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Analysis of Kerr nonlinearity enhancement in silicon nitride waveguides using one-dimensional slow light structure

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ABSTRACT

A corrugated based slow-light silicon nitride waveguide is studied numerically to enhance Kerr nonlinearity by increasing the group index of the waveguide at the band edge. The structure is optimized taking into account the limitations existing in CMOS-compatible platforms. Bandwidth limitations of the structure are investigated at different wavelengths for various slow-down factors. Finite size realizations of the structure are studied using transfer matrix method to obtain the desired transmission and group velocity at the band edge. Optical loss corresponding to slow-light effect is modeled, and the limitations imposed by the slow-light loss on the nonlinear phase shift saturation are considered. It is shown that by employing slow-down factor of 3, the nonlinear phase shift is improved by a factor of 5. Also, in comparison with a straight waveguide, shorter corrugated waveguides (up to nine times) can provide the same accumulated nonlinear phase shift.

1. Introduction

Integrated nonlinear optical signal processing has been proposed for various applications like all-optical sampling, wavelength conversion, and parametric amplification in recent years [1–4]. Owing to its low loss and negligible two-photon absorption (TPA) in Telecom band, silicon nitride (SiN_x) has been introduced as a promising material for this purpose [5,6].

Low loss silicon nitride waveguides have been realized by several researchers over the last few years. For example, a research group at the University of California, Santa Barbara, has realized an ultra-low loss silicon nitride waveguide (at 1550 nm wavelength), with 0.1 dB/m loss using thin (100 nm) waveguides exploiting Triplex technology [6]. Based on these ultra-low loss waveguides, ring resonators with ultra-high quality factor ($Q \approx 81 \times 10^6$ at 1580 nm) have been later realized by the same research group [7].

Lipson's group showed that the stress limitation of the silicon nitride thick film could be overcome using crack resistant trenches. This approach resulted in a low propagation loss (4.2 dB/m). The group also reported a high-quality factor ring resonators ($Q \approx 7 \times 10^6$ at 1550 nm) for 910 nm thick waveguides [8].

Other studies have been reported to improve nonlinear properties of SiN_x waveguides. For example, in one approach, Kippenberg group has realized high confinement Si_3N_4 waveguides with a thickness of up to 900 nm by introducing Si_3N_4 filled trenches in oxide layer [9]. In another technique, Krückel et al. showed that by increasing the silicon content in nitride platform that can be resulted in the higher refractive index (and therefore, higher optical field confinement) and higher nonlinear Kerr coefficient than pure silicon nitride waveguides [10]. Later on, following the similar approach, Ooi et al. improved previous attempts by reporting ultra-silicon-rich nitride in the form of Si_7N_3 possessing a high Kerr nonlinearity of 2.8×10^{-17} m^2 W^{-1} [11]. The same group has also shown the possibility of achieving the enhanced optical Kerr nonlinearity using two-dimensional photonic crystals exhibiting high group index of 22 [12].

The parameter which affects the performance of the devices working on the basis of Kerr nonlinearity in the waveguides (e.g. switches, all optical sampling devices, wavelength converters) is the accumulated nonlinear phase shift (NLPS) [13,14]. Nonlinear phase shift comes from solving Nonlinear Schrödinger Equation (NLSE) [15]. Nonlinear Phase Shift, in general, depends on the waveguide's length, attenuation coefficient, optical input power (P_0), nonlinear Kerr coefficient (n_2) and two-photon absorption coefficient (β_{TPA}). For silicon nitride waveguides, n_2 and β_{TPA} have values of 0.24×10^{-18} m^2 W^{-1} and $\sim$0 cm GW^{-1}, respectively [5]. Nonlinear coefficient (γ) is more often used in nonlinear processes which is related to the nonlinear Kerr coefficient (n_2), the wavelength (λ), and the effective area (A_{eff}) of the waveguide and expressed by $\gamma = (2\pi n_2)/(\lambda A_{eff})$.

To avoid TPA and further free carrier absorption (FCA) and free carrier index (FCI), silicon nitride can be chosen for nonlinear-optic

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Table 1
Dimensions of the proposed waveguides.

Λ [nm]	W [nm]	Thickness [nm]	L_{cor} [nm]	W_{cor} [nm]
500	540	300	250	270

applications. For instance, Kerr nonlinearity and low loss silicon nitride waveguides are being widely used in realizing the microresonator Kerr frequency combs [16–18]. Furthermore, it is obtained that nonlinear coefficient of a silicon nitride waveguide is almost two orders of magnitude smaller than silicon (taking into account the larger dimensions of silicon nitride waveguides in comparison to silicon waveguide) [5]. Therefore, the required length of a silicon nitride waveguide to achieve a specific nonlinear phase shift is greater than that of silicon by the same amount of nonlinear phase shift.

To enhance the nonlinear Kerr effect in silicon nitride waveguides and to increase, specifically, the nonlinear phase shift in silicon nitride, the slow-light effect is employed in this paper. The design of one-dimensional silicon nitride slow-light waveguides is investigated to decrease the required length for achieving certain NLPS. The slow-light effect performance can be quantified by introducing an index called slow-down factor. Slow-down factor (S) is defined as the ratio of the group index in the presence of slow-light effect to the group index of the waveguide out of slow-light regime [19]. Two different approaches are used to study the designed slow-light structures in this paper. First, an infinite length of the waveguide is analyzed in terms of group index and bandwidth. Then, a finite length of the waveguide is studied to determine the loss in the desired practical case of the slow-light structure. Next, the modeled optical loss of slow-light effect is employed to predict the NLPS behavior accurately. Finally, the effect of slow-light structure on the nonlinear phase shift of silicon nitride waveguides is studied. It is shown that if a structure with higher slow-down factor is used, shorter length of the waveguide is required to provide the desired NLPS [20].

Although many, traditionally two-dimensional photonic crystals have been used to provide the structural slow-light effect [21,22], in this study, we focus on enhancing Kerr nonlinearity in silicon nitrides using the one-dimensional photonic crystals namely, corrugated waveguides, to reduce on-chip area. Therefore, the waveguide size is shrunk from a typical cross-sectional footprint of 5 μm^2 at two-dimensional photonic crystals to 0.2 μm^2 at corrugated waveguides used in this research.

2. Analysis of slow-light waveguides

2.1. Infinite size study

Corrugated waveguides are employed in order to realize the slow-light waveguides. Thus, a periodically corrugated silicon nitride waveguide (with a refractive index of 1.98) buried in silicon dioxide (with a refractive index of 1.44) is used to slow down the group velocity of light in the band edge frequency, and therefore enhancing the Kerr nonlinearity. The waveguide is shown in Fig. 1(a). Based on the Finite Element Method simulations (using HFSS software), dispersion diagram of the waveguide can be obtained. By operating at the frequencies near the band edge, low group velocities can be achieved. There are four degrees of freedom which can be tuned to achieve the desired slow-light performance. The main parameter which set the frequency at the band edge is the waveguide period. The band edge frequency, as well as slow-down factor, have been finely tuned using waveguide's width, and length and width of the corrugated parts. The structural parameters of the considered corrugated waveguide, to achieve a slow-light condition at the band edge in the desired wavelength (in our case, Telecom wavelength) are shown in Table 1.

The performance of the slow-light waveguides, at the band-edge, would be limited by the slow-light bandwidth. Optical bandwidth of the slow-light waveguide indicates the frequency (or wavelength) range in which the slow-light effect can be effectively exploited. To be consistent with previous works, we define the bandwidth as the wavelength range where group-index variations of plus and negative 10% are tolerated [23,24]. On the other hand, the slow-light waveguide should have enough bandwidth to give to the spectrum of the signals considered to be transmitted along the waveguide. For example, for bit rates of 40 Gbit/s, the structures with a maximum bandwidth higher than 0.8 nm are required [25]. The optical bandwidth for the initial slow-light waveguide is shown in Fig. 1(b). It can be seen that around 0.8 nm (≈100 GHz) optical bandwidth can be achieved at slow-down factor of 3.

The optical bandwidth is decreasing by increasing the frequency at the band edge. Then, the higher group index and, therefore, the larger slow-light effect will be employed. It means we face a tradeoff between bandwidth and slow-down factor. To consider both parameters simultaneously, the idea of normalized bandwidth-delay product figure of merit has been employed [26]. This figure of merit is defined as

$$FOM = \tilde{n}_g \times \frac{\Delta\omega}{\omega_0} \tag{1}$$

where $\tilde{n}_g$ is the average group index, $\Delta\omega$ is the slow-light bandwidth, and ω_0 is the center angular frequency of the slow light, which here is equal to $2\pi \times 193.4 \times 10^{12}$ [rad/s]. Using this definition, we have obtained FOM of 2.4×10^{-3}. We found that the optical bandwidth can be increased to 200 GHz at slow-down factor of 3 by introducing holes perforated in each unit cell. However, due to impractical optical bandwidths of slow-down factors higher than 10, the presented FOM remains in the same order of magnitude which is also in agreement with previously reported results [25].

Although this paper discusses only one-dimensional all dielectric-based slow-light waveguides, the authors believe that it is important to shortly mention the recently reported progress of the normalized bandwidth-delay product figure of merit in other types of slow-light structures as well. For example, it has been shown that the normalized bandwidth-delay product of 0.552 has been achieved in a one-dimensional metal–insulator–metal (MIM) slow-light waveguide [27]. It has also been reported that two-dimensional photonic crystals can be particularly designed in order to obtain a large value of the FOM. The FOM value of 0.3 has frequently been reported [28–30], and to best of our knowledge, the FOM value of 0.38 is the maximum one which has been so far reported [31].

2.2. Finite size study

Although the dispersion diagram could be used to theoretically calculate the band gap and band edge of a periodic structure, it is not precise enough to predict the slow-down factor and optical loss of the practically limited structures. Thus, waveguides with a finite number of unit cells should be simulated afterward. Full-wave simulations can be used to analyze slow-light structures with a limited length which requires large amounts of computing resources. A structure with several unit cells (up to 150 unit cells due to the limited computational resources) is simulated. The finite size transmittance is approaching the transmittance of an infinite photonic crystal structure by increasing the number of unit cells. The group velocity of finite size structures is also studied, and it is also observed that the group velocity is approaching the group velocity of infinite size structure by increasing the number of unit cells. This analysis enables us to predict the minimum number of unit cells which are required to obtain a specific level of group velocity or slow-down factor.

In order to increase the speed of simulations and, also, simulate the slow-light waveguides with more than 150 unit cells, a cascade matrix model is used. A single unit cell is simulated in full wave to obtain scattering parameters. Scattering parameters are converted to Transfer (T)-matrix parameters [32], and the T-matrix of the whole structure is calculated by self-multiplication of the single block T-matrix based