Design of Polarization-Insensitive Demultiplexing Lattice Filters in SOI

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Abstract—In this paper, we propose a novel optimization technique that make use of nonlinear cost functions to design polarization-insensitive wavelength division demultiplexing (DEMUX) lattice filters in Silicon-On-Insulator (SOI) waveguides. These waveguides are characterized by large effective index and group index birefringences that are fully taken into account in the simulations. The optimization takes advantage of the periodicity of spectral responses of the various elements building a lattice filter. In performing the design, we consider design sensitivity to parameter variations and propose solutions that are compatible with CMOS processes using a waveguide thickness of 220 nm. The design can nonetheless be generalized to other waveguide dimensions and filter topologies for the realization of more complex integrated photonic circuits. Finally, we illustrate the approach by designing and simulating four channel demultiplexers with 200 GHz and 800 GHz channel spacing in both the O- and C-band. Compared to the conventional polarization diversity scheme, this polarization-insensitive design methodology may reduce the total footprint and power consumption by up to 50%, and is therefore of great interest for short reach data communication applications.

Index Terms—Integrated optics, Lattice filters, Polarization insensitivity, Silicon-On-Insulator, Wavelength division multiplexing, Wavelength filtering devices

I. INTRODUCTION

ORIGINALLY stemming from a desire to improve properties such as propagation losses [1], the large cross-section asymmetry of typical submicron Silicon-On-Insulator (SOI) waveguides has the unintended consequence of making polarization management on this platform somewhat challenging. This asymmetry is further enhanced by the large (∼2) refractive index contrast between the Si core and SiO₂ cladding [2]. Predictably, this results in quasi-TE and quasi-TM modes with very different effective refractive indices \(n_{eff}\) and group indices \(n_g\) [2], [3]. As non-absorbing optical filters such as those used for wavelength division multiplexing (WDM) rely on interferometric principles, these quantities are directly involved in the control of optical path differences defining a given optical band [4].

The problem of polarization management in WDM systems is most relevant at the receiver side. This is because the polarization state of the light is well controlled at the transmitter, but undergoes random transitions inside the optical fibers, leading to an unknown and time-varying polarization state at the receiver. An efficient demultiplexing design is one that accepts both polarizations, as otherwise a significant (almost complete) loss of signal is to be expected from time to time, leading to fading. To better exploit the advantages of the SOI platform, which are low fabrication costs, compatibility with CMOS processes, and compactness, an efficient polarization-insensitive design must exhibit limited fabrication complexity. Framing the problem of polarization management in such a manner already excludes a vast array of potential solutions based on an in-depth modification of waveguide parameters [5]–[9] that would not be compatible with most fabrication processes. In this paper, we make the more pragmatic choice of keeping single-etch waveguides of a standard fixed height. This keeps fabrication complexity to a minimum and allows sharp bend radii to be used.

Lately, various polarization diversity schemes have been proposed. They rely on polarization splitting, sometimes combined with a polarization rotator (leading to a polarization rotation splitter [10]), to process the two incoming polarizations separately [11]–[13]. This solution is fairly straightforward, but has the obvious drawbacks of doubling both the footprint and the expected power consumption, if thermal tuning is employed. The sensitivity to fabrication errors is also significantly increased, as there are now two independent filters that must be aligned with each other. With regard to devices with shared paths [14], [15] for a \(N\) channel demultiplexer, \(N + 1\) polarization rotators are required, adding to complexity, losses, and footprint. Instead, we propose here a novel monolithic solution exploiting the spectral periodicity of interferometric devices to align different orders of TE and TM responses. In this paper, this technique is applied to the design of a polarization-insensitive optical lattice filter, a building block for the demultiplexing of a (small) power of two number of channels that consists of cascaded Mach-Zehnder interferometers [4]. This approach, initially presented in [16], is extended here in order to provide details on the performance trade-offs of the optimized solutions in both the O- and C-band.

The paper is organized as follows. In section II, we describe the lattice filter configuration that was previously proposed in the literature for operating with a single polarization (TE mode). We then discuss the impact of the effective index and group index birefringences of SOI waveguides on the filter spectral response. Finally, we propose a two-step process to achieve polarization insensitivity by optimizing the wavel-
Fig. 1. Schematic of the four channel demultiplexer implemented with lattice filters. The imbalance of the successive Mach-Zehnder stages are indicated in terms of the unit delay length $\Delta L$. The coupling ratios of all couplers are also specified.

Fig. 2. Ideal spectral amplitude response of the four channel demultiplexer shown Fig. 1. Each color represents a different output port.

II. OPTIMIZATION OF LATTICE BUILDING BLOCKS

Fig. 1 shows the complete schematic of the demultiplexer to be optimized, Fig. 2 shows the spectral amplitude response for a single polarization, computed with the transfer matrix method (TMM) [4]. The assumptions built into this model are a constant group index and ideal (wavelength independent) power coupling ratios. The phase is not shown, but it is linear everywhere, as there are no feedback elements or resonances. The design is similar to what was recently demonstrated in SOI for eight channels instead of four [17], in that it effectively makes use of the same coupling ratios and delay lines arrangements. The coupling required originates from the decomposition of the underlying transfer function for each stage in the Z-domain [4]. In this paper, the waveguides are kept at a fixed height of 220 nm.

The optimization is done in two steps. Firstly, we assume that the couplers have ideal coupling ratios, shown in Fig. 2, for both TE and TM modes. We then optimize the waveguide width of the Mach-Zehnder structure to align the filter passbands of both polarizations. Secondly, we focus on the couplers and optimize their dimensions to achieve polarization independent coupling ratios. Both these steps make use of the spectral periodicity of the responses of Mach-Zehnder interferometers and directional couplers.

A. Optimization of the Mach-Zehnder waveguide widths to match TE and TM responses

In this section, taking into account the $n_g$ and $n_{eff}$ birefringences, we optimize the waveguide width to reduce the polarization dependence of the passbands. To achieve this goal, we must optimize the spectral offset and filter passbands. In doing so, we keep the coupling ratios fixed and assume identical values for both TE and TM modes.

For a lattice filter, the unit delay length $\Delta L$ in Fig. 1 is related to the -3 dB bandwidth $\Delta f$ of the demultiplexed channels (in Hz) through the following expression:

$$\Delta L = \frac{c}{2n_g\Delta f}$$

where $c$ is the speed of light in vacuum and $n_g$ the group index of the mode in the delay lines. This assumes a negligible group delay dispersion, such that $n_g$ can be considered constant over the band of interest. The delay lines are halved at each stage to further separate the odd and even channels. Already, a problem arises from Eq. (1) that shows that, if $n_g^{TE}$ differs significantly from $n_g^{TM}$, the bandwidths will not match. Another important characteristic of these channels is their absolute position on the wavelength axis. A given output has a periodic spectral response with central passband wavelengths $\lambda_{k,m}$:

$$\lambda_{k,m} = \frac{n_{eff}\Delta L}{m\log_2 N} + \delta\lambda(k - 1), \quad m \in \mathbb{N}$$

where $\delta\lambda$ is a constant group index and ideal (wavelength independent) power coupling ratios. The phase is not shown.
where \( \delta \lambda \) is the channel spacing \( \approx \lambda^2 / (2 n_g \Delta L) \), and \( k \) the channel number, from 1 to \( N \). The dependence of the channel spacing and \( n_{eff} \) on wavelength adds some complexity to the equation above. A non-trivial requirement is therefore to match \( \lambda^E_k \), with \( \lambda^{TM}_{k,m} + \Delta n \) for all \( k \) in the optical band of interest as optimally as possible. Luckily, the ordering of the channels from 1 to \( N \) on the wavelength axis remains invariant to changes in \( n_{eff} \) or polarization, and for this reason, a suitable choice of \( n_{eff} \) and \( n_g \) can lead to an optimized solution. Recalling that the waveguide width is the only available degree of freedom due to the fixed height, Fig. 3 shows the birefringence of \( n_{eff} \) and \( n_g \) as a function of the waveguide width for a standard height of 220 nm and wavelengths of 1.55 \( \mu \)m and 1.31 \( \mu \)m. As the effective and group indices of Fig. 3 are computed numerically, it is necessary to solve Eq. (2) through numerical means as well. For this purpose, a cost function quantifying the mean squared error over the optical band of interest \( \Delta \lambda \) (covering at least all \( N \) channels) is defined as follows:

\[
C_1(w) = \frac{1}{N \Delta \lambda} \sum_{k=1}^{N} \int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} \left[ H_k^E(\lambda,w) - H_k^{TM}(\lambda,w) \right]^2 d\lambda
\]

where \( \lambda_0 \) is the central design wavelength, \( w \) the width, and \( H_k \) the amplitude transmission response of the \( k^{th} \) output port, calculated using a transfer matrix model with ideal couplers. The width must be changed equally for all the delay lines of the filter in order to conserve proper optical path differences. Fig. 4 (a) and (b) show computed cost functions for the layout of Fig. 1. The minimum value attained in each valley, representing a suitable width, is directly related to the \( n_g \) birefringence. This shows that, although the effect of \( n_{eff} \) can be fully compensated, the effect of \( n_g \) cannot, a fact already apparent from Eq. (1). Incidentally, this demonstrates the importance of geometries minimizing this \( n_g \) birefringence rather than the more classical \( n_{eff} \) birefringence, which has been up to now the usual point of interest of previous studies [5]–[9]. The width of the valleys in Fig. 4, directly related to \( \partial n_{eff} / \partial w \), illustrates the tolerance to fabrication errors: as this derivative diminishes, it becomes increasingly harder to produce spectral shifts that are able to synchronize the responses again. In general, wider widths should also be preferred for their better tolerance to phase errors due to waveguide roughness as this noise is also related to \( \partial n_{eff} / \partial w \). However, wider widths also lead to longer adiabatic tapers, which are necessary to ensure proper single-mode operation of wide multimode waveguides. These long tapers simultaneously increases the optical path length, offsetting some of the potential gains due to a relationship between phase errors and the total length [18]. These tradeoffs are not a formal part of the cost function of Eq. (3), but must be considered when opting for the final design solution.

Finally, it is worth noting that Eq. (1) and (2) have obvious similarities to the classical Fabry-Perot resonator, as well as with many other interferometric devices, which is quite encouraging from the point of view of a possible generalization of this design approach to other wavelength filtering structures.

**B. Optimization of directional coupler lengths to match TE and TM coupling ratios**

Attention must now be directed to the optimization of the response of the directional couplers with different input polarizations. As these two modes differ significantly in confinement, vastly different coupling properties are expected. As a starting point, consider the expression for the fraction of cross-coupled power \( \Gamma_c \):

\[
\Gamma_c = \sin^2 \left( \frac{\pi \Delta n_{eff} L}{\lambda_0} \right)
\]

where \( L \) is the length of the coupler from Fig. 5 (a), \( \lambda_0 \) the wavelength for which the coupler is designed, and \( \Delta n_{eff} \) the effective index difference between the symmetric and asymmetric supermodes. The latter is very strongly affected by the difference in confinement. Fig. 6 shows the ratio of the TE coupling length \( L^E_c \), defined as the shortest length.
that produces $\Gamma_c = 1$ in Eq. (4), to the TM coupling length $L_c^{TM}$ as a function of the minimum separation gap between the waveguides. The large difference between $L_c^{TE}$ and $L_c^{TM}$ can be attributed to the difference in mode confinement through $\Delta n_{eff}$. Nevertheless, it is interesting to note that Eq. (4) is periodic. When plotted as a function of the coupler length $L$, both $\Gamma_c^{TE}$ and $\Gamma_c^{TM}$ are sinusoidal functions of different spatial frequencies, and thus a beating pattern ensues if their sum is considered. A cost function for the mean squared error with respect to the required $\Gamma_c$, exhibiting this beating pattern, is defined. This time, two degrees of freedom are available, in the form of the length $L$ and separation gap $g$:

$$C_2(L, g) = \frac{1}{2} \left( [\Gamma_c - \Gamma_c^{TE}(L, g)]^2 + [\Gamma_c - \Gamma_c^{TM}(L, g)]^2 \right)$$

(5)

An optimum must be found using this cost function for each required $\Gamma_c$. The computation of $\Gamma_c$ in itself must be done in a simplified manner due to the considerable two-dimensional search space. The term $\Delta n_{eff}$ in Eq. (4) can be computed for the straight sections of the coupler as a function of the gap with a simple mode solver. However, the bend sections in Fig. 5 are more problematic. The effect of these bends is mostly negligible for the TE mode if the gaps remain above 200 nm, but this is not the case for the TM mode as a result of the difference in confinement, especially if the bend radii are also increased (e.g., 10 $\mu$m) to accommodate for the higher TM propagation losses. A solution is to simulate only the bend sections through point coupling, shown in Fig. 5 (b), while varying the gap. Computationally intensive rigorous electromagnetic propagation methods such as the popular finite-difference time-domain (FDTD) algorithm are required to simulate effectively such a structure. The coupling obtained can then be mapped to an effective $\phi_{bend} = \sin^{-1} \sqrt{\Gamma_c_{bend}}$ and introduced as a small correction inside the expression of Eq. (4) so that it becomes $\sin^2 \left( \frac{\pi \Delta n_{eff}}{\lambda_0} L + \phi_{bend} \right)$. This avoids lengthy computations of whole directional couplers with computationally intensive solvers without incurring any penalty to accuracy.

Fig. 7 shows a way to visualize $C_2(L, g)$. In this figure, the optimal areas are visible from the intersection of the lines, each representing the desired coupling value obtained for different coupling orders for the TE (solid black) and TM (dashed blue) modes. Such a visualization has been used in the past in the context of polarization-insensitive SOI rib waveguides for coupling with a ring resonator [19]. $C_2(L, g)$ is still useful for the precise determination of $L$ and $g$ through a non-linear optimization algorithm such as the Nelder-Mead method. A suitable initial value for the algorithm is found from the figures, leading the two to be complementary. As in the previous section, the larger is the optimal area, or the more tangential the two lines are to each other, the more tolerant is the design to fabrication errors. Sometimes, however, the options are fairly limited. It is generally true that smaller coupling are harder to achieve. This is because consecutive solutions are either very close to each other, being on both sides of either a crest or through, or separated by nearly a full sine period. For example, for Fig. 7 (b), a seemingly inevitable choice is the second TE line instead of the first. This has some consequences for the compactness of the device, but also most importantly for the wavelength response. The following expression gives this sensitivity:

$$\left| \frac{\partial \Gamma_c}{\partial \lambda} \right| = 2 \sin \left( \frac{\pi \Delta n_{eff}}{\lambda} L \right) \frac{-\Delta n\pi}{\lambda^2} L$$

(6)

For a given $\Gamma_c$, the impact of the sine term is the same no matter the choice of $L$ and $\Delta n_{eff}$, as it is simply the field coupling coefficient. On the other hand, the term $-\Delta n\pi$ ($> 0$), the difference between the group indices of the symmetric and asymmetric supermodes, decreases approximately quadratically with the gap. This means that a higher gap is always preferable to going to the next order, if the two optimal lengths are close. However, for a given order, shorter gaps are still a better choice due to the much reduced required length, making $L$ the dominant term of Eq. (6). Yet, smaller gaps are generally harder to fabricate, which makes the two considerations difficult to reconcile. In the case of Fig. 7 (b), in order to make the first TE coupling order intersect a TM one, another option is to modify the waveguide width itself, in order to tune the overall coupling characteristics. This option is fairly constrained, however, in that this width must retain the single mode operation; and it is often, by default, already very close to this limit in order to relax fabrication tolerances. Further reducing this width brings the TM mode even closer to cut-off, which in turn reduce its coupling length, thereby increasing its sensitivity to both wavelength and fabrication variations. The length required for the adiabatic tapers before the delay sections as well as the propagation losses are also increased. For these reasons, modifying uniformly the waveguide width of directional couplers is not a promising avenue.

### III. Simulation results

The procedure explained in the previous sections is used to generate suitable designs with central wavelengths of 1.31 $\mu$m
and 1.55 \( \mu \text{m} \) with channel spacings of 800 GHz and 200 GHz. The TMM used to simulate these designs fully implements the wavelength dependence of the directional couplers through the group index of the supermodes, although it assumes this value to be constant over the whole optical band of interest. Losses of \(-3\) dB per centimeter are included in the delay lines. With a choice of radii of 10 \( \mu \text{m} \), tables I and II shows the parameters used for the directional couplers, with an eye towards a balance between the sensitivity of Eq. (6) and fabrication tolerance constraints. The choices are indicated by the circles in Fig. 7. The worst case for the wavelength sensitivity of these couplers is shown in Fig. 8 for the two wavelengths bands. The effect of this coupling ratio error for wavelengths away from the central one is to create more sidelobes, without however shifting or scaling...
Fig. 9. Transmission spectra of the designed optical filters calculated with the TMM, with one color per output port. TE polarized outputs are represented by solid lines and TM outputs by dashed ones.

(a) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.781 \, \mu m$

(b) $\lambda_0 = 1.31 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.410 \, \mu m$

(c) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 200$ GHz, $w = 0.786 \, \mu m$

(d) $\lambda_0 = 1.31 \, \mu m$, $\Delta f = 200$ GHz, and $w = 0.412 \, \mu m$

Fig. 10. Transmission spectra of the devices presented in Fig. 9 a) with variations on the waveguide width of $\pm 20$ nm and on the waveguide height of $\pm 1$ nm, with respect to nominal values. TE polarized outputs are represented by solid lines and TM outputs by dashed ones.

(a) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.761 \, \mu m$, $h = 220$ nm

(b) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.801 \, \mu m$, $h = 220$ nm

(c) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.781 \, \mu m$, $h = 219$ nm

(d) $\lambda_0 = 1.55 \, \mu m$, $\Delta f = 800$ GHz, $w = 0.781 \, \mu m$, $h = 221$ nm
the bandpass response – which is the justification behind the sequential optimization approach presented here. Because of the relatively small dimensions of the directional couplers for the C-band, mostly similar in size to the reference design [17], the estimated footprint of $\sim 200 \, \mu m \times 400 \, \mu m$ is within the approximate dimensions for such a device as conventionally designed, indicating a factor of two reduction in footprint compared to a copy for the other polarization. For the O-band, this factor is diminished due to the larger size of the directional couplers, but remains well below the total footprint of two identical circuits.

Spectral responses of filter designs implemented with these parameters for the couplers, along with suitable waveguide widths for the delay lines shown by circles in Fig. 4, were numerically simulated. For the C-band filter, we choose the second minimum of the cost function of Fig. 4 a) because this solution leads to a design that is more tolerant to waveguide width variations. Unfortunately, choosing the rightmost minimum is not an option for the O-band because of the simultaneous increase of the group index birefringence. The results are shown in Fig. 9 for C- and O-band four-channel demultiplexers with spacing of 800 and 200 GHz. By examining these results and comparing to Fig. 2., it can be seen that good polarization insensitivity is obtained for filters in the C-band for both channel spacing, while polarization insensitivity is more difficult to achieve for the O-band filter with 800 GHz spacing (Fig. 9 b)). In this latter case, the remaining mismatch in the coupling ratio (Fig. 8 b)) becomes significant. To overcome this effect, other methods of producing broadband couplers could be considered including phase compensated couplers [20], purely asymmetric couplers [21], as well as grating assisted coupled couplers [22]. If necessary for the application at hand, either method could be combined with the above optimization procedure to study possible polarization insensitive designs over larger spectral bands.

Finally, using the nominal values of Fig. 9 a), Fig. 10 shows the impact, on the demultiplexed output spectra, of \( \pm 20 \) nm variations on the width and \( \pm 1 \) nm on the height. For width variations, the crosstalk in the middle of the passbands is marginally affected, but a slight reduction in the effective bandwidth is noted due to the now mismatched effective indices. Comparing Fig. 4 a) and b), we can reasonably expect that the O-band design will be less tolerant to width variations than the C-band design. Furthermore, as expected, variations on the wafer height have a stronger impact on the TM mode (see Fig. 9 c) and d)). This is particularly true with a \( 220 \) nm thick waveguide. In the present case, a variation of only \( 1 \) nm introduces a strong offset between the TE and TM bands. This sensitivity to thickness variations could be reduced through the use of thicker waveguide layers. Luckily, fluctuations of the silicon layer height across a die are usually fairly slow [23]. Taking advantage of the small footprint, and of the relatively strong thermo-optic coefficient of bulk silicon [24], an evenly applied temperature control of a few tens of degrees (20–30 at most), should, even the worst case, ensure proper passband alignment. Such temperature control and stabilization schemes are routinely used in silicon photonics to prevent temperature drifts [25]. Due to the unidirectional nature of thermal tuning in its ability to modify the refractive index, a practical implementation targeting a minimization of the expected power expenditure would require designing the filter for a slightly lower wafer height than nominal, based on available statistical data relevant to the specific fabrication process.

**IV. CONCLUSION**

In this paper, we have shown how to achieve a polarization-independent demultiplexing lattice filter for four channels in both the O-band (1.31 \( \mu m \)) and C-band (1.55 \( \mu m \)) using simple optimizations procedures based on non-linear cost functions. Likely obstacles pertaining to wavelength and fabrication sensitivities have been discussed in each case, along with potentials mitigations procedures. Finally, in-depth simulations conform the concept of these polarization-insensitive demultiplexers. These results are of great interest for the practical realization of polarization-insensitive transceivers for short reach optical communications at high data rates. The proposed design decreases the necessary footprint and power consumption by up to 50% compared to traditional polarization diversity schemes. In this regard, the lattice interleaving topology is relatively simple and easily scalable, hence its choice as a first target for optimization.

**REFERENCES**


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