Analysis of chromatic dispersion in symmetric and asymmetric silicon slot waveguides

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Abstract: We investigate the chromatic dispersion properties of silicon nanophotonic slot waveguides in a broad spectral region centered at ~1.5μm. 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. Symmetric as well as asymmetric geometries are considered. Two different dispersion regimes are identified.

1. Introduction

In general, any silicon-based photonic component is affected by chromatic dispersion. Then, the design and optimization of silicon photonics 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 [1]. 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 [2,3]. In fact, a careful control of the waveguide shape and size allows for the tailoring of the group velocity dispersion (GVD) so that normal, anomalous, or even zero GVD can be achieved in the spectral region centered at ~1.5μm [2,3]. In this contribution, a detailed analysis of chromatic dispersion in silicon slot waveguides is performed. Our study shows that a careful control of the slot geometrical parameters, i. e., width and position, enables the tuning of the GVD characteristics.

2. Dispersion in silicon slot waveguides

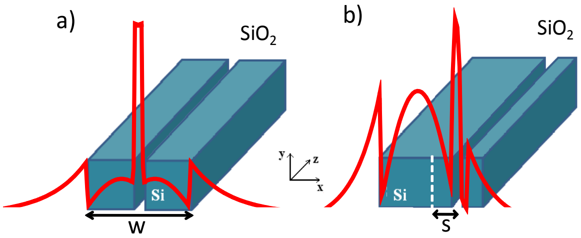

Fig.1. (a) Symmetric slot and (b) asymmetric slot silicon-on-insulator channel waveguides with same cross sectional area. The electric field distribution of the quasi-TE mode in the *x* dimension corresponding to λ=1.55μm is plotted.

The analysis is based on three different cross-sectional areas: 1 μm^2, 0.5 μm^2, and 0.1 μm^2. In addition, for simplicity, a fixed aspect ratio of 1-to-1.5 (height-to-width) will be assumed. 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. In Fig. 1(a), a typical geometry of a symmetric 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. The resultant GVD curves are shown in Fig. 2(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. 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. 2(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. 2(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 a different region that we name geometrical dispersion regime while the fill factors 1:25 and 1:50 present

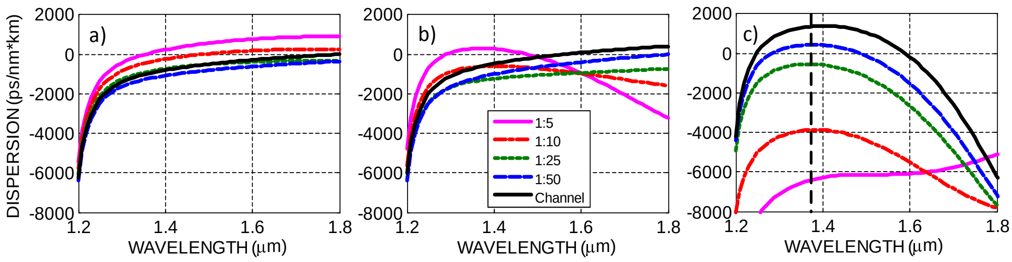

Fig. 2. Group velocity dispersion profiles of symmetric slot waveguides for different slot fill factors. Three different cross-sectional areas have been considered: (a) 1 μm^2, (b) 0.5μm^2, and (c) 0.1μm^2, with a fixed aspect ratio equal to 1:1.5. The dispersion curve of a conventional channel waveguide is also plotted.

GVD curves quite similar to the silicon material dispersion profile. For small cross-sectional areas, 0.1 μm^2, Fig. 2(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 1.4μm. Interestingly, for 1:5 slot fill factor, a dispersion curve with a flat profile is obtained in the ~1.4μm – 1.6μm spectral range.

In asymmetric silicon slot waveguides, the slot location is different than the geometrical center of the waveguide [4], as shown in Fig. 1(b). We define the asymmetry degree as k=2s/w, where s is the distance from the center of the waveguide to the center of the slot, in absolute value, and w/2 is half of the total width of the waveguide. We have analyzed the GVD for different asymmetry degrees, namely, k = 0, 0.25, 0.5, and 0.75 while keeping the same cross-sectional area. Figure 3, shows the results from numerical simulations for the three different above introduced cross-sectional areas with a fixed slot fill factor of 1:10. In general, we note in the figure that the GVD is more sensitive to asymmetry changes when smaller cross-sectional areas are considered. For large areas, 1 μm^2, Fig. 3(a), the waveguide always operates in the material dispersion regime and a small change in the GVD is observed when the asymmetry degree is increased. For intermediate areas, 0.5 μm^2, more significant changes are found in the GVD. In Fig. 3(b), by starting in the geometrical dispersion regime, a change in the asymmetry degree modifies the dispersion profile in such a way that the maximum-dispersion wavelength shifts to longer values. For larger asymmetry degrees, k = 0.75, the GVD is switched from the geometrical to the material dispersion regime. Finally, for small cross-sectional areas, 0.1 μm^2, we find a significant larger GVD variation compared with previous examples. Note the different scales in the dispersion axis. In Fig. 3(c) the waveguide exclusively operates in the geometrical dispersion regime for all the asymmetry degrees but exhibits a variation in the maximum-dispersion wavelength.

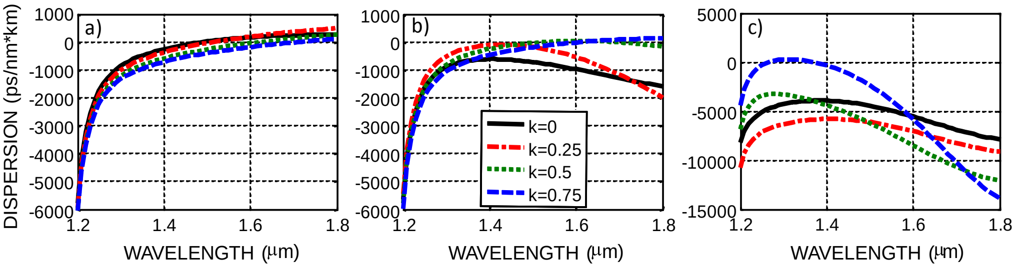

Fig. 3. Dispersion profiles for different asymmetry degrees. Three different cross-sectional areas are considered (a) 1 μm^2, (b) 0.5 μm^2, and (c) 0.1 μm^2. The aspect ratio and the slot fill factor is 1:1.5 and 1:10, respectively.

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