Tailored Chromatic Dispersion in Silicon-on-Insulator Slot Waveguides

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***Abstract*— We investigate the chromatic dispersion properties of silicon channel slot waveguides in a broad spectral region centered at ~1.5 μm. The variation of the dispersion profile as a function of the slot fill factor, i.e., the ratio between the slot and waveguide widths, is analyzed. Two different dispersion regimes are identified.**

Keywords- integrated optics; silicon photonics; dispersion.

I. INTRODUCTION

The recent progress in nanofabrication techniques has enabled the development of basic photonic building blocks on a silicon-on-insulator platform including light sources, modulators, and photodetectors [1]. In general, any silicon-based photonic component is affected by chromatic dispersion. Then, the design and optimization of silicon photonic devices requires a very precise knowledge of the dispersion properties. In this context, the chromatic dispersion of a simple silicon waveguide with a cross-sectional area of a few μm^2 is primarily determined by the intrinsic silicon dispersion [2]. In contrast, when the cross-sectional area is reduced, the optical confinement is stronger and, then, the effective dispersion is the result of the interplay between the material and the waveguide or geometrical dispersion [3,4]. In fact, a careful control of the waveguide shape and size allows for the tailoring of the group-delay dispersion (GVD) so that normal, anomalous, or even zero GVD can be achieved in the spectral region centered at ~1.5 μm [3,4].

On the other hand, the so-called silicon nanophotonic slot waveguides have been proposed and fabricated for different applications [5,6]. In these waveguide structures, the optical field is strongly confined in a very thin region of low refractive index material which is sandwiched between two silicon layers and, as a result, the nonlinear optical performance is highly enhanced [6]. An early analysis of the dispersion properties of symmetric slot waveguides was reported by Zheng et al. [7]. However, the analysis by Zheng et al. was limited to a small spectral range of only 0.15 μm centered at ~1.55 μm and the dispersion control capabilities were unexplored.

In this contribution, we perform a detailed analysis of chromatic dispersion in silicon channel slot waveguides. In particular, we analyze the influence of the slot on the GVD of the channel waveguide by considering different slot fill factors. Two different dispersion regimes are distinguished. In general, the slot fill factor determines the dispersion regime in which the guiding structure operates.

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II. DISPERSION IN NANOPHOTONIC SLOT WAVEGUIDES

Let us first consider a conventional silicon channel waveguide consisting on a silicon channel embedded in a silica cladding, as shown in Fig. 1(a). Throughout this paper, three different cross-sectional areas are considered, 1 μm^2, 0.5 μm^2, and 0.1 μm^2, for both, conventional and slot waveguides. In addition, for simplicity, a fixed aspect ratio of 1-to-1.5 (height-to-width) will be assumed. Our numerical simulations are performed by using a full-vectorial mode solver based on the beam propagation method. In Fig. 1(a) a typical electric field profile of the fundamental quasi-TE mode is plotted.

By using the mode solver, we compute the effective index, $n_{eff}(\lambda)$, in a broad spectral range and by numerical differentiation the GVD parameter as a function of wavelength, $D_\lambda=-(\lambda/c_o)d^2n_{eff}/d\lambda^2$, is obtained. It is worth mentioning that our analysis includes the contribution of material dispersion to the GVD, by considering the Sellmeier equations for both silicon and silica. In Fig. 2, we show the resultant GVD profiles for the three cross-sectional areas under analysis. For comparison, the normal dispersion of pure crystalline silicon is also plotted. On the one hand, note that for larger cross-sectional areas, the GVD profile is similar to that corresponding to the silicon dispersion in such a way that the GVD gradually increases for longer wavelengths. We name this GVD behavior as material dispersion regime. A vertical up shifting in the dispersion profile is observed so that, eventually, a region with anomalous GVD is found. The more the cross-sectional area is reduced, the more the anomalous GVD region is increased. On the other hand, for smaller areas, the GVD profile is quite different having a maximum GVD along the spectral region and two zero GVD wavelengths when the maximum dispersion value is positive, as shown in the figure. These GVD characteristics describe the geometrical dispersion regime. Two different qualitative dispersion behaviors are then observed depending on the cross-sectional area of the channel waveguide.

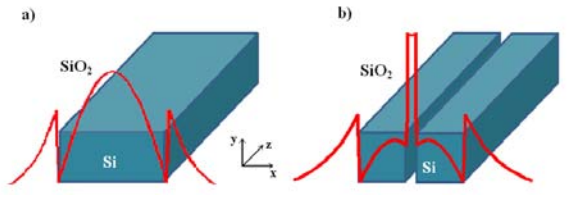

Figure 1. (a) Conventional and (b) slot silicon-on-insulator channel waveguides with same cross-sectional area. The electric field distribution of the quasi-TE mode in the *x* dimension and λ=1.5 μm is plotted.

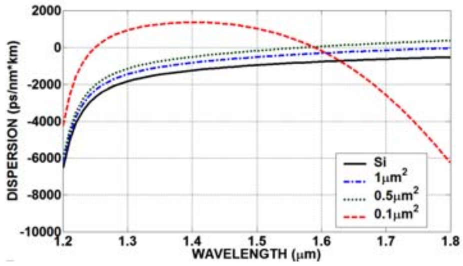

Figure 2. GVD for the fundamental quasi-TE mode of a silicon nanophotonic channel waveguide with a fixed aspect ratio of 1:1.5 and three different cross sectional areas. The intrinsic pure crystalline silicon dispersion is also plotted.

We now turn our attention to the case of silicon waveguides with a vertical slot. In Fig. 1(b), a typical geometry of a slot waveguide is shown. Note that the modal electric-field distribution has a strong discontinuity at the high-index-contrast interfaces and the optical field is significantly increased in the slot region. We have computed the dispersion properties of three different slot waveguides with the above introduced cross-sectional areas, i.e., 1 μm^2, 0.5 μm^2, and 0.1 μm^2, with the same aspect ratio. The resultant GVD curves are shown in Fig. 3(a-c), respectively. For each cross-sectional area, different slot fill factors have been considered, namely, 1:5, 1:10, 1:25, and 1:50. The fill factor is defined as the normalized ratio between the slot and the waveguide widths. Generally, in Fig. 3(a-c) the dispersion profiles can be grouped into the two dispersion regimes previously defined for a conventional waveguide. As expected, when the slot fill factor is decreased, the GVD profiles asymptotically converge to the dispersion of conventional channel waveguides.

The effect of the slot on the waveguide dispersion is different for each particular cross-sectional area. For a cross-sectional area equal to 1 μm^2, Fig. 3(a), a change in the slot fill factor translates into a relatively small variation in the GVD curve. In fact, all the dispersion profiles lie in the so-called material dispersion regime. Note that for larger fill factors, the dispersion profile exhibits a zero-GVD wavelength and, as a result, a spectral region with anomalous dispersion is found. For intermediate cross-sectional areas ~0.5 μm^2, Fig. 3(b), we find that the slot width strongly determines the dispersion regime in which the waveguide operates. More particularly, for the fill factors 1:5 and 1:10 we have GVD profiles in the geometrical dispersion regime while the fill factors 1:25 and 1:50 present GVD curves quite similar to the silicon material dispersion profile. For small cross-sectional areas, 0.1 μm^2, Fig. 3(c), we find that the slot waveguide mostly works in the geometrical dispersion regime. Note that the dispersion curve is significantly up shifted when the slot fill factor is decreased while the wavelength with maximum-GVD is nearly constant at 1.4 μm. Interestingly, for 1:5 slot fill factor, a dispersion curve with a flat profile is obtained in the ~1.4 μm – 1.6 μm spectral range.

We have also analyzed the dispersion behavior of asymmetric slotted structures, i.e., when the slot is placed in a region different than the geometrical center of the waveguide. Numerical simulations show that, in general, the asymmetry degree significantly modifies the GVD of the guiding structure.

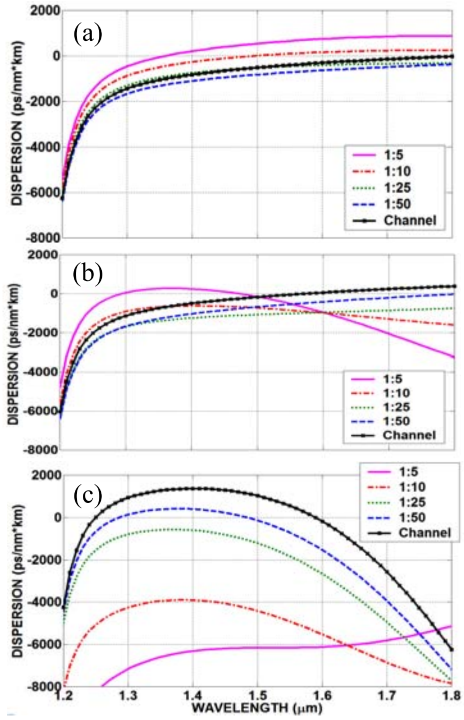

Figure 3. GVD of symmetric slot waveguides as a function of the slot fill factor. Three different cross-sectional areas have been considered: (a) 1 μm^2, (b) 0.5 μm^2, and (c) 0.1 μm^2, with a fixed aspect ratio equal to 1:1.5. The dispersion curve of a conventional channel waveguide is also plotted.

III. CONCLUSIONS

A detailed analysis of the dispersion properties of silicon-on-insulator vertical slot waveguides has been performed. Our study shows that, in general, the dispersion behavior of slot waveguides strongly depends on the slot dimension and location. Two different dispersion regimes have been qualitative distinguished. Our study shows that a careful control of the slot structural parameters enables the tuning of the GVD characteristics.

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