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طراحی بهینه موجبر سیلیکونی با شرایط غیرخطی زیاد و پاشندگی فوق العاده مسطح برای کاربردهای غیرخطی

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چکیده - در این مقاله، موجبری سیلیکونی ارائه می‌شود که با تنظیم پارامترهای ساختاری آن، مقدار پاشندگی و تغییرات آن در سرتاسر پهنای باند به طور قابل ملاحظه‌ای کاهش یافته است، به گونه‌ای که پاشندگی سرعت گروه برای پهنای باندی در حدود *350 nm* **بین دو مقدار بسیار کم** *-1.1* **و** *+3.3 ps/(nm.km)* **تغییر می‌کند. به دلیل فوق‌العاده مسطح بودن منحنی پاشندگی سرعت گروه، پاشندگی‌های مراتب بالاتر نیز، برای ساختار بهینه دارای مقادیر بسیار کمی هستند. بخش حقیقی پارامتر غیرخطی برای موجبر بهینه در طول موج** *1550 nm*، *355.6 ($W^{-1}m^{-1}$)* **است. بنابراین، توازن مناسبی بین پارامتر غیرخطی و پاشندگی در این موجبر برقرار شده است که آن را برای کاربردهای غیرخطی با بازده بالا، در محدوده طول موجی** 1.55-µm **مناسب می‌گرداند.**

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Optimum Designation of a Highly Nonlinear Silicon Waveguide with Ultra-flat Dispersion for Nonlinear Applications

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Abstract- A silicon waveguide is proposed in which dispersion value and its variation is effectively reduced over bandwidth. Dispersion tailoring is performed by tuning the structural parameters of the waveguide. Group velocity dispersion is varied between very low values of -1.1 and +3.3 ps/(nm.km) over an approximately 350-nm bandwidth for an optimum structure. Because of ultra-flat group velocity dispersion profile, higher order dispersions are also very low. Real part of nonlinear parameter for the optimum waveguide is 355.6 ($W^{-1}m^{-1}$) at 1550 nm. Therefore, a good balance between nonlinearity and dispersion is provided that makes the waveguide applicable for highly efficient implementation of nonlinear functions in 1.55-µm wavelength range.

Keywords: Dispersion engineering, integrated optics, nonlinear optics, slot waveguide.

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1 Introduction

In the last few years, nonlinear silicon photonics has attracted many interests. In this regard, silicon waveguides are extensively studied and used because of their high confinement, high nonlinearity, cost-effectiveness and compatibility with CMOS technology [1]. For a wide variety of nonlinear applications such as four-wave mixing [2], soliton formation [3] and supercontinuum generation [4, 5], dispersion tailoring is an essential step in design procedure. However, dispersion engineering of silicon waveguides is a difficult task due to their high index contrast of materials which it causes large waveguide dispersion. Slot silicon waveguides have brought more design freedom not only in dispersion engineering [3-5], but also in nonlinearity tailoring [3, 6]. Recently, a silicon waveguide with a centered slot; made of silicon nano-crystal (SiNC); has been proposed in which nonlinear parameter (γ_{re}) is a high value of 2874 ($W^{-1}m^{-1}$) at 1550 nm. There is a high group velocity dispersion (GVD) of ±160 ps/(nm.km) over a 244-nm bandwidth, and dispersion profile has two zero-dispersion wavelengths (ZDW) [6]. In another work, Zhang *et al*. [4] have presented a strip/slot hybrid silicon waveguide with a silicon dioxide slot. The waveguide exhibits a flat dispersion profile with four ZDWs. Dispersion variation is from -22 to +20 ps/(nm.km) over a 670-nm bandwidth. Nonlinear parameter of the waveguide is almost 100 ($W^{-1}m^{-1}$) at 1550 nm.

In this paper, a strip/slot hybrid silicon waveguide is presented in which dispersion profile has four ZDWs, and dispersion is extremely reduced over bandwidth. On the other hand, nonlinear parameter of the flattened dispersion waveguide is large enough at 1550 nm. It should be pointed out that reduction of dispersion and enhancement of nonlinear parameter are two important aims for utilizing highly efficient phased-matched nonlinear effects, which are reached in this work.

2 Dispersion Tailoring

As shown in Fig. 1, to design a highly nonlinear waveguide, a horizontal SiNC slot is surrounded by two layers of silicon. SiNC is a highly nonlinear material with a Kerr index of 4.8×10^{-17} at 1550 nm [7] (approximately one order of magnitude greater than that of silicon [8]). Substrate of the waveguide is made of SiO_2, and has a 3-μm thick. Cladding layer is considered to be air. Due to large index discontinuity between the slot and the silicon strips, electric field is enhanced in the slot region for the fundamental quasi-TM mode [9]. Power distribution of the fundamental quasi-TM mode for an optimum structure (W=626 nm, HL=307.5 nm, HS=65 nm, HH=90 nm) at different wavelengths is shown in Figure 2.

Simulations are carried out by using finite-element-method. GVD is defined as

$$D = -(\frac{\lambda}{c})(\frac{\partial^2 n_{eff}}{\partial \lambda^2}), \tag{1}$$

and calculated by fitting effective indices to a 9-order polynomial. Material dispersion of Si, SiNC and SiO_2 are taken into account via their sellmeier relations [10-12]. The waveguide's real part of nonlinear parameter is calculated by a full-vectorial model presented in [13]

$$\gamma_{re} = \frac{2\pi\varepsilon_0}{\lambda\mu_0} \frac{\int n^2(x,y) n_2(x,y) [2|e|^4 + |e^2|^2] dA}{3|\int (e\times h^*).\hat{z} dA|^2}, \tag{2}$$

where n is material refractive index, n_2 is Kerr index of materials, and λ is wavelength. It has a high value of 355.6 ($W^{-1}m^{-1}$) at 1550 nm, for the optimum structure.

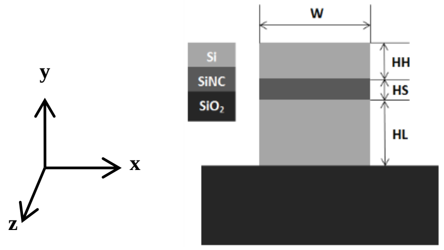

Figure 1: Structure of the waveguide

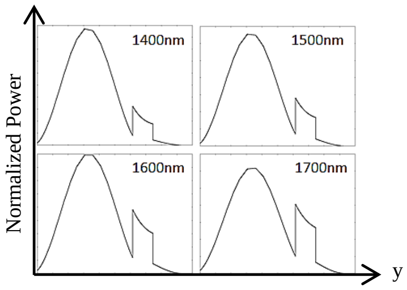

Figure 2: Power distribution of the fundamental quasi-TM mode at different wavelengths

Dispersion engineering is performed by properly tuning the structural parameters of the waveguide. As depicted in Figure 3, a saddle-shaped dispersion profile with four ZDWs is achieved by setting the structural parameters as W=626 nm, HL=307.5 nm, HS=65 nm and HH=90 nm. Ultra-flat and low GVD is varied between -1.1 and +3.3 ps/(nm.km) over a 349-nm bandwidth from 1421 to 1770 nm. ZDWs are located at 1428, 1549, 1642 and 1764 nm. Total dispersion variation is also very low; in such a way that flatness parameter (which is defined as total dispersion variation divided by bandwidth) is 0.0126, considerably lower than that of the previous works [5, 6].

Because of ultra-flat GVD profile and its very low slope, higher order dispersions of the optimum waveguide are also very low. Specifically, third order dispersion (TOD) is studied. As shown in Figure 4, TOD dispersion variation is from -0.4×10^{-3} to 0.088×10^{-3} (ps^3/m) over the bandwidth.

Principle of dispersion tailoring is valuable to be investigated, and can be explained as follows. At short wavelengths, most part of the mode is propagated in the lower silicon layer. Thus, material dispersion of silicon is dominant, and total dispersion is negative. At long wavelengths, more parts of mode power enter to the substrate and cladding layers. As a result, waveguide dispersion is dominant, and makes total dispersion negative. In the middle wavelength range, some unique features, so-called mode transition and anti-crossing effect cause providing additional negative dispersion in the middle of bandwidth and generating another two ZDWs. Thus, a saddle-

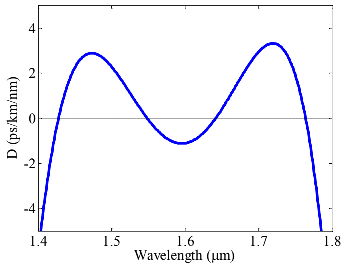

Figure 3: Dispersion profile of the optimum waveguide

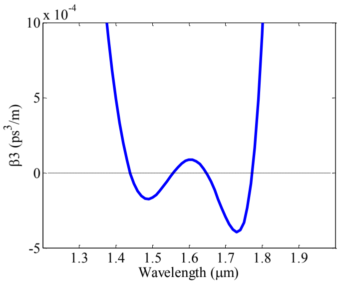

Figure 4: Third order dispersion of the optimum waveguide

shaped dispersion profile with four ZDWs is obtained [4, 6].

To Study effects of each structural parameter on the dispersion properties, it is changed slightly around the optimum value, while the other parameters are constant [4]. As depicted in Figures 5(a) and 5(b), lower and upper silicon heights (HL and HH) can be used for moving dispersion profile into normal or anomalous dispersion regime. Furthermore, total dispersion variation can be efficiently reduced by decrease of HH. This point is utilized here for reduction of total dispersion variation. On the other hand, width of the waveguide (W) and slot height (HS) can be utilized for controlling location of ZDWs and slope of dispersion profile (to control higher order dispersions), as shown in Figures 5(c) and 5(d). Thus, changing the structural parameters of the waveguide provides a valuable space in device design for nonlinear applications.

3 Conclusion

A strip/slot hybrid silicon waveguide with a horizontal SiNC slot was proposed to design a highly nonlinear waveguide. Dispersion is effectively reduced over bandwidth for an optimum structure in comparison with the previous works. On the other hand, real part of nonlinear parameter is large enough. Therefore, the waveguide is suitable for implementing highly efficient phased-matched nonlinear applications such as four-wave mixing based amplification and wavelength conversion.

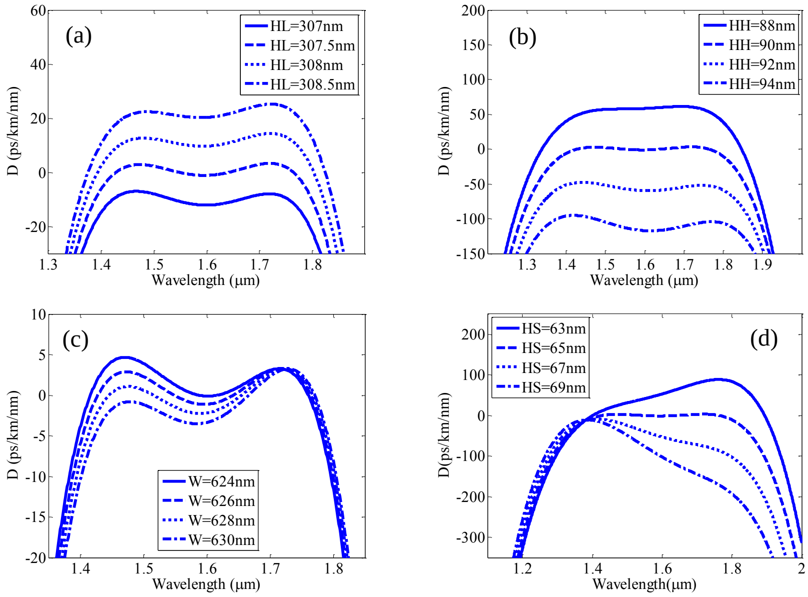

Figure 5: Dispersion profile for different structural parameters

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