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The research of nonlinear optical phenomena in silicon slot waveguide structures

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Abstract. This work is devoted to the study of nonlinear phenomena in silicon waveguides, as well as in silicon-organic hybrids, which help to obtain improved characteristics of the initial device by compensating for the limitations imposed by second- and third-order nonlinearities in Si. The slot waveguide model is analyzed using computational methods such as the finite element method, the finite difference method in the time domain, and the singular perturbation method.

Keywords: nonlinearity, doped polymers, slot waveguides, FEM, FDTD, SPT

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Материалы конференции
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Исследование нелинейных эффектов в кремниевых щелевых волноводных структурах

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Аннотация. Работа посвящена исследованию нелинейных явлений в кремниевых щелевых волноводах, а также в кремнийорганических гибридах, при интеграции которых возможно получить улучшенные характеристики исходного устройства за счет компенсации ограничений, налагаемых нелинейностями второго и третьего порядка в Si. Модель щелевого волновода анализируется с использованием таких вычислительных методов, как метод конечных элементов (МКЭ), метод конечных разностей во временной области (FDTD) и метод сингулярных возмущений (SPT).

Ключевые слова: нелинейные эффекты, легированные полимеры, щелевые волноводы, МКЭ, FDTD, SPT

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Introduction

The silicon technological foundation has the great potential in conjunction with electronics, photonics and quantum technologies. It has opportunities in performing as solution for growing demands in such applications as data processing and telecommunications industry. Using the linear optical phenomena significant quantity of devices have been implemented on the SOI platform, for example optical buffers, interconnections [1] and sensors.

The second and third-order nonlinearities provide optical power losses, but in same time nonlinear optical effects may lead to new applications such as multiplexing and modulating signals. Therefore, researchers come across with the new challenge – to create the device with minimal losses and best functional characteristics.

Materials and Methods

The second-order nonlinearity in silicon is lower due to the centrosymmetric crystal structure, while the third-order nonlinearity is high and caused by such effects as two-photon absorption, forced scattering, four-wave mixing and the Kerr effect [2]. To solve that problem was carried out an analysis of various materials, among them silicon-organics hybrids (SOH), which also has strong second and third-order nonlinearities [3]. The propagation of optical radiation in waveguide structures is influenced by both the properties of silicon and SOH materials [4].

Currently, the model of slot waveguide with nonlinear properties is under development. It consists of silicon strips with a high refractive index and a nanoscale gap with a low refractive index, which formed between them as shown in Fig. 1.

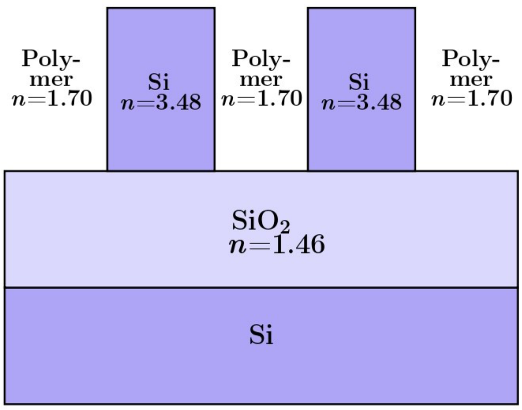

Fig. 1. Planar overview of waveguide parameters

This configuration is capable of providing new applications, such as optical capture, optical switching and sensors technology. In order to adapt the model to new applications, waveguides are coated with dopped polymer or other organic substances, such as the Ormocore polymer, in which both second- and third-order nonlinearities are demonstrated. Such waveguides are good candidates for electro-optical modulators with high data transfer rates and optical signal processing devices [5]. These devices have advantages such as high efficiency and integration with new materials conformant with CMOS.

The nonlinear phase shift was caused in the slit waveguide by the nonlinear optical Kerr effect. The analysis of this structure is carried out using software for modeling based on the finite element method (FEM) and the finite difference method in the time domain (FDTD). In order to minimize optical losses, it was decided to optimize the geometric parameters of the model using machine learning methods. An analytical approach to obtain the parameters of a slot waveguide with nonlinear characteristics using the singular perturbation technique (SPT) is also considered. SPT is used to study the behavior of waveguides with spatial perturbation [6] and weak second- and third-order nonlinearities, leading to solutions with sufficiently high accuracy [7].

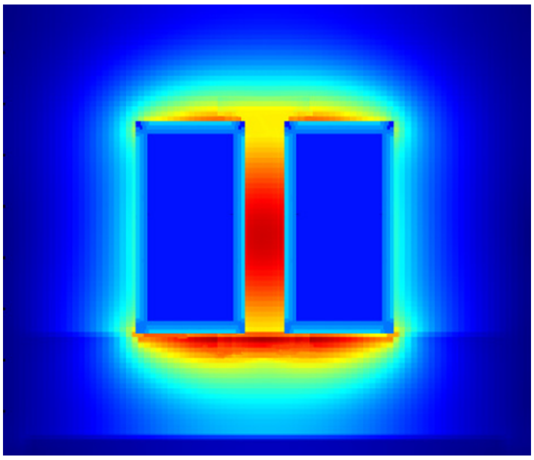

Fig. 2. Mode profile

Results and Discussion

In this paper, an analysis of silicon-organic compounds with second- and third-order nonlinearities was carried out, the polymer Ormocore was selected as a coating for waveguides. Nonlinear index coefficient n_{NL} and third-order susceptibility $\chi^{(3)}$ are interrelated as follows:

$$n_{NL} = \mathrm{Re}\left(\chi^{(3)}\right)/\left(4\varepsilon_0 c n_L^2\right),$$

where ε_0 and c are dielectric constant and velocity of light in vacuum and n_L is the linear refractive index of the selected nonlinear material. For polymer Ormocore, the nonlinear refractive index is $2{\cdot}10^{-17}$ m²/W, while for Si it is $6{\cdot}10^{-18}{\cdot}$m²/W.

A nonlinear material's relevance is influenced by its nonlinear losses as well as its nonlinear index coefficient. Two photon absorption (TPA) tends to be the cause of significant power losses. Unfortunately, excited band states are occupied by the carriers produced by TPA. These nanosecond lifetime carriers then take on the role of a highly absorbent plasma, lowering optical power and impairing nonlinear performance. Figure of merit (FOM), which relates the nonlinear phase shift to the associated intensity change, is defined as:

$$FOM = \frac{1 n_{NL}}{\lambda \alpha_{NL}},$$

where α_{NL} is the nonlinear absorption coefficient. Si although has a relatively large n_{NL} is the coefficient but unfortunately it has a low, caused by TPA, figure of merit. However, silica has a large FOM yet weak nonlinear characteristics. On the other hand, polymer Ormocore shows both a large nonlinear index n_{NL} and a small nonlinear absorption coefficient α_2, thus leading to a good FOM.

To obtain maximal nonlinearity in slot waveguides, not only the material dependent refractive index but also the mode confinement must be optimized. The nonlinearity parameter is:

$$\gamma = \frac{2\pi n_{NL}}{\lambda A_{eff}^{(3)}}.$$

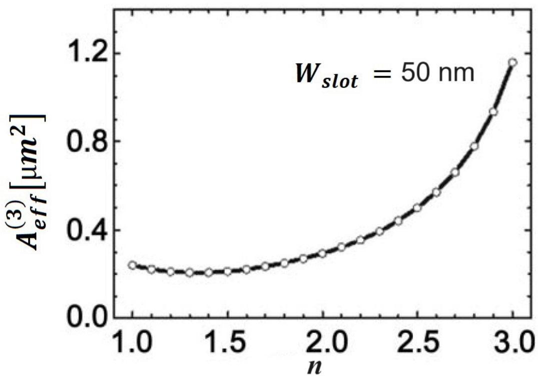

Fig. 3. Effective areas of nonlinear interaction $A_{eff}^{(3)}$ for a cover material with a linear refractive index n

To attain the highest possible nonlinearity in waveguides, it is necessary to optimize both the confinement of the mode and the material-dependent refractive index. It heavily depends on the third-order nonlinear interaction's effective area $A_{eff}^{(3)}$.

The silicon slot waveguide structure of Fig. 1 has $A_{eff}^{(3)}$ smaller than 0.1, which can be obtained with such geometry parameters as slot width of 50 nm, a core width 180 nm, and a core height 350 nm as shown in Fig. 3. The unique advantage of the slot waveguide structure is that it concentrates the field inside the slot as shown in Fig. 2., so that the nonlinearities in the silicon material become less important, and the slot material determine the nonlinear behavior.

Conclusion

In the conducted research, silicon-organic hybrids materials were analyzed. The modeling of the structure was carried out during which the distribution of fields in the structure was revealed depending on the characteristics of the source and the geometric parameters of the slot waveguide. A value for the minimum effective area of nonlinear interaction was also obtained, which will further help to improve the characteristics of waveguides by optimizing geometric parameters, increasing FOM of the device.

It is planned to build model's optimization based on the genetic algorithm in order to improve its characteristics. The problem of a bent silicon slot waveguide is also under consideration, it will solve the common issue of reducing rotation losses. It is also intended to develop biological sensors based on slot waveguide structures that use nonlinear optical phenomena.

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