Optical Solitons in Si-nc Sandwiched Optical Slot Waveguides

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Abstract— **We propose, for the first time to our knowledge, the theoretical investigation of optical soliton excitation inside very short silicon nanocrystal based sandwiched slot waveguides, only 1.6 mm long. Several parametric simulations have been carried out by means of finite element method in order to select the best waveguide cross section for anomalous-dispersion regime around 1550 nm.**

Keywords-component; Slot waveguides; Optical solitons; Silicon nanocrystals; Non linear effects.

I. WAVEGUIDE DESIGN

Silicon is the ideal platform for Integrated Optics and Optoelectronics due to its very broad application potential, going from optical interconnects to biosensing to nonlinear signal processing [1]. In particular, solitons have been observed, for the first time, inside 5 mm long Silicon on Insulator (SOI) waveguides, using an input 120 fs Gaussian pulse aligned as quasi-TM mode [2]. The enhancement of non-linear effects in silicon based photonic components is still a key point in order to achieve active and more complex structures for signal processing. Novel non-linear materials, as silicon nanocrystals (Si-nc) embedded in silicon oxide can be developed by using standard CMOS fabrication processes. This material possesses interesting optical properties, such as Kerr coefficient (n_2) one or two orders of magnitude larger than in silicon [3]. In this paper, the formation of optical solitons in Si:nc based slot waveguides is theoretically demonstrated.

Optical soliton results from a critical interplay between the effects of group-velocity dispersion (GVD) and self-phase modulation (SPM), when the wavelength of input optical pulse is placed inside the anomalous dispersion region. The GVD-induced pulse broadening scales with the dispersion length $L_D = T_0^2 / |\beta_2|$, where β_2 is the GVD coefficient and T_0 is the pulse width, whereas the SPM-induced chirp scales with the nonlinear length $L_{NL} = (\gamma P_0)^{-1}$, $\gamma = 2\pi n_2 / (\lambda A_{eff})$ is the nonlinear parameter and P_0 is the peak power of pulses launched at the wavelength λ as fundamental mode with effective mode area A_{eff}. The formation of fundamental soliton requires to have $L_{NL} = L_D \ll L$, being L the waveguide length. The previous relationship indicates that both $|\beta_2|$ and γ should be quite large to induce the formation of solitons in waveguides with $L \le 1$ cm. In this sense, the waveguide based on Si-nc slot, as sketched in Fig. 1, could guarantee better conditions for soliton formation with respect to the standard SOI waveguide.
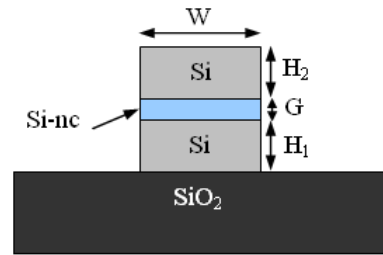

Figure 1. Scheme of slot waveguide based on silicon nanocrystals.

The waveguide of Fig. 1 has a rib width W, a slot region filled with Si-nc with thickness G, and bottom and top silicon layers with thickness H_1 and H_2, respectively. The first step for the excitation of solitons is to find the anomalous dispersion region of considered structure. GVD coefficient spectra for different combinations of waveguide parameters have been evaluated by a number of simulations based on finite element method (FEM) [4] in the wavelength range $1200 \div 1800$ nm, in case of quasi-TM slot modes and including the Sellmeier equation for index dispersion. For fixed values of W and G, the zero GVD point (ZGVD) shifts towards higher wavelengths with increasing the silicon layers thickness. On the contrary, the ZGVD point can be changed towards smaller wavelengths by decreasing the thickness of Si-nc slot region. However, for a given value of G, if $W > H$ (with $H = H_1 = H_2$) only a normal dispersion behavior is revealed in this waveguide structure. Therefore, the design guideline to follow is a Si-nc slot thickness $G < 80$ nm with the aim to induce optical solitons at 1550 nm.

In Fig. 2 both GVD coefficient and nonlinear parameter evaluated at 1550 nm are shown as a function of $H = H_1 = H_2$ for different values of W and G. These results well demonstrate how sensible is this structure to any change of slot thickness G and rib width W. In particular, for $W > 200$

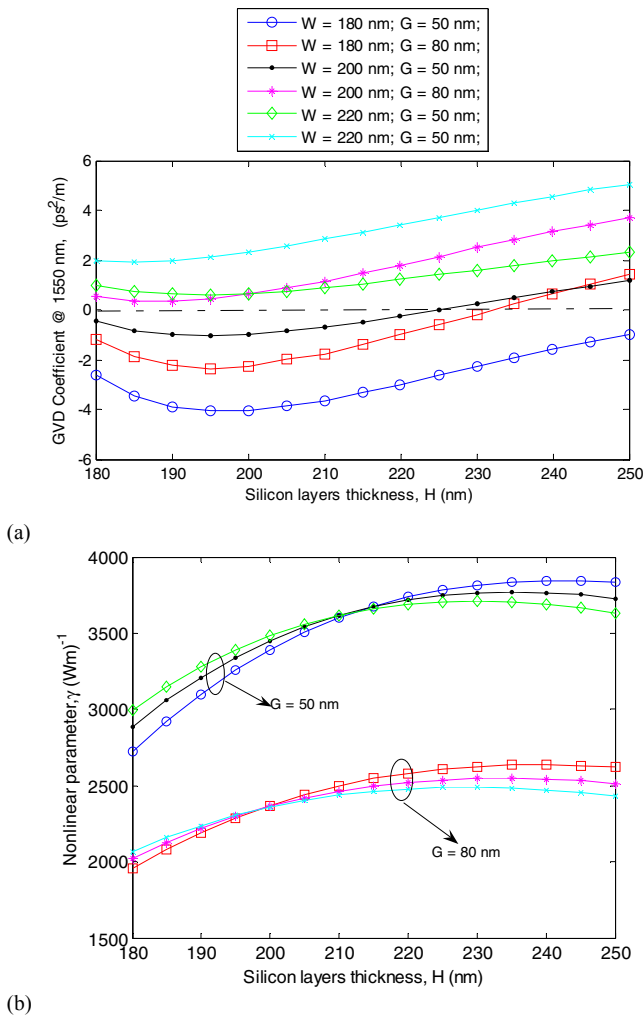nm and $G > 80$ nm, the Si-nc slot waveguide does not present any anomalous dispersion at 1550 nm.

(a)

(b)

Figure 2.   GVD coefficient (a) and nonlinear parameter (b) versus silicon layers thickness, for different values of W and G @ 1550 nm.

Moreover, GVD coefficient becomes more and more negative with decreasing G and W. On the contrary, the nonlinear parameter γ increases with decreasing the slot thickness. Now, the very high value of γ obtained in our numerical investigations mainly depends on a combination of very small effective mode areas, induced by the slot region, and very large Kerr coefficients $n_2 = 4 \times 10^{-17}$ m^2/W in silicon nanocrystals. Thus, the best choice of waveguide parameters are $W = 180$ nm, $G = 50$ nm, and $H = 195$ nm. The potential of Si-nc slot waveguide with respect to the standard rib SOI waveguide is well shown in Table I, where several important parameters are summarized.

II.   SOLITON EXCITATION

The space-time evolution of optical solitons is governed by the well known non linear Schroedinger equation [5], including GVD, free carrier absorption, two photon absorption, third order dispersion, SPM and propagation losses.

TABLE I. Optical parameters of optimized waveguides.

	Ref. [2]	This paper
Rib width [nm]	860	180
Total rib height [nm]	400	440
Polarization state	quasi-TM	quasi-TM
Effective mode area A_{eff} [μm^2]	0.13	0.04881
Nonlinear parameter γ [(W m)$^{-1}$]	193.33	3255
GVD coefficient β_2 [ps^2/m]	-2.26	-4.074

We have considered the Si-nc slot waveguide excited by one Gaussian optical pulse with $T_{FWHM} = 116$ fs, and peak power selected to match the condition $N = (L_D/L_{NL})^{1/2} = 1.7$ ($P_0 = 0.73$ W), assuming $\beta^{(TPA)} = 5$ cm/W [3]. Fig. 3 shows that the input Gaussian pulse excites a *sech*-like profile soliton by propagating inside the Si-nc slot waveguide, only 1.6 mm long.
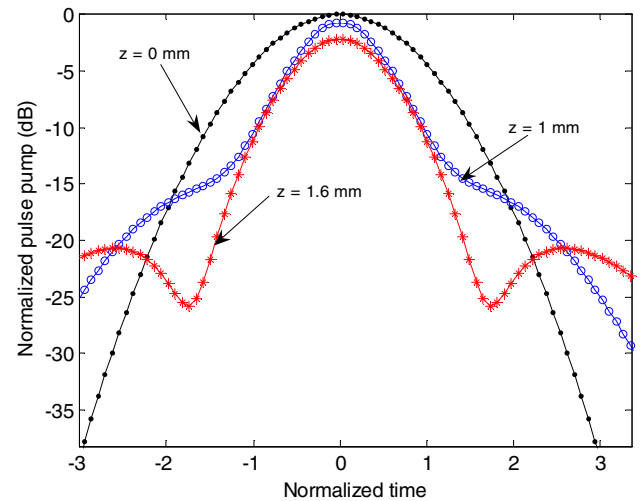

Figure 3.   Temporal evolution of Gaussian pulse in a soliton, for various propagation lengths (quasi-TM mode).

III.   CONCLUSIONS

In this paper the theoretical demonstration of optical solitons excitation inside a Si-nc slot waveguide is presented. The designed waveguide can induce optical solitons with a length 3 times shorter than in SOI rib waveguides. The potential of the Si-nc slot waveguide is very significant and it could represent a very promising technology for ultrafast optical processing.

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