Design of nonlinear SOI slot waveguides

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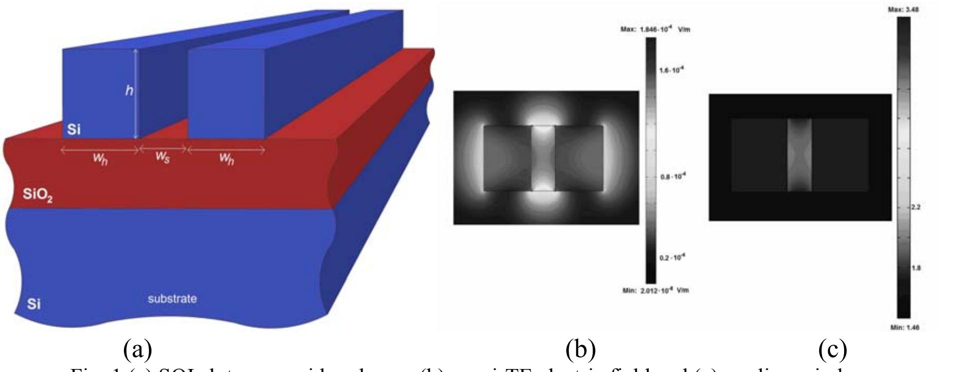
Abstract. *An investigation and optimization of silicon-on-insulator nanometer slot waveguides for nonlinear applications is proposed by using a novel iterative calculation method.*

Introduction

The actual use of existing CMOS-compatible technologies enables Silicon Photonics to exhibit many advantages with respect to III-V semiconductors in terms of high-density integration of photonic devices [1]. At the same time, some kinds of nonlinear optical effects have been observed in silicon waveguides, leading to focus significant attention on device applications using third order optical nonlinearity [2]. Recently, the possibility of guiding light in a low refractive index medium of a waveguide by total internal reflection has been proposed and demonstrated [3] due to an innovative structure, well known as a Silicon-on-Insulator (SOI) slot waveguide, as in Fig. 1(a). It is constituted by two silicon wires spaced by a nanometer low index region (called either slot or gap region), and confined by a silicon oxide layer (SOI substrate). The discontinuity of the electric field on the high index contrast interface between slot and wires causes a high confinement factor in the slot region for quasi-TE mode, whose E_x component is orthogonal to the interface. Using slot waveguides, a great variety of optical devices has been recently proposed and fabricated, including sensors [4]. In such an ultrasmall waveguide, the light intensity is considerably larger than that of conventional optical waveguides, giving a dramatic enhancement of nonlinear optical effects. A stationary modal analysis of nonlinear slot waveguides is presented in this work by a full-vectorial 2D finite element method (FEM) [5], using at least 100,000 triangular mesh elements.
To calculate the nonlinear effective index of quasi-TE mode, an iterative method based on FEM has been implemented and compared with a different approach in literature [6].



(a) (b) (c)
Fig. 1.(a) SOI slot waveguide scheme; (b) quasi-TE electric field and (c) nonlinear index.

Our method consists of solving the full vectorial e.m. wave equation and, then, deriving the refractive index in each region as:

$$n = n_0 \left(1 + \frac{n_2 |\mathbf{E}|^2}{Z_0} \right)^{1/2} \tag{1}$$

where Z_0 is the free-space impedance, and n_0 and n_2 are the linear and non linear refractive indices for each region, respectively. Then, new values of effective index and field distributions are calculated and new refractive index evaluated again by Eq. (1). This iteration is repeated until a fixed effective index tolerance has been reached. The correctness and applicability of the described method has been verified and proved by comparing with other results [6] in terms of nonlinear effective index. The guiding structure used for comparison is a SOI slot waveguide with silicon wires and SiO_2 cover, while the slot (gap) region is filled with silicon nanocrystals (Si:nc), which allow a larger value of n_2 than SiO_2 to be obtained. The physical and geometrical parameters include silicon wire index 3.48, cover and buried oxide index 1.46, slot region index 1.46, slot width 100nm, wire width 200 nm, waveguide height 250 nm, nonlinear index of silicon nanocrystals in slot region 10^{-16} m^2/W, operative wavelength 1550 nm. The nonlinear index has been considered only in the slot region, while all the other materials are assumed as linear, as in [6]. Moreover, the tolerance on successive iterative steps was assumed as 10^{-4}, in order to ensure a sufficient accuracy for the effective index convergence without excessive time consuming. After setting the simulation parameters, modal analyses for estimating the quasi-TE effective index versus input power have been performed.

Numerical results

As an example, the graphs in Fig. 1(b-c) show the field distribution module $|\mathbf{E'}|$ for a linear waveguide (i.e. $n_2 = 0$), and the nonlinear refractive index in gap region, as given by Eq. (1), respectively. A linear effective index of 1.728703, in very good agreement with 1.729706 given in [6], has been evaluated. Calculation of quasi-TM mode shows an effective index of 1.755593, very similar to 1.755922 [6]. In Fig. 2 the convergence of iteration method is sketched. Clearly the number of iterative cycles, required to reach the fixed tolerance, depends on the input power P. In fact, six cycles are needed for $n_2^{nc}P =$ 0.01 μm^2, while the cycles are up to 23 for $n_2^{nc}P$=0.04 μm^2. After the final nonlinear effective index n_{eff}^{NL} is found, the nonlinear phase shift per unit length is calculated as:

$$\Delta\phi_{slot} = \frac{2\pi}{\lambda_0}\left(n_{eff}^{NL} - n_{eff}^{L}\right) \tag{2}$$

where n_{eff}^{L} is the linear effective index and $\Delta\phi_{slot}$ stands for a phase change depending on nonlinear material in the slot region. Then, $\Delta\phi_{slot}$ versus product $n_2^{nc}P$ has been compared with results in [6], as illustrated in Fig. 2(b). It can be noted a remarkable agreement at low input powers. In fact, the graphs are substantially identical for $n_2^{nc}P \le 0.02$ μm^2, but the other method tends to overestimate $\Delta\phi_{slot}$ when $n_2^{nc}P > 0.02$ μm^2. In fact, our phase difference is 13% smaller than in [6] for $n_2^{nc}P =$ 0.04 μm^2. This result is satisfactory, because larger input powers are unlikely due to possible optical damage and necessity of high quality light sources with large intensity.

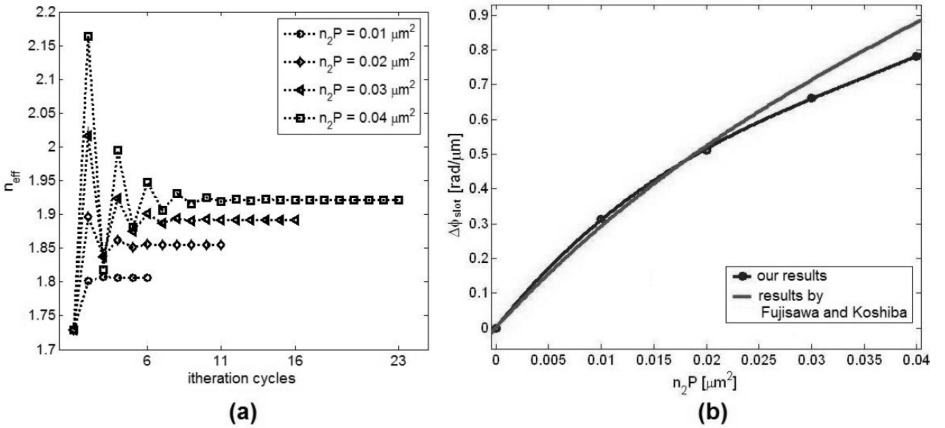


Fig. 2.(a) Quasi-TE effective index versus iteration cycles for various $n_2^{nc}P$ (tolerance 10^{-4}); (b) nonlinear phase difference per unit length versus $n_2^{nc}P$: by our method and as in [6].

The above results are relevant to a medium nonlinearity only in the slot region, i.e. where the transversal electric field of quasi-TE mode is at least one order of magnitude larger than in the other regions. Although only a slight influence on the guided field is expected, nonlinearities are to be considered in the whole domain, allowing a more accurate analysis of nonlinear phase change $\Delta\phi_{glob}$ to be carried out, closer to real case. For instance, $\Delta\phi_{glob}$ is defined as in Eq.(2) including nonlinearities in each material and Si:nc nonlinear index $3\cdot 10^{-17}$ m^2/W [7]. Then, the results show a linear increase of $\Delta\phi_{glob}$ with increasing the input power, the slope varying with geometrical parameters (slot width, wire width and height). However, the trend of $\Delta\phi_{glob}$ as a function of waveguide height h and wire width w_h is surprisingly different from that expected. Results can be seen in Fig. 3(a-b) in terms of nonlinear phase shift and effective area (A_{eff}) versus h and w_h, being A_{eff} defined as [8]:

$$A_{eff} = \frac{\left(\iint\limits_{\mathbb{R}^2} \left| \mathbf{E}(x,y) \right|^2 dx\, dy \right)^2}{\iint\limits_{slot} \left| \mathbf{E}(x,y) \right|^4 dx\, dy} \tag{3}$$

It can be observed the different trend of linear effective area and nonlinear phase shift versus both width and height of silicon wires. In fact, w_h values giving maxima of $\Delta\phi_{glob}$ do not correspond to those for A_{eff} minima. For example, for h=300 nm minimum A_{eff} occurs for w_h = 210nm but, for the same value of h, the maximum of $\Delta\phi_{glob}$ is obtained for w_h = 190nm. Furthermore, while the effective area decreases with h, nonlinear phase shift shows a maximum in correspondence of wire height h = 300nm. Thus, it can be deduced that $\Delta\phi_{glob}$ is only partially influenced by the optical field confinement in the gap region. These simulation results can be fitted by a third order polynomial function. Our results demonstrate that an effective area minimization is not a correct criterium for nonlinear applications, although usually used for linear devices.

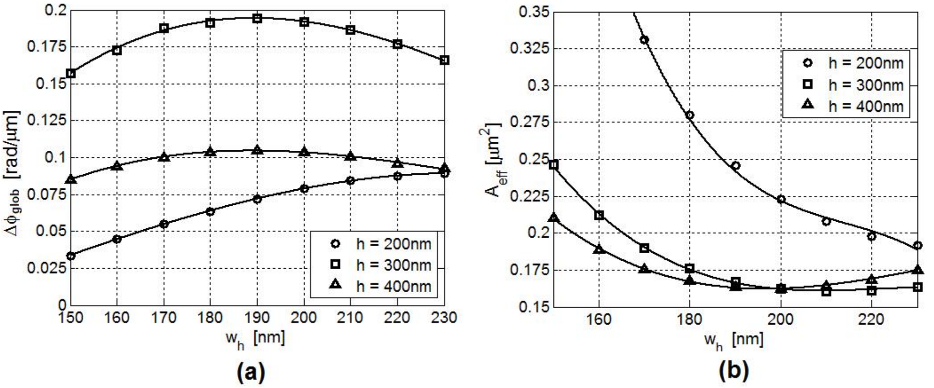


Fig. 3. (a) Quasi-TE mode nonlinear phase shift and (b) effective area as a function of silicon wire height and width (w_s = 100 nm).

Finally, the largest nonlinear response of a SOI slot waveguide, approaching 0.2 rad/μm, can be achieved with w_h = 190 nm and h = 300 nm, assuming a technological limitation on the slot width as w_s = 100 nm.

Conclusion

An optimization of nonlinear behavior of silicon nanometer slot guiding structures is presented in this work. A different behavior between effective area and nonlinear phase shift versus waveguide sizes has been demonstrated for quasi-TE mode when silicon nanocrystals are used as nonlinear material. Finally, taking into account the technological limitation on slot width, the slot geometrical parameters have been optimized to achieve the maximum nonlinear shift.

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