Broadband near-zero dispersion with multiple mode couplings

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Abstract: We present a thin silicon nitride waveguide array that achieves a broadband near-zero dispersion profile at near-infrared (1350 – 1800 nm). Multiple mode couplings are introduced at four different wavelengths by coupling different orders of modes.

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Controlling dispersions of a photonic waveguide is essential in many nonlinear optical processes, as it helps to satisfy the required phase-matching conditions for various frequency conversions [1–7]. Among other dispersion profiles, a broadband near-zero dispersion is highly desired in many parametric processes such as supercontinuum and Kerr frequency comb generations, as it naturally matches the phases among other frequencies. In earlier works, various silicon (Si) slot waveguides [2, 3] have been explored to achieve near-zero dispersion profiles. However, Si is not an ideal material for on-chip nonlinear processes as it has a strong two-photon absorption. Alternatively, silicon nitride (Si_3N_4) has a high nonlinearity and low two-photon absorption coefficient, and it has been widely used for Kerr frequency comb [4] and supercontinuum [5, 6] generations. However, for a near-zero or anomalous dispersions at near-infrared, a thick Si_3N_4 film thickness ($>$ 600 nm) is required, which is prone to crack due to its high film stress and is not compatible with the current complementary metal-oxide-semiconductor (CMOS) technology. Thus, for the full integration of Si_3N_4 devices with the CMOS foundry, an advanced dispersion engineering method is required on a thin Si_3N_4 waveguide. Here, we present a thin (300 nm) Si_3N_4 waveguide array design, which is compatible with the CMOS technology and achieves a broadband near-zero dispersion at near-infrared. Multiple mode couplings are introduced to engineer dispersions at four different wavelengths, covering the wavelengths of 1350 – 1800 nm.

Figure 1 shows the cross-section of the proposed waveguide array with geometric parameters. Five Si_3N_4 waveguides (blue) are arrayed with different widths and gaps, and they are cladded with a SiO_2 (gray). The thickness of the waveguide array is set to h=300 nm, which is compatible with the current CMOS foundry [4]. The first two Si_3N_4 on the left (with w_1-g_{11}-w_1) form a single slot waveguide mode (TE_{slot}), which has a faster group velocity than other transverse-electric (TE) modes. The idea here is to couple different orders of modes at different wavelengths, so the widths of the other waveguides are increased gradually to allocate a higher order mode in a consecutive waveguide. More specifically, the fundamental TE (TE_0) mode is allocated to the waveguide with the width w_2 (right side of the slot waveguide), the first-order TE (TE_1) mode to the waveguide with the w_3, the second-order TE (TE_2) mode to the waveguide with the w_4, and the third-order TE (TE_3) mode to the waveguide with the w_5.

The widths of the waveguides are engineered in such a way that they couple with the adjacent waveguide modes at different wavelengths. A mode coupling happens when the effective refractive indices (n_{eff}) of the two different modes are matched [1, 7]. In our configuration, different orders of modes are used to match the refractive indices, and the wavelength of a mode coupling is engineered with different combinations of waveguide widths. First, we fixed the slot waveguide geometries (w_1 = 805 nm and g_{11} = 120 nm) and plotted the n_{eff} of TE_{slot} mode as a function of wavelength, along with the n_{eff} of TE_0 mode with different widths. Then, we could find the waveguide width that gives a mode coupling at the desired wavelength. Our goal is to introduce a mode coupling at near-infrared and we chose w_2 = 1080 nm to introduce the first mode coupling between the TE_{slot} and TE_0 modes at $\lambda_1 \approx$ 1430 nm. Then, we followed the same approach to choose the w_3 = 2560 nm for the second mode coupling between the TE_0 and TE_1 modes at $\lambda_2 \approx$ 1580 nm. The whole step was repeated to find the other waveguide widths for the TE_2 and TE_3 modes, and the w_4 =

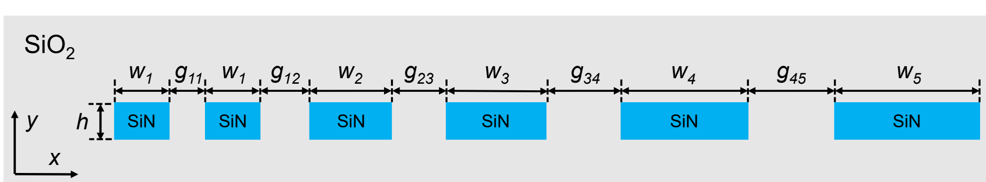

Fig. 1: Schematic cross-section of the waveguide array (blue: Si_3N_4 waveguides, grey: SiO_2 cladding). The heights of the waveguides are fixed to h=300 nm, and the waveguides widths (w_i) and gap sizes (g_i) are engineered to achieve multiple mode couplings.

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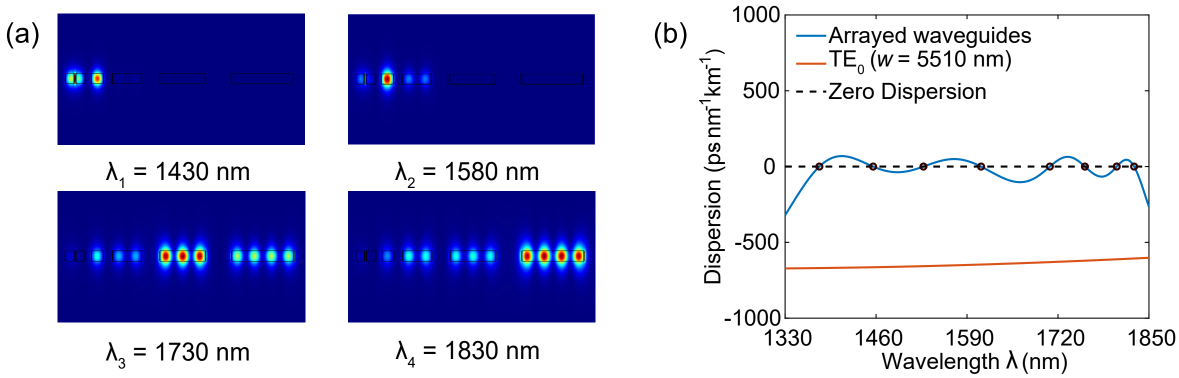

Fig. 2: (a) Normalized electric fields ($|\boldsymbol{E}|$) of the coupled modes at the coupling wavelengths at λ_1=1430 nm, λ_2 = 1580 nm, λ_3 = 1730 nm, and λ_4 = 1830 nm. Gradual mode transitions from the TE_{slot} to TE_0, TE_1, TE_2, and TE_3 are shown. (b) Simulated and optimized near-zero dispersion profile (blue solid). The dashed black line indicates the zero dispersion and the circles show the exact zero dispersion wavelengths. The dispersion profile of a TE_0 mode (h = 300 nm and w = 5510 nm) is shown with an orange solid line for a comparison.

4000 nm and w_5 = 5510 nm are chosen to introduce the third and fourth mode couplings at $\lambda_3 \approx$ 1730 nm and $\lambda_4 \approx$ 1830 nm, respectively. These mode couplings can be visualized from the simulated mode profiles, and Fig. 2(a) shows the normalized electric fields ($|\boldsymbol{E}|$) at each mode coupling wavelength. For the simulations, we used an eigenmode solver considering the material dispersions of both Si_3N_4 and SiO_2.

The blue line in Fig. 2(b) shows the optimized dispersion profile of the waveguide array with four mode couplings. For comparison, the dispersion profile of a TE_0 mode in a strip waveguide (h = 300 nm and w = 5510 nm) is also plotted with an orange line, which shows a normal dispersion. This is a typical dispersion profile of a thin (<300 nm) Si_3N_4 waveguide that prevents it from being used in many nonlinear applications such as supercontinuum generations and Kerr frequency combs. Here, a mode coupling can induce an anomalous dispersion to the anti-symmetric mode and leverages a normal dispersion to a near-zero dispersion by properly controlling the coupling strength. The maximum magnitude of the dispersion peak is inversely proportional to the coupling strength (or coefficient), which can be engineered by the gap size between the two coupling modes. There is a trade-off between the dispersion peak and the bandwidth of a mode coupling; i.e., a stronger coupling induces a lower dispersion peak but a broader bandwidth, and it is opposite for a weaker coupling [7]. Our goal in this work is to introduce a broadband near-zero dispersion profile on a thin Si_3N_4 film (whose base dispersion profile is normal); thus, we introduce multiple mode couplings, whose coupling coefficients are as strong as possible (for a broader bandwidth) but are weak enough to show slight anomalous dispersions. Considering these characteristics of mode coupling, we optimized the gap sizes to be g_{12} = 525 nm, g_{23} = 750 nm, g_{34} = 1620 nm, g_{45} = 2260 nm, which show the flattened near-zero dispersion profile of the blue line in Fig. 2(b). The black circles indicate the wavelengths of the exact zero-dispersion-wavelengths, and there are eight zero-dispersion-wavelengths with four mode couplings.

In summary, we proposed a thin Si_3N_4 waveguide array that involves multiple mode couplings to achieve a broadband near zero dispersion at near-infrared. The resultant dispersion is within $\pm$70 ps/nm/km with eight zero-dispersion-wavelengths over a bandwidth of 520 nm. The thin Si_3N_4 film thickness allows the structure to be compatible with the CMOS process, and its broadband near-zero dispersion profile should be useful in on-chip supercontinuum generations.

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