Optical Dispersion Management in Silicon Nanocrystal Slot Waveguides for Soliton Control

F. De Leonardis, V. M. N. Passaro, B. Troia *
Photonics Research Group, * CNIT UdR Bari
Dipartimento di Elettrotecnica ed Elettronica
Politecnico di Bari
Via Edoardo Orabona n. 4, 70125 Bari – Italy
E-mail: passaro@deemail.poliba.it
URL: http://dee.poliba.it/photonicsgroup

A. V. Tsarev
Laboratory of Optical Materials and Structures
A.V. Rzhanov Institute of Semiconductor Physics
Siberian Branch of Russian Academy of Sciences
Novosibirsk, 630090, Russia
E-mail: tsarev@isp.nsc.ru

***Abstract*— An investigation of group velocity dispersion for silicon nanocrystals-based sandwiched slot waveguides is proposed in this paper. Main guidelines to manage the group-velocity dispersion for controlling optical solitons in optical processing applications are found. Comparisons between single and double slot nanocrystal structures show intriguing properties.**

Keywords-Nanoscrystals; Nonlinear optics; Group Velocity Dispersion; Optical Soliton.

I. INTRODUCTION

In the last few years, a number of research study has been performed in order to exploit the third-order nonlinear effects in silicon for ultrafast signal processing [1-2]. However, the enhancement of non-linear effects in silicon based photonic components is still a key point in order to achieve active and more complex guiding structures. Non-linear materials, such as silicon nanocrystals (Si-nc), can be developed by using conventional CMOS fabrication processes [3]. In this paper, formation and control of optical solitons are theoretically demonstrated in dispersion-engineered silicon nanocrystal slot waveguides.

II. WAVEGUIDE OPTICAL DISPERSION

In this Section, a full parametric analysis is presented in order to design the Si-nc slot waveguides with a desired group velocity dispersion (GVD) coefficient. Then, design guidelines for excitation and control of optical soliton in Si-nc slot waveguides are found. The GVD-induced pulse broadening is known to scale with the dispersion length $L_D = T_0^2/|\beta_2|$, being β_2 the GVD coefficient and T_0 the pulse width, while SPM-induced chirp scales with the nonlinear length $L_{NL} = (\gamma P_0)^{-1}$, with $\gamma = 2\pi n_2/(\lambda A_{eff})$ the nonlinear parameter, n_2 the Kerr coefficient and P_0 the peak power of pulses launched at wavelength λ into the fundamental mode with effective mode area A_{eff}. The formation of fundamental soliton ideally requires $L_{NL} = L_D \ll L$ for a waveguide of length L. The previous relationship indicates that both $|\beta_2|$ and γ should be large enough to induce the formation of solitons in short waveguides, with lengths $L \le 1$ cm. In this sense, the horizontal slot waveguide based on Si-nc should guarantee an optimization in the soliton formation with respect to standard SOI rib waveguides. Two Si-nc slot waveguides, named WG1 and WG2, have been investigated, as in Fig. 1(a) and (b). The rib width is W, the slot region filled with Si-nc has thickness G for WG1 and G_1, G_2 for WG2. The bottom and top silicon layers have thickness H_1 and H_2, respectively. Finally, the silicon layer between two slot regions in WG2 has thickness h. These geometrical parameters can be selected in order to control the values of $|\beta_2|$.

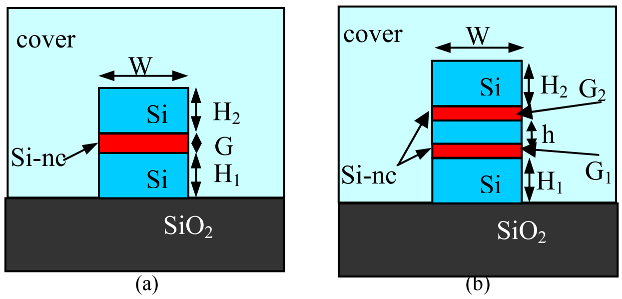

Figure 1. Cross section of SOI horizontal slot waveguide based on Si-nc: a) single slot, b) double slot.

In order to investigate the influence of geometrical parameters of Si-nc slot waveguide and the cover medium on the optical dispersion properties, a number of parametric simulations have been carried out. In Fig. 2 GVD coefficient spectra for quasi-TM modes are shown as a function of different values of cover refractive index n_c (air, water solution, silicon oxide), assuming H_{rib} = 430 nm for both structures WG1 and WG2. Each curve has been achieved by full vectorial Finite Element Method (FEM) [4] in the wavelength range 1250 ÷ 1750 nm, taking into account the Sellmeier equation for refractive index dispersion. In Fig. 2 we have assumed $H_1 = H_2$ = 200 nm, W = 200 nm and G = 30 nm for WG1, while $H_1 = H_2$ = 135 nm, W = 200 nm, $G_1 = G_2$ = 30 nm and h = 100 nm for WG2. Waveguide WG1 can clearly guarantee both normal and anomalous regime. On the contrary, structure WG2 only moves its GVD spectra in the normal region. In addition, the increase of cover refractive index induces either $|\beta_2|$ increasing or decreasing for WG1 and WG2, respectively. In its turn, this effect induces a shift of zero GVD point (ZGVD) towards higher wavelengths, confirming the superiority of WG1 over WG2 regarding GVD dispersion.

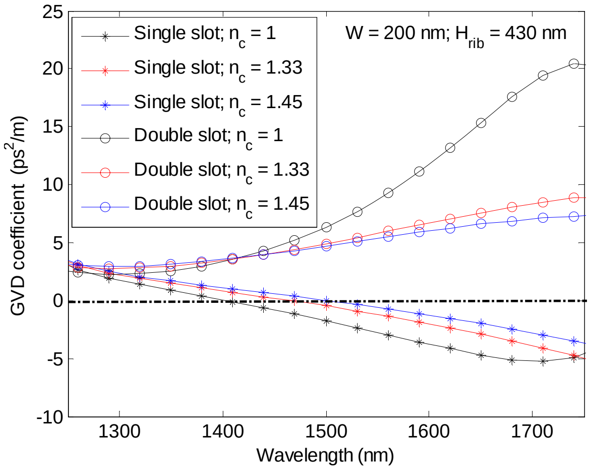

Figure 2. GVD coefficient spectra for various cover refractive indices.

GVD spectra for different values of W and slot thickness are shown in Fig. 3. The curve peak increases with increasing the structure width and decreasing the slot thickness. Thus, Figs 2-3 leads to conclude that WG2 structure is not suitable for soliton formation.

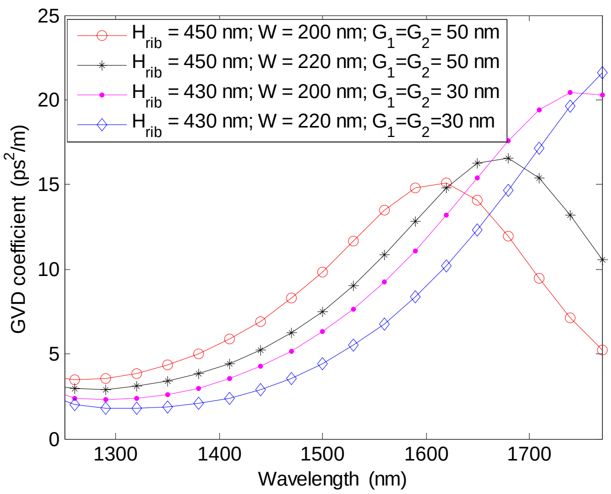

Figure 3. GVD coefficient spectra of WG2 structure for various widths and slot thicknesses.

Fig. 4 show the GVD coefficient at λ =1550 nm versus the total rib height for both structures considered and for different cover refractive index. The curves of Fig. 4 can be considered an useful tool to design the Si-nc slot waveguide with a desired GVD coefficient. Third order dispersion (TOD) coefficient has been also evaluated as a function of total rib height and different cover refractive index, showing moderate values, always less than 0.03 ps^3/m for WG1.

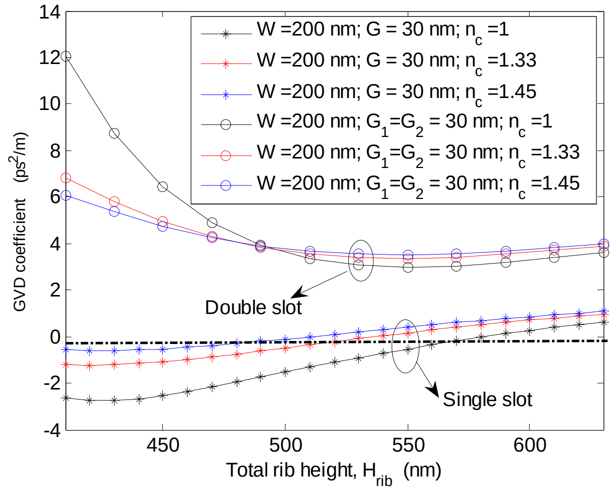

Figure 4. GVD coefficient versus rib total height for various cover refractive indices (λ =1550 nm).

III. Soliton Theory

Space-time evolution of optical solitons is described by the pulse propagation equation written for the slowly-varying amplitude $A(z,t)$ of the modal electric field $E(\mathbf{r},t)$ traveling along the propagation direction z [1]. We have considered the Si-nc slot waveguide WG1 (W = 200 nm, G = 30 nm, n_c= 1, and H_{rib} = 378 nm) excited by a Gaussian optical pulse with T_{FWHM} = 100 fs, and peak power selected to satisfy a specific condition, $N=(L_D/L_{NL})^{1/2}$ = 1.9. Kerr coefficient in silicon nanocrystals, n_2 = 4×10^{-17} m^2/W, α_{Si} = 1 dB/cm, α_{Si-nc} = 15 dB/cm , β_{Si}^{TPA} = 0.5 cm/GW and β_{Si-nc}^{TPA} = 5 cm/GW for silicon and Si-nc layers, respectively, are assumed. After travelling over length less than 1.5 mm, the optical pulse is affected by a temporal broadening and distortion but, at around 3 mm, the pulse recovers and converts itself in a compressed hyperbolic-secant shape. Optical losses, TPA and FCA have an initial influence but, however, a stable soliton is expected to be achieved for lengths larger than 4 mm.

References

[1] F. De Leonardis and V. M. N. Passaro, “Ultrafast Raman Pulses in SOI Waveguides for Nonlinear Signal Processing,” *IEEE J. Sel. Top. in Quantum Electron.*, vol. 14, pp. 739-751 (2008).

[2] Y.-H. Kuo, H. Rong, V. Sih, S. Xu, M. Paniccia and O. Cohen, “Demonstration of wavelength conversion at 40Gb/s data rate in silicon waveguides,” *Opt. Express*, vol. 14, n. 24, pp. 11721–11726 (2006).

[3] A. Martınez, J. Blasco, P. Sanchis, J. V. Galan, J. Garcıa-Ruperez, E. Jordana, P. Gautier, Y. Lebour, S. Hernandez, R. Spano, R. Guider, N. Daldosso, B. Garrido, J. M. Fedeli, L. Pavesi, and J. Martı, “Ultrafast All-Optical Switching in a Silicon-Nanocrystal-Based Silicon Slot Waveguide at Telecom Wavelengths,” *Nano Lett.*, vol. 10, pp. 1506–1511 (2010).

[4] Comsol Multiphysics by COMSOL, Stockholm, single license (2005).