Nonlinear and Dispersive Effects in Silicon Organic Hybrid Slot Waveguides

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A mathematical investigation of nonlinear and dispersive effects in silicon-organic hybrid (SOH) technology is presented. Optical properties of slot waveguides filed with DDMEBT polymer are found. Kerr effect, group-velocity dispersion and third-order dispersion effects are evaluated for propagating subpicosecond optical pulses. Improvements up to 50% in group velocity dispersion and 300% in third order dispersion versus standard SOI technology are theoretically demonstrated. By exploiting the advantages of silicon integration and nonlinear effects of organic materials, SOH technology could be used for ultrafast nonlinear photonics.

Introduction

In the last years silicon is likely become a very important platform for Nanophotonics. In fact, the compatibility with silicon integrated circuits manufacturing and silicon Micro-Electro-Mechanical Systems (MEMS) technology is a fundamental reason for the interest in Silicon Photonics [1]. As a transmission medium, silicon has much higher nonlinear effects than the commonly used silicon dioxide, in particular Kerr and Raman effects, and it allows high optical field confinement due to its high index contrast, too. The combination of these properties enables efficient nonlinear interaction of optical pulses at relatively low power levels inside silicon-on-insulator (SOI) waveguides over millimetre-scale interaction length. For this reason, a considerable effort has been recently directed towards many nonlinear phenomena in SOI waveguides, such as Raman amplification [2-3] and ultrafast optical pulses [4-5]. Moreover, research effort in the field of optical materials has allowed the development of polymers with very interesting properties, in particular large electro-optic and nonlinear effects [6]. Thus, a further step in the development of a new platform for practical nonlinear optics could be given by a silicon organic hybrid (SOH) technology, simultaneously exploiting the advantages of silicon integration and ultrafast performance of organic materials.

Numerical results

In this section a mathematical investigation of propagation of optical sub-picosecond pulses in slot waveguides based on SOH technology is proposed. Nonlinear optical properties are evaluated by considering SOI slot waveguides filed with DDMEBT polymer [7]. When such optical pulses propagate inside a waveguide, both dispersive and nonlinear effects largely influence their shapes and spectra. Then, the basic equations must take into account a number of effects, such as self phase modulation (SPM) induced by Kerr effect, group velocity dispersion (GVD) and third-order dispersion (TOD) effects. Therefore, the sub-picosecond regime can be investigated by the following nonlinear equation [3]:

$$\frac{\partial A}{\partial z}+j\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial\tau^2}-\frac{1}{6}\beta_3\frac{\partial^3 A}{\partial\tau^3}=-\frac{\left(\alpha^{(prop)}+\alpha_{Si,eff}^{(FCA)}\right)}{2}A-0.5\beta_{Si,eff}^{(TPA)}f\left|A\right|^2A+j\gamma A\left|A\right|^2 \tag{1}$$

being A the slowly varying electric field amplitude. The terms $\alpha^{(prop)}$, β_2, and β_3 represent the propagation loss, GVD and TOD coefficients, respectively. Moreover, the SPM coefficient is $\gamma = n_2\omega f/c$, being c the light velocity and n_2 the nonlinear refractive index of the organic material. The inverse of modal area f is given by:

$$f=\frac{\iint\left|F(x,y)\right|^2\left|F(x,y)\right|^2dxdy}{\iint\left|F(x,y)\right|^2dxdy\iint\left|F(x,y)\right|^2dxdy} \tag{2}$$

being $F(x,y)$ the optical mode distribution in the waveguide cross section. Finally, $\beta_{Si,eff}^{(TPA)}$ and $\alpha_{Si,eff}^{(FCA)}$ represent the Two Photon Absorption (TPA) and Free Carrier Absorption (FCA) effective coefficients, respectively, as calculated by considering the silicon-polymer hybrid structure. Fig. 1 shows the quasi-TE electric field distribution in a SOH slot waveguide, assuming λ = 1500 nm, silicon wire width *W* = 250 nm, slot height *H* = 250 nm and slot width *G* = 80 nm. Since the quasi-TE electric field is confined mainly inside the slot, the nonlinearities are dominated by DDMEBT over silicon, as expected.

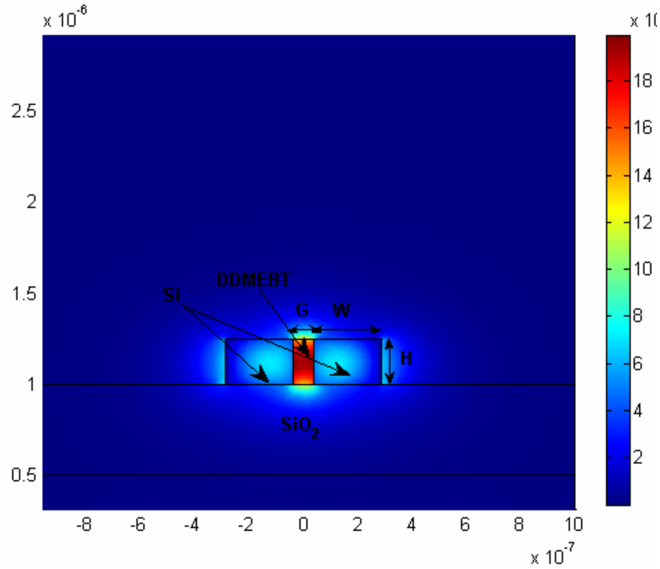

Fig. 1. Electric field distribution of quasi-TE mode in SOH slot waveguide.

Fig. 2 shows the GVD coefficient spectra for the fundamental slot quasi-TE mode in the range 1.2 ÷ 1.8 μm, for different geometrical parameters (*H*, *W* and *G*). For all cases considered, GVD coefficient exclusively varies in the normal region, assuming values well larger than in SOI rib waveguides (up to +50%). Moreover, the curves show how GVD coefficient is strongly influenced by both slot width and silicon wire geometry. In particular, it increases with increasing the slot width and moving from rectangular to square silicon wire cross section. In Fig. 3 TOD coefficient spectra are sketched for the slot fundamental quasi-TE mode, again in the range 1.2 ÷ 1.8 µm for different *H, W* and *G*. The plots clearly demonstrate how TOD coefficient presents an opposite trend versus GVD coefficient. In fact, it is weakly influenced by the slot width, while increasing when square cross section of the silicon wire moves to rectangular. A TOD coefficient significant increase versus SOI rib waveguides is also found (up to three times)..

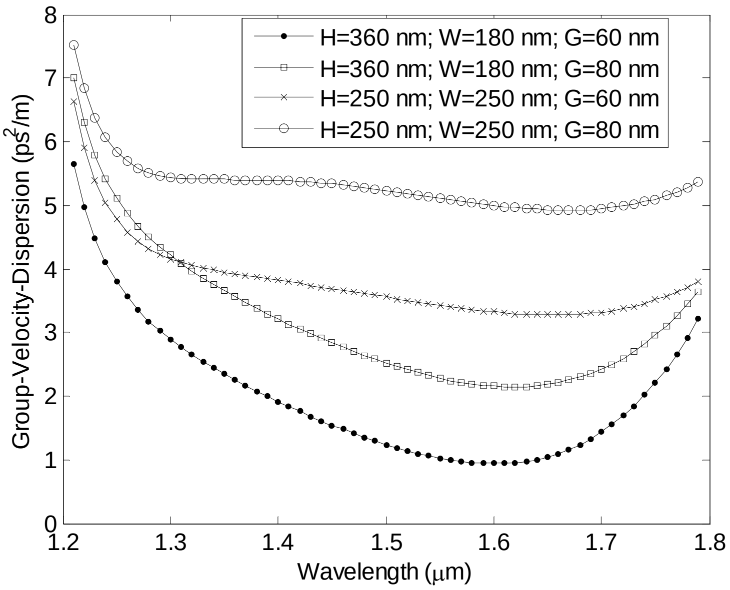

Fig. 2. Group-velocity-dispersion spectra for different slot structures.

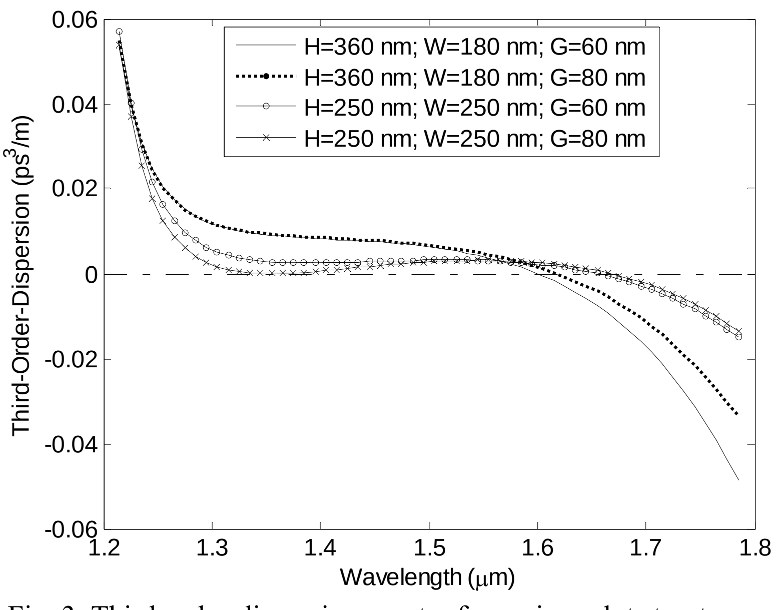

Fig. 3. Third-order-dispersion spectra for various slot structures.

Finally, Fig. 4 shows the broadening of 80 fs Gaussian pulse as induced by SPM effect in a slot waveguide only 0.4 mm long. A peak power of 9.8 W is achieved using λ = 1500 nm, *W* = 250 nm, *H* = 250 nm, *G* = 80nm, β_2 = 5.236 ps^2/m, β_3 = 2.77×10^{-3}

ps^3/m, and assuming $\alpha^{(prop)}$= 15dB/mm and n_2 = 2×10^{-17} m^2/W [6]. Calculations of field distributions, effective indices, GVD and TOD coefficients and modal areas have been carried out by full-vectorial finite element method, including Sellmeier dispersion equation for DDMEBT polymer [7]. These preliminary results well demonstrate the potential of this hybrid technology to be used in several nonlinear tasks (pulse frequency compression, dispersion control, all-optical logic gates, four-wave mixing) in guided-wave optical devices over submillimeter-scale length.

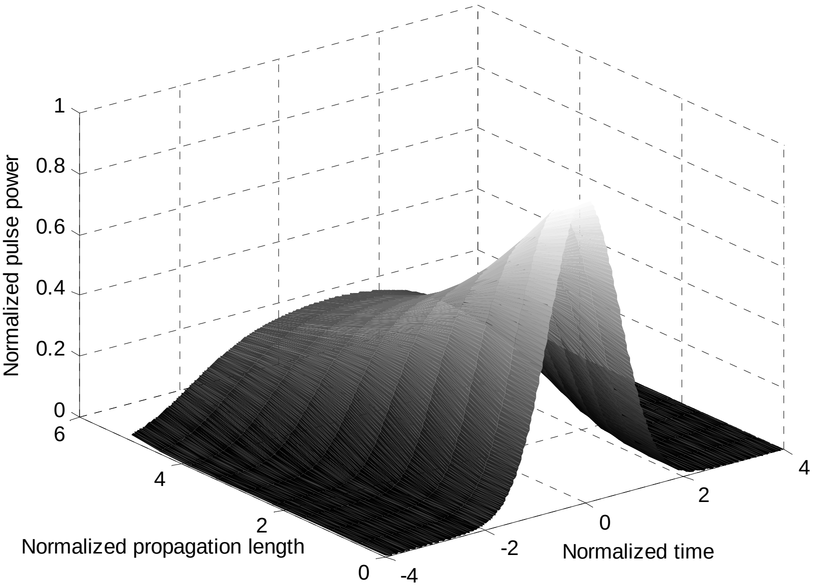

Fig. 4. Space-time evolution of a 80 fs Gaussian pulse.

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