Dual width waveguides for all-integrated giant group velocity dispersion

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It is known that coupled waveguide structures exhibit a resonant giant group velocity dispersion (GVD) phenomenon. Through simulations we demonstrate that giant GVD can be realized in a dual-layer InP waveguide platform where coupled waveguides of different widths are stacked on top of each other. The simulations demonstrate how the platform supports tailoring of the sign and value of the dispersion. It is also shown that it is possible to achieve more than one order of magnitude improvement in GVD compared to dispersion in single layer waveguides. To enable practical dispersive circuits a set of efficient mode converters are also proposed and simulated.

Introduction

Dispersive elements can have a multitude of applications including ultrafast pulse processing. Components such as arrayed waveguide gratings (AWGs) and Eschelle gratings can be realized in integrated photonic platforms. However, the output of such components is a discrete spatial sampling of the input's frequency spectrum. For certain applications dispersive waveguides would be an advantage as an analogue to fiber dispersion. A primary challenge is to achieve sufficient dispersion in planar photonic waveguides.

Giant group velocity dispersion (GVD) is a resonant phenomena where the waveguide dispersion can exceed the material dispersion by several orders of magnitude. It can be observed in coupled waveguides [1] and the effect has been demonstrated in slab waveguides [2] and ridge waveguides [3]. When two waveguide modes with propagation constants that coincide at a certain wavelength are coupled, these modes can only exist as linear combinations of an asymmetric and a symmetric super mode. These super modes exhibit the giant GVD. The GVD of these super modes have opposite sign and thus full flexibility is afforded in engineering of value and peak dispersion bandwidth.

In this paper we show simulations of a dual layer dual width waveguide geometry exhibiting giant GVD and which is integrable in an InP photonics platform. We also show a design to selectively excite the super modes. The simulations have been performed using a commercial mode solver [4].

Dual width waveguides

Dispersion in optical waveguides depends on the waveguide material as well as the geometry. The geometry of dual layer waveguide structures has been shown to exhibit strong GVD in certain resonant super modes [1]. We propose that giant GVD can be practically realized in a dual width geometry as illustrated in fig. 1a. The proposed waveguide is composed of an upper and lower waveguide core with the upper core having a width w_1

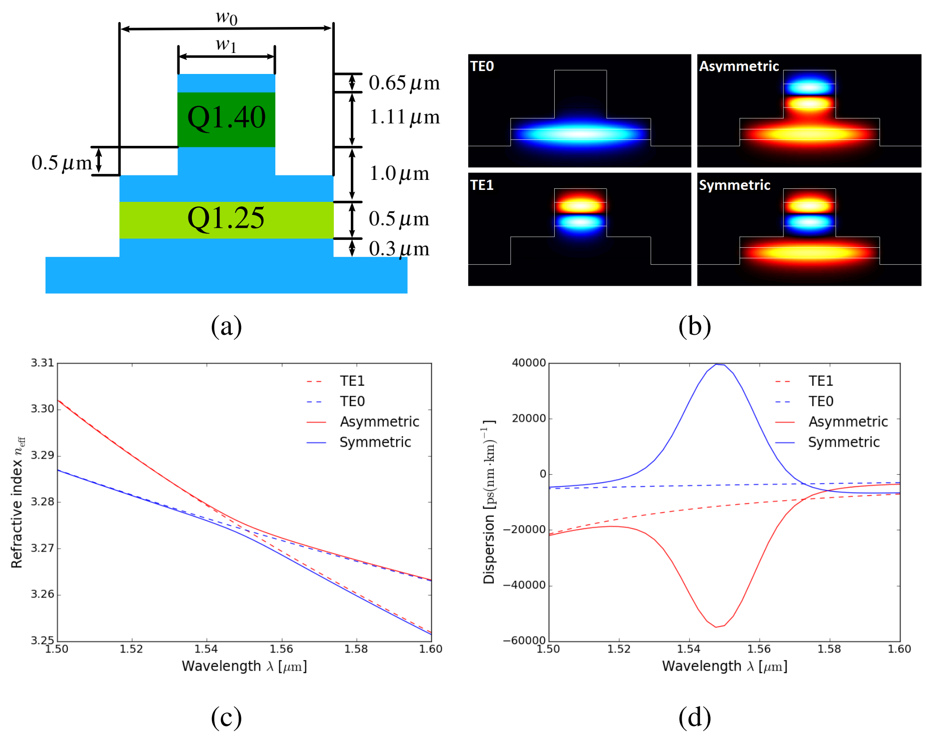
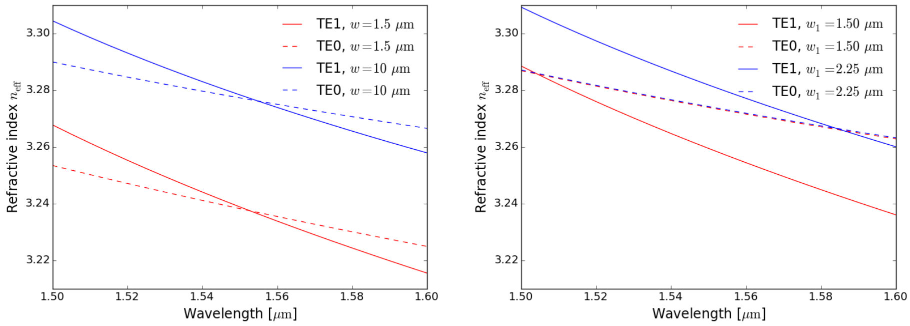


Figure 1: (a) Crossections of dual layer, dual width InP/InGaAsP based waveguide and (b) corresponding horizontal electric field distribution for the uncoupled modes (TE0 and TE1) and the super modes (asymmetric and symmetric.) (c) Dispersion relation and (d) calculated dispersion for the same modes.

that is smaller than the lower core's width w_0. This approach allows the effective refractive index of each core to be individually tuned, enabling the resonance wavelength to be more freely designed. The design of the lower core is chosen to match existing generic InP photonic platforms, retaining compatibility with existing component designs.

The giant GVD occurs at a wavelength where the effective refractive index n_0 of a mode in the lower waveguide core equals the effective refractive index n_1 of the upper waveguide core. Furthermore, the magnitude of the enhanced GVD depends on the difference of the slope of the dispersion relation of the two modes. Similar modes would have similar slopes and would require similar waveguide parameters in order to have an intersection point. Thus modes of different orders are selected as well as having different core material compositions. Here we choose to use the first order TE0 mode in the bottom waveguide as is shown in fig. 1b. The same figure also shows the TE1 mode that is chosen for the upper waveguide core. Using higher order modes in the upper waveguide would increase the layer thickness and etch depths.

When taken in isolation, these two modes, TE0 and TE1, have dispersion relations $n_{0,1}(\lambda)$ as shown in fig. 1c. That is, the dispersion relation has been calculated for the TE0 mode with the upper core substituted with InP and for the TE1 mode with the lower core substituted with InP. The plot also shows the dispersion relation of the super modes which appear when the waveguides are coupled. The super modes come in pairs with an asymmetric and a symmetric mode distribution as seen in fig. 1b and they are similar to the superposition of the TE1 and TE0 mode. The terms asymmetric and symmetric refer to the symmetry along the vertical axis of the mode profile. These illustrations of the modes are taken at resonance; off resonance, the majority of the energy will be distributed



(a) (b)

Figure 2: Dispersion relation of TE0 and TE1 modes for (a) single width waveguide ($w = w_0 = w_1$, 1.01 μm upper core thickness) and (b) dual width waveguide.

in either the upper or the lower core and the mode distribution will approach either the TE1 mode or the TE0 mode. This can be understood from the dispersion relation in fig. 1c where in the limits away from the resonance, the dispersion relation of the super modes converge on the dispersion relation of the isolated TE0 and TE1 modes. Near the intersection point of the TE1 and TE0 mode, there is a bending for the asymmetric and symmetric super modes. Since GVD depends on the second derivative of the dispersion relation, this bending is the source of the super mode's giant GVD. The intersection point and GVD peak is designed to be at 1.55 μm by choosing $w_0 = 5\,\mu$m and $w_1 = 1.877\,\mu$m.

Figure 1d shows the associated GVD as a function of wavelength. Again, the super modes converge on the TE0 and TE1 modes at the limits. The higher dispersion in the TE1 mode over the TE0 mode is attributed to higher material dispersion in the top core. Peak dispersion is near 1.55 μm with peak values of 40 000 $\text{ps}\,\text{nm}^{-1}\,\text{km}^{-1}$ and $-55\,000\ \text{ps}\,\text{nm}^{-1}\,\text{km}^{-1}$. In comparison, the isolated TE0 mode—which can be considered a generic ridge waveguide—has a GVD of $-3800\ \text{ps}\,\text{nm}^{-1}\,\text{km}^{-1}$. It is also crucial to note that for these super modes the sign of the GVD can be either positive or negative. In contrast, generic ridge waveguides are dominated by the strong negative material dispersion of InGaAsP. Thus, dual layer super mode waveguides extends the functionality of generic waveguides.

The advantage of this dual width structure is that a single layer stack allows design over a larger wavelength range compared to the single width case (i.e., $w_0 = w_1$) which has been previously proposed [3]. Figures 2a and 2b show the dispersion relation for the upper and lower cores in isolation for both the single width and dual width geometries, respectively. Since GVD resonance will occur at the intersection point, fig. 2a shows that in the single width case a variation in the width w from 1.5 μm to 10 μm gives a bandwidth (i.e., distance between intersection points) of less than 5 nm. In contrast, fig. 2b shows that a dual width geometry with a bottom width of $w_0 = 5\,\mu$m and a top width w_1 between 1.5 μm and 2.25 μm covers an 80 nm band. Thus the dual width geometry has a much larger design range for the giant GVD resonance wavelength.

Mode excitation

Converting from the fundamental mode of a waveguide which only contains the lower core into the super modes of the dual width waveguides can be achieved using a simple

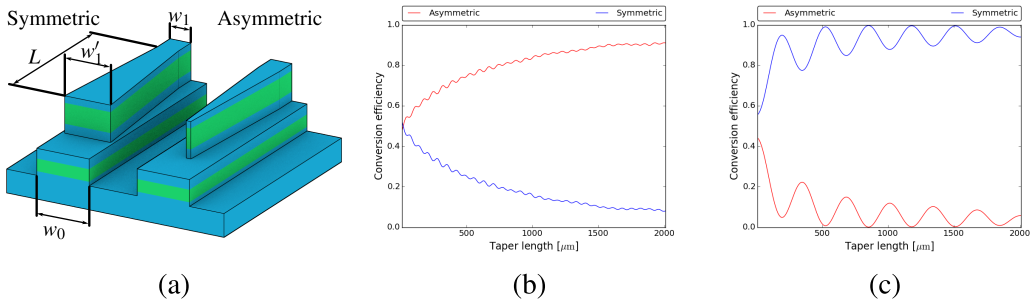


Figure 3: (a) Tapered mode converter for exciting the symmetric and asymmetric super modes. Conversion efficiency as a function of taper length for converters with taper start width of (b) $w'_1 = 1.0\,\mu$m and (c) $w'_1 = 2.2\,\mu$m.

butt joint. High conversion efficiency, however, corresponds to an off resonance, low dispersion mode as the super modes then converge on the TE0 mode. At short wavelengths the symmetric super mode approaches the TE0 mode and is confined to the lower core while at long wavelengths the asymmetric super mode approaches the TE0 mode. This effect can be used to selectively excite either one of the two super modes at a butt joint between a single layer waveguide and a dual layer waveguide. At the width where GVD resonance occurs, the TE0 mode couples equally into the asymmetric and symmetric super modes. By tapering the upper core to this width, it is possible to transform the mode from the off resonant mode distribution confined only in the lower core to the on resonant distribution which exhibits the giant GVD. Such devices are illustrated in fig. 3a. Choosing $w'_1 = 2.2\,\mu$m and $w'_1 = 1.0\,\mu$m for the symmetric and asymmetric mode converters requires mm length scales for 90% coupling efficiency. This can be seen in the plots of conversion efficiency vs. taper length in fig. 3b and fig. 3c. The oscillations in fig. 3c are attributed to the excitation of both super modes with mismatched phase velocities causing them to interfere and the energy to oscillate between the two waveguide cores. The geometry of these tapers has not been optimized, but serves as proof of concept.

Conclusion

We have shown how giant GVD can be achieved in dual layer, dual width waveguides. They show an order of magnitude increase in dispersion compared to generic waveguides and support both positive and negative GVD. Selective excitation of the giant GVD modes is demonstrated with high coupling efficiency using mm-scale linear tapers.

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