as wide as 740 GHZ to an optical link, being able to support up to 65 K of temperature variation when suitably designed and fabricated.

On the third chapter, we have theoretically and experimentally demonstrated another device with broadband characteristics based on the tuning of the ring resonator resonance, allowing filtering, optical signal processing, and tailoring the optical spectrum as desired within a particular range.

On the fourth chapter, a proof-of-concept for a new and entirely CMOS compatible thermo-optic reconfigurable switch based on a coupled ring resonator structure was theoretically and experimentally demonstrated. Results showed that a single optical device is capable of combining several functionalities, such as tunable filtering, non-blocking switching and reconfigurability, in a single device with compact footprint (~50 μm x 30 μm), avoiding the use of several independent devices to obtain similar functionality.

On the fifth section, a new proof-of-concept for a new and entirely CMOS compatible tunable nanobeam cavity was demonstrated, showing that a compact nanobeam cavity (~20 μm²) with high Q-factor (~50,000), high FSR, and integrated with a micro-heater atop, is able of tuning the resonant wavelength up to 15 nm with low power consumption (0.35 nm/mW), and of attaining high modulation depth with only ~100 μW of electrical power. Such device promises to be useful in several applications, such as WDM and sensing in general, owing to its unique characteristics.

Finally, on chapter sixth, we demonstrated the first unidirectional Bragg grating by means of a special designed structure, being the one of the few ever reported demonstrations that light can be routed unidirectionally in a CMOS compatible chip, showing that
asymmetric reflection of up to 7.5 dB can be experimentally attained. This new device concept may open the doors for unveiled photonic device structures, owing to its innovative and novel approach.

Therefore, the results reported by this thesis show new classes of proof-of-concept devices, some of them being novel and/or innovative solutions for long-standing challenges of Silicon Photonics, which may open the doors for applications that were not previously possible or foreseen.
8 AWARDS AND PUBLICATIONS

Award:


Journal publications:


Conference Publications:


4. FEGADOLLI, W. S.; Almeida, V. R.; COUTINHO, O. L; Oliveira, J. E. B. . Silicon


**Articles in magazines:**

REFERENCES


61 DEOTARE, P. B. et al, High quality factor photonic crystal nanobeam cavities. *Applied


Highly Integrated Silicon Photonics Devices

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This doctorate thesis has focused on the scientific and technological development of knowledge based on the long-standing challenges of Silicon Photonics technology. By means of design, fabrication, and characterization of entirely CMOS-compatible photonic devices, this thesis demonstrates new classes of highly integrated Silicon Photonics devices that enable particular functionalities, such as insensitivity to temperature, reconfigurability, low power consumption, and unidirectionality. The photonic devices insensitive to temperature comprise two distinct designs, which are also considered reconfigurable devices. This thesis reports that two particular resonant structures are able to attain wideband optical properties, and such a characteristic can be exploited to reduce devices’ sensitivity to temperature over a broad range of wavelength and temperature. Theoretical results show that a particular configuration is able to support up to 95 K of temperature variation for digital applications. A third reconfigurable photonic device consists of a proof-of-concept for a new thermo-optic reconfigurable switch, based on a coupled ring resonator structure. Results show that a single optical device with compact footprint is capable of combining several functionalities, such as tunable filtering, non-blocking switching, and reconfigurability. The fourth photonic device consists of a new tunable photonic crystal nanobeam cavity. Preliminary results show that a compact device (~20 μm²) with high Q-factor (~50,000) and integrated with a micro-heater atop, is able of tuning the resonant wavelength up to 15 nm with low power consumption (0.35 nm/mW), providing FSR higher than 100 nm, and attaining high modulation depth with only ~100 μW of electrical power consumption. The last proof-of-concept photonic device reported in this thesis consists of the first unidirectional reflectionless passive Bragg grating photonic device, where the break of symmetry for light propagation is demonstrated by means of asymmetric reflection of 7.5 dB.