Dispersion tailoring of a silicon strip waveguide employing Titania-Alumina thin-film coating

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***Abstract*—We numerically demonstrate dispersion tailoring of a silicon strip waveguide employing Titania-Alumina thin-film coating using a finite-difference mode solver. The proposed structure exhibits spectrally-flattened near-zero anomalous dispersion within the telecom wavelength range. We also numerically predict the wavelength conversion efficiency for degenerate four-wave mixing, and obtain a 3 dB bandwidth of 80 nm.**

I. Introduction

In the past decade, silicon waveguides have, due to mature fabrication methods, shown a large potential in monolithically integrating all-optical communication systems on-chip [1]. Silicon waveguides have tailorable dimension, high refractive index contrast, strongly nonlinear interaction, and are naturally used in third-order nonlinear processes, e.g. degenerate four-wave mixing (FWM) that enables wavelength conversion [1]. Efficient FWM takes place when phase matching is satisfied, which requires anomalous dispersion to cancel the Kerr-induced phase-shift. Furthermore, near-zero dispersion enables broadband FWM processes, while spectrally-flattened dispersion may also be applied, for example supercontinuous generation [2].

Silicon strip waveguides, made from silicon-on-insulator(SOI) wafers, usually have the height fixed by the silicon layer thickness. Therefore dispersion tailoring, in essence, is to optimize the core width W to design the frequency-dependent propagation constant $\beta(\omega)$. As this optimization involves only a single degree of freedom, it remains a challenge to achieve spectrally-flattened, near-zero, and anomalous dispersion simultaneously. To mitigate this, we propose a structure using Titania-Alumina thin-film coating in-between the core and the cladding, while such a structure might also be useful for other applications that require a high degree of dispersion control [3].

II. Dispersion tailoring

As shown in Fig.II inset, the proposed structure has a rectangular-shaped silicon core, with a height of $H = 250$ nm and a variable width of W. Titania [4] and Alumina [5] thin-film layers of 50 nm are deposited on both the top and side surface of the silicon core, and then covered by a silica cladding with a thickness of around 1 μm. The refractive index is designed to reduce in each region from the core to the cladding to prevent slot-modes [6].

Through a finite-difference mode (FDM) solver [7], we simulate β_2 at 1550 nm versus core width in the proposed structure (see Fig.II blue solid), and in a silica-cladded structure (see red dashed) for comparison. Note that we use the second-order derivative of the propagation constant with respect to frequency $\beta_2(\omega)$ to quantify dispersion, and only focus on the fundamental transverse electric (TE) mode that has anomalous dispersion at 1550 nm. When W is in-between 400 nm and 550 nm, the structure with coating exhibits anomalous dispersion, with a maximum absolute value $|\beta_2|$ of 0.18 $\mathrm{ps^2/m}$ ($W = 450$ nm). When W is in-between 380 nm and 680 nm, the structure without coating exhibits anomalous dispersion, with a maximum absolute value of $|\beta_2| = 1.4$ $\mathrm{ps^2/m}$ ($W = 450$ nm). In this extreme case, $|\beta_2|$ with coating reduces to one-eighth of that without coating, proving that thin-film coating can efficiently be used to tailor SOI waveguides for near-zero anomalous dispersion.

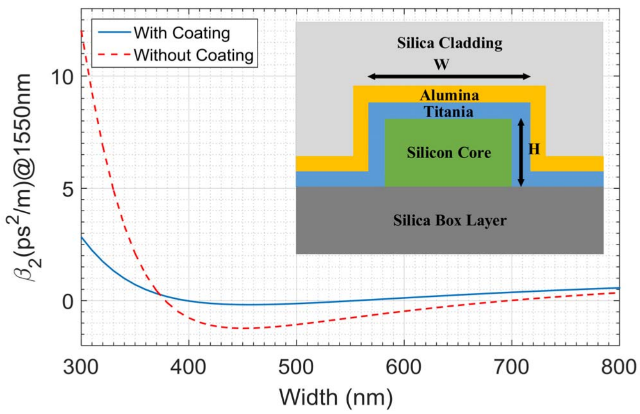

Fig. 1. Simulation of β_2 at 1550 nm versus core width for the structures with/without thin-film coating. The inset is the cross section of the proposed structure.

The refractive index of the coating depends on the investigated thin-film materials. It is possible to tailor dispersion by varying the thickness of each layer. We simulate β_2 versus wavelength in the telecom range (1460 nm-1625 nm) based on a core dimension of 250 nm $\times$ 450 nm. As shown in Fig.II, β_2 tends to be positive when the thickness of Titania layer T_t increases from 20 nm (blue solid), 50 nm (black solid) to 80 nm (red solid), where the thickness of Alumina layer T_a is conformally 50 nm, vice versa. Note that when T_t and T_a have the same thickness of 50 nm, β_2 is not only near-zero in the anomalous region, but also spectrally-flattened. The

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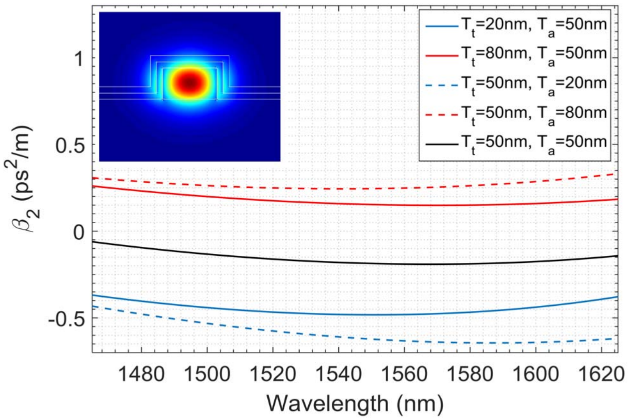

Fig. 2. Simulation of β_2 versus wavelength at different Titania (T_t)and Alumina (T_a) layer thickness. The inset shows an example of the TE mode profile.

maximum $|\beta_2|$ is $0.19\ \mathrm{ps}^2/\mathrm{m}$ at $1570\ \mathrm{nm}$, and $|\beta_2|$ for other wavelengths are even smaller. As shown in Fig.II inset, a part of fields leaks into the coating. However, the mode is still well confined in the silicon core, i.e., the effective mode area in the proposed structure is $0.75\ \mu\mathrm{m}^2$, which is slightly larger than that of the corresponding silica-cladded structure of $0.67\ \mu\mathrm{m}^2$. Although the expanded mode profile leads to a reduction of nonlinear interaction, the proposed structure has a dispersion that enables efficient FWM in a large spectral range which is useful for broadband wavelength conversion.

III. FWM WAVELENGTH CONVERSION EFFICIENCY EVOLUTION

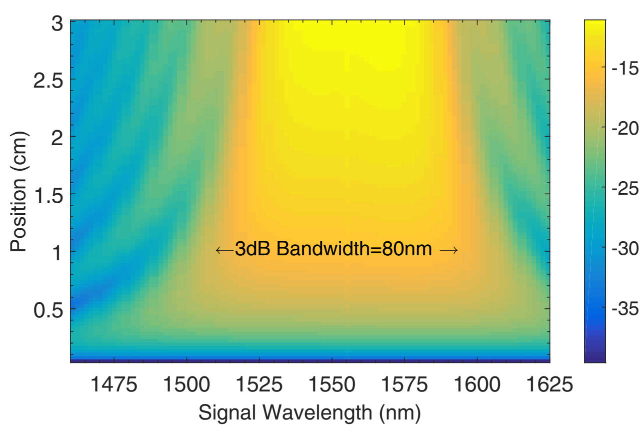

Fig. 3. Simulation of CE evolution along the longitudinal position of waveguide, pumped at $1550\ \mathrm{nm}$ with power of $20\ \mathrm{dBm}$, while signal is tuned in telecom range with power of $0\ \mathrm{dBm}$. We assume the propagation loss of $3\ \mathrm{dB/cm}$ and a free carrier lifetime of 10 ns. Other parameters are in Ref.[8]

Using the model and the parameters of Ref.[8], we predict the wavelength conversion efficiency CE of the proposed waveguide structure. Conversion efficiency, given by the ratio of the idler and signal power in each longitudinal position, is often used to quantify FWM evolution, while the $3\ \mathrm{dB}$ bandwidth describes the spectral range with efficient wavelength conversion. As shown in Fig.III, the maximum CE increases with propagation until a position of $1.6\ \mathrm{cm}$, and then saturates. The $3\ \mathrm{dB}$ bandwidth reduces, that is, parametric gain concentrates towards the pump in the frequency domain. For example, at a position of $1\ \mathrm{cm}$, the $3\ \mathrm{dB}$ bandwidth is $80\ \mathrm{nm}$ with a maximum CE of -17 dB. While the maximum CE is smaller than that in the corresponding silica-cladded structure ($-15\ \mathrm{dB}$), the $3\ \mathrm{dB}$ bandwidth increases by a factor of 2 ($36\ \mathrm{nm}$ for a silica-cladded structure). In addition, $3\ \mathrm{dB}$ bandwidth of the CE is around or even wider than $80\ \mathrm{nm}$ when the pump is tuned in the telecom wavelength range.

IV. CONCLUSION

In conclusion, we propose a silicon strip waveguide structure employing Titania-Alumina thin-film coating that exhibits spectrally-flattened, near-zero, and anomalous dispersion in the telecom wavelength range. This method of dispersion tailoring is feasible and reproducible based on the SOI-compatible approaches, and can be further generalized in other on-chip platforms. The simulations also reveal that the proposed structure can be applied in broadband wavelength conversion.

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