Wavelength Conversion by Four Wave Mixing in Silicon Nanocrystal Slot Waveguide

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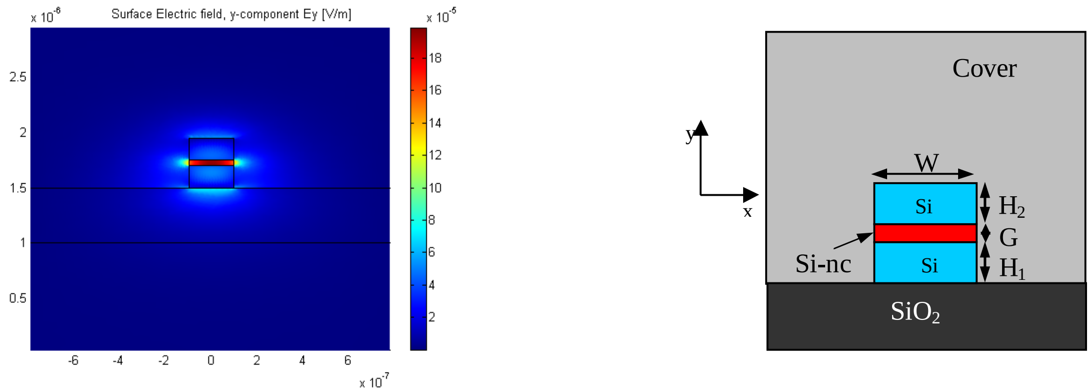
Novel non-linear materials such as silicon nanocrystals can be developed by using conventional CMOS fabrication process and engineering in order to enhance their non-linear effects. We present a theoretical investigations of wavelength conversion effect in Si-nc slot waveguides, taking simultaneously into account the Four Wave Mixing process and the rate equation for four level system in silicon nanocrystal slot waveguides. Due to the generalization of this model, it is possible to evaluate the influence of electron excitation on the conversion efficiency, as induced by the two photon absorption mechanism.

1.Waveguide design

In the last few years, silicon has become the ideal platform for Integrated Optics and Optoelectronics due to its broad application potential from optical interconnects to biosensing. However, the enhancement of non-linear effects and the engineering of optical dispersion properties in silicon based photonic components is still a key point in order to achieve active and more complex guiding structures. Novel non-linear materials, such as silicon nanocrystals (Si-nc), can be developed by using conventional CMOS fabrication processes. In particular, this material possesses interesting optical properties, i.e. non-linear Kerr coefficient (n_2) one or two orders of magnitude larger than in silicon [1-2]. In this work, we want to investigate how it is possible to manage the optical dispersion properties in order to induce an efficient wavelength conversion by means of Four Wave Mixing (FWM) process. With this goal, we present a numerical investigation of group velocity dispersion (GVD) for the Si-nc slot waveguide, sketched in Fig. 1 as a function of different geometrical and physical parameters.



(a) (b)

Fig. 1. (a) Cross section of SOI slot waveguide based on Si-nc; (b) 2D distribution of E_y component.

In order to investigate the influence of geometrical parameters of Si-nc slot waveguide on its optical dispersion properties, the design variable $q = H_1/W$ is introduced. In Fig. 2, GVD coefficient β_2 at λ=1550 nm is shown as a function of G and q parameter, assuming $H_1 = H_2$, air cover and W = 200 nm and W = 240 nm, respectively. The plots clearly show that β_2 coefficient monotonically increases or decreases as a function of G for $q < 1$ or $q \geq 1$, respectively. Moreover, for a given value of G, GVD coefficient presents a positive maximum point for $q < 1$ and a negative minimum point close to $q \cong 1$. It is worth noting the curve down-shift or up-shift with increasing W, depending on the specific value of q parameter. Thus, the plot of Fig. 2 is very useful to find the waveguide design guidelines in order to induce the anomalous dispersion region at λ =1550 nm, as required to realize the phase matching condition in FWM process.

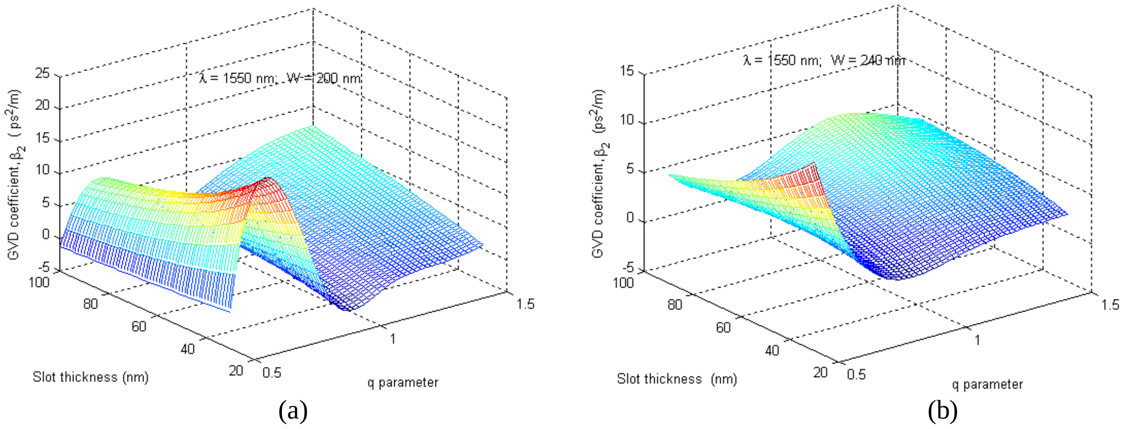


Fig. 2. GVD coefficient versus slot thickness G and q parameter: (a) W=200 nm; (b) 240 nm.

2. Modeling and numerical results

Hereinafter, we focus on the FWM mechanism where two pump beams at frequencies ω_1, ω_2 are employed for the simultaneous creation of two beams at two new frequencies, ω_3 (idler), ω_4 (signal), being $\Omega_s = \omega_1 - \omega_3 = \omega_4 - \omega_1$. To enhance the efficiency of FWM process, both pumps, signal and idler waves are assumed to be identically polarized in the fundamental quasi-TM mode. The partial differential equations system governing FWM process in a Si-nc slot waveguide is presented in Ref. [3]. A correct estimation of propagation loss coefficient ($\alpha_i^{(prop)}$) and Free Carrier Absorption (FCA) coefficient ($\alpha_i^{(FCA)}$) induced by TPA of the pump pulses can be performed by means of relationship $\alpha^{(prop)} = \Gamma_{Si}\alpha_{Si} + \Gamma_{Si-nc}\alpha_{Si-nc}$, and $\alpha^{(FCA)} = \Gamma_{Si}\alpha_{Si}^{FCA} + \Gamma_{Si-nc}\alpha_{Si-nc}^{FCA}$, respectively. The terms α_{Si} and α_{Si-nc} are the propagation loss coefficients for the silicon layers and Si-nc slot region, respectively. Similarly, FCA effect induced inside the silicon layers and inside the slot region filled with Si-nc is taken into account by means of $\alpha_{Si}^{(FCA)}$ and $\alpha_{Si-nc}^{(FCA)}$, respectively. Moreover, Γ_{Si} and Γ_{Si-nc} are the power fractions in silicon and silicon nano-crystals, respectively. According to [3], the term $\alpha_{Si}^{(FCA)}$ can be evaluated proportionally to the density of electron-hole pairs (N_c) generated by TPA process inside the silicon layers, as a solution of the following rate equation:

$$\frac{dN_c}{dt} = -\frac{N_c}{\tau_{eff}} + \frac{\beta_{Si}^{(TPA)}}{2\hbar\omega}\left(\left|A_1(z,t)\right|^2 f_{1,1} + \left|A_2(z,t)\right|^2 f_{2,2}\right)^2 \quad (1)$$

Similarly, $\alpha_{Si-nc}^{(FCA)}$ can be calculated considering the excited population of nanocrystals (N_{exc}) by the relationship $\alpha_{Si-nc}^{(FCA)} = \sigma_{Si\_nc} N_{exc}$, where σ_{Si_nc} is the FCA cross section, i.e. 2.6×10^{-17} cm^{-2} [2]. In our model, the electron excitation is induced by TPA effect around

λ = 1550 nm, following a four level equation system:

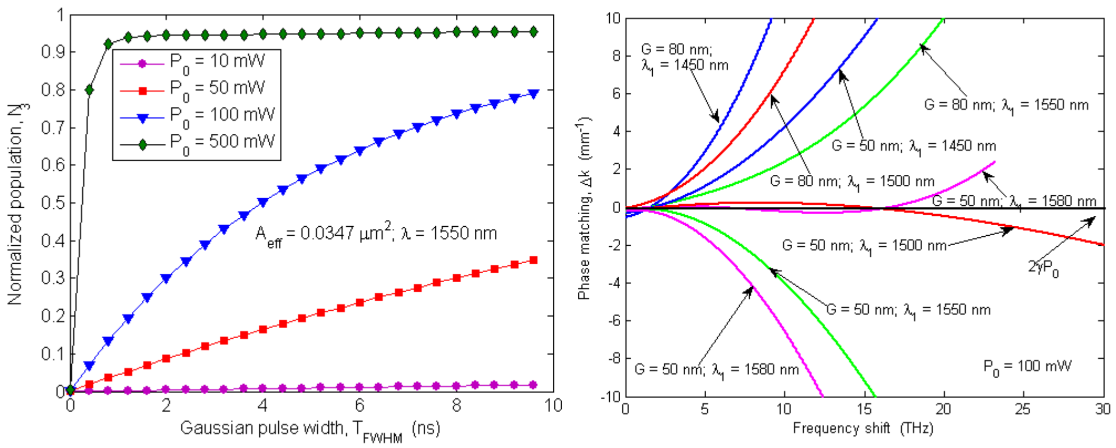
$$\frac{dN_1}{dt} = -\sigma_2 N_1 \left(\frac{I(z,t)}{2\hbar\omega}\right)^2 + \frac{N_2}{\tau_{21}} \tag{2.1}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} + (C_{A1} + C_{A2})N_3^2 \tag{2.2}$$

$$\frac{dN_3}{dt} = -\frac{N_3}{\tau_{32}} + \frac{N_4}{\tau_{43}} - (2C_{A1} + C_{A2})N_3^2 \tag{2.3}$$

$$\frac{dN_4}{dt} = -\frac{N_4}{\tau_{43}} + C_{A1}N_3^2 + \sigma_2 N_1 \left(\frac{I(z,t)}{2\hbar\omega}\right)^2 \tag{2.4}$$

being τ_{ij} the decay lifetime from *i*-state to *j*-state, σ_2 the TPA cross section, and C_{A1} and C_{A2} the Auger coefficients as detailed in [4]. The term $I(z,t)$ is the optical pulse intensity propagating in the structure, which could be typically considered a Gaussian pulse. Finally, the TPA coefficient β^{TPA} can be interpreted as an effective TPA coefficient, as $\beta_{eff}^{TPA} = \Gamma_{Si}\beta_{Si}^{TPA} + \Gamma_{Si-nc}\beta_{Si-nc}^{TPA}$. In Fig. 3 we show the normalized population $N_{exc} = N_3$ versus the Gaussian pulse width for different values of pulse peak power, by numerically solving the equations system (2). The plot indicates clearly that for optical pulses larger than few nanoseconds, the number of excited nanocrystals N_{exc} start to become considerable and increases with increasing the peak power. In this sense, the nonlinear effects operating in CW regime will suffer of higher losses (propagation and FCA), as induced by the strong TPA effect.



(a) (b)

Fig. 3. (a) Normalized population N_3 versus Gaussian pulse width for different values of peak power for various pump wavelengths and G; (b) Phase matching Δk versus frequency shift.

It is well known that an efficient FWM process requires the phase-matching condition $\kappa = 0$ to be met, being κ the net phase mismatch defined as $\kappa = \Delta k + \gamma(P_1 + P_2)$, Δk the mismatch due to both material and waveguide dispersion, and $\gamma(P_1 + P_2)$ the nonlinear phase mismatch. The terms P_1 and P_2 are the two pump powers, where $P_1 = P_2 = P_0$ for degenerate case. Fig. 3 shows Δk as a function of frequency shift Δf between pump and signal wave, for different pump wavelengths. We have considered a Si-nc slot waveguide with W=200 nm, q=1, $H_1 = H_2$ and two values for the slot thickness, G=50 nm and G=80 nm, respectively. The Δk parameter assumes negative values for pump wavelengths larger than ZGVD wavelength, evaluated as λ_z =1502.5 nm and λ_z =1577.4

nm for G=50 nm and G=80 nm, respectively. As a result, in case of large pump powers P >20 dBm (i.e., in the presence of nonlinear effects), the exact frequency shift to achieve $\kappa = 0$ can be always found. Moreover, the curves show a flat profile, close to zero. The extension of this region depends on the pump wavelength, being maximum for λ_1 approaching λ_z, and decreasing far from ZGVD. Then, for very low pump powers (i.e., negligible nonlinear effects), condition $\kappa \cong 0$ occurs over a wide range 1÷15 THz, depending on the pump wavelength. Moreover, it is worth to outline the interesting case for λ_1=1500 nm, and G=50 nm, where the mismatch due to nonlinear effects $2\gamma(P_0)$ crosses the λ_1=1500 nm curve for a frequency shift of 22.32 THz. Fig. 5 shows the conversion efficiency defined as $\eta_c = P_{idler}(L)/P_{signal}(0)$, versus the waveguide length for different pump wavelengths and frequency shifts, as derived from curves of Fig. 4. Thus, degenerate FWM in CW regime is assumed with P_0=20 dBm, P_3 =-40 dBm (idler) , and P_4 =-10 dBm (signal). Moreover, three different values of frequency shift are given, Δf =22.32 THz, 4.35 THz, and 3.15 THz, for different pump wavelengths, λ_1= 1500 nm, λ_1= 1550 nm, and λ_1= 1580 nm, respectively. The plot clearly demonstrates that choosing a waveguide length around 2÷2.6 mm it is possible to achieve the maximum conversion efficiency on the idler wave, ranging between -18.47 dB and -20.53 dB with Δf = 4.35 THz, and 22.32 THz, respectively.

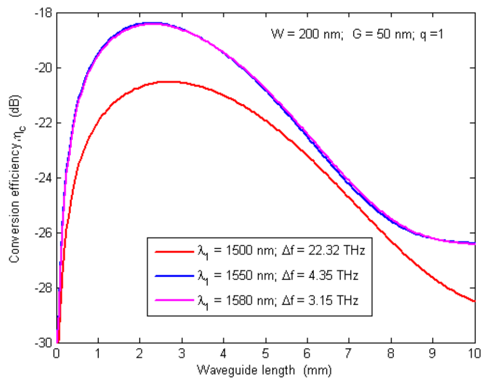


Fig. 5. Conversion efficiency versus the waveguide length.

3. Conclusions

In this paper the complete modelling of FMW process in Si-nc slot waveguide is presented and discussed. The presented results lead to find the design guidelines to induce large wavelength conversion efficiency, taking into account the detrimental effect induced by TPA effect inside the silicon nanocrystal layer.

References

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