Generation of ultrafast dark pulse based on non-degenerate two-photon absorption in silicon nanophotonic chip

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A novel project has been proposed and demonstrated for generating the ultrafast dark pulse by utilizing the non-degenerate two-photon absorption (TPA) in silicon-on-insulator (SOI) nanophotonic chip, in which by a pump bright pulse with pulsewidth of 100fs at 1/e intensity point and continue wave (CW) co-propagating along the SOI waveguide, an ultrafast dark pulse at CW wavelength can be achieved at the end of waveguide. Investigation results show that the pulsewidth and contrast of dark pulse are strongly dependent on the pump initial power and waveguide length.

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1. Introduction

In past researches, various approaches have been presented for generating bright pulse [1, 2], however, few reports can be found about the dark pulse generation. In fact, the ultrafast dark pulse has advantages in terms of loss, noise, and mutual interactions between adjacent pulses when compared with their bright counterparts. To obtain significant dark pulse, only some projects are demonstrated, in which these schemes involve very complicated experimental requirements. In these approaches, both the cross-phase modulation in optical fibers and modulation instability are often attended [3, 4], in which the long fiber in the range from several meters to several kilometers is required to produce effective nonlinear process, and other affiliated elements are also combined for pulse compression and shaping as a result that it is not realistic for optics integration in modern optics communications. Motivated by these limits, we apply ourselves to explore other projects to obtain dark pulse, and found that submicron scale silicon waveguide is an ideal device for integration. In recent years, silicon photonics has attracted much attention because of its potential for providing a monolithically integrated optoelectronic platform [5]. In particular, SOI waveguide has the tight optical confinement by the large index mismatch between the silicon and SiO_2 leading to high nonlinear processes such as self-phase modulation (SPM), stimulated Raman scattering (SRS), TPA, and TPA induced free carrier absorption, and so on. In these nonlinear processes, TPA is an ultrafast process comparing with the free carrier absorption, which denotes that the combination energy of two photons is larger than the band gap energy in silicon, and can be classified into degenerate TPA (two same photons) and non-degenerate TPA (two different photons). In this letter, by using the ultrafast non-degenerate TPA process, we have developed a novel project to generate ultrafast dark pulse.

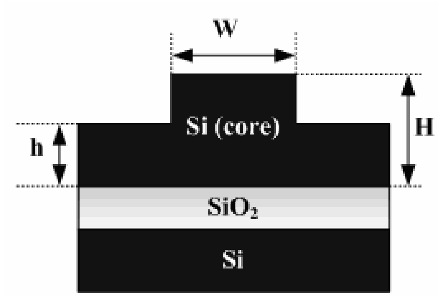
This letter is organized as follows. In section 2, the theoretical modeling and equations are presented. In Section 3, we display the simulation results and discussions. Section 4 summarizes the work.

2. Modeling and equations

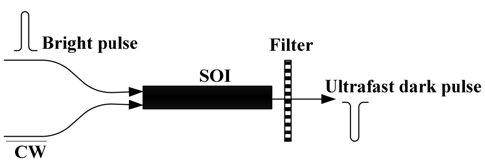
In the Fig. 1 (a), the ridge waveguide structure with width W, rib height H, and slab height h. The free carriers will be produced when optical waves propagating in SOI waveguide, whose effective recombination lifetime τ_{eff} may be denoted by [6]

$$\tau_{eff}^{-1} = \frac{S}{H} + \frac{w+2(H-h)}{wH}S' + 2\frac{h}{H}\sqrt{\frac{D}{w^2}(\frac{S+S'}{h})} \tag{1}$$

where the first term refers to the interface recombination lifetime, the second term refers to the surface recombination at the sidewalls, and last term refers to transit time out of the modal area. S and S' are the effective surface recombination velocity, D is diffusion coefficient.



(a)



(b)

Fig. 1. Schematic diagrams of (a) cross section of SOI ridge waveguide and (b) the operation principle for generation of ultrafast dark pulse.

In the Fig. 1(b), the nonlinear interaction between CW and pump bright pulse will perform in SOI waveguide when they co-propagating, where the wavelengths of CW and pump pulse are set at the λ_c at 1500 nm and λ_d at 1550 nm, respectively. After the CW is modulated by the pump pulse, it will pass through the filter that makes the pump pulse be turned off as a result that the dark pulse is obtained at the end of the device at wavelength of 1500 nm.

The nonlinear propagation equations modified of CW and pump pulse in SOI waveguide can by described by [7, 8]

$$\begin{aligned}&\frac{\partial A_c}{\partial z}+\beta_{c1}\frac{\partial A_c}{\partial t}+i\frac{1}{2}\beta_{c2}\frac{\partial^2 A_c}{\partial t^2}-\frac{1}{6}\beta_{c3}\frac{\partial^3 A_c}{\partial t^3}=\\&-\frac{1}{2}\alpha_{cl}A_c-\frac{1}{2}\alpha_{cFC}A_c-\frac{1}{2}\frac{\beta_{ccTPA}}{A_{cAeff}}|A_c|^2A_c-\frac{\beta_{cdTPA}}{A_{cAeff}}|A_d|^2A_c\\&+i\gamma_{c,c}|A_c|^2A_c+i2\gamma_{c,d}|A_d|^2A_c+i\frac{2\pi}{\lambda_c}\Delta n_{\lambda c}A_c\end{aligned} \quad (2)$$

$$\begin{aligned}&\frac{\partial A_d}{\partial z}+\beta_{d1}\frac{\partial A_d}{\partial t}+i\frac{1}{2}\beta_{d2}\frac{\partial^2 A_d}{\partial t^2}-\frac{1}{6}\beta_{d3}\frac{\partial^3 A_d}{\partial t^3}=\\&-\frac{1}{2}\alpha_{dl}A_d-\frac{1}{2}\alpha_{dFC}A_d-\frac{1}{2}\frac{\beta_{ddTPA}}{A_{dAeff}}|A_d|^2A_d-\frac{\beta_{dcTPA}}{A_{dAeff}}|A_c|^2A_d\\&+i\gamma_{d,d}|A_d|^2A_d+i2\gamma_{d,c}|A_c|^2A_d+i\frac{2\pi}{\lambda_d}\Delta n_{\lambda d}A_d\end{aligned} \quad (3)$$

where the subscript c and d denote CW and pump pulse, respectively. A is the slowly varying pulse envelope, β_1, β_2, and β_3 the first-, second-, and third-order dispersion coefficients. The parameter β_1 is related to the group velocity v_g of the pulse by $v_g=1/\beta_1$, while β_2 governs the effect of GVD, β_3 governs the effects of TOD and becomes important for ultrashort pulses because of their wide bandwidth. $\gamma=2\pi n_2/\lambda A_{Aeff}$ is the nonlinear parameter (n_2 is the nonlinear coefficient, and A_{Aeff} is known as the effective core area, λ is the center wavelength of optical wave.), α_l is the linear propagation loss. α_{FC} is the FCA coefficient, β_{TPA} is the TPA coefficient, which has identical values for all kinds of TPA processes. The first four terms on the right-hand side of each equation denote the propagation loss, FCA loss, degenerate TPA and non-degenerate TPA, respectively. The next two terms represent the self-phase modulation and cross-phase modulation, respectively, and the final term describes free carrier dispersion that is related to efficient index change Δn that can be described by

$$\Delta n_{\lambda c,d}=-8.8\times10^{-22}\cdot(\frac{\lambda_{c,d}}{1.55})^2\Delta n_e-8.5\times10^{-18}\cdot(\frac{\lambda_{c,d}}{1.55})^2(\Delta n_h)^{0.8} \quad (4)$$

and FCA coefficient is written as

$$\begin{aligned}\alpha_{FC}&=8.5\times10^{-18}\cdot(\frac{\lambda_{c,d}}{1.55})^2\Delta n_e+6.0\times10^{-18}\cdot(\frac{\lambda_{c,d}}{1.55})^2\Delta n_h\\&=\sigma\cdot n\\&=\sigma_0\cdot(\frac{\lambda_{c,d}}{1.55})^2 n\end{aligned} \quad (5)$$

where The coefficient $\sigma_0=1.45\times10^{-17}cm^2$ is the free-carrier absorption cross section measured at $\lambda=1.55\mu m$. $n=n_e=n_h$ is the density of electron-hole pairs generated by the TPA and non-degenerated TPA processes, and given by

$$\begin{aligned}\frac{dn}{dT}=-\frac{n}{\tau_{eff}}&+\frac{\beta_{ccTPA}}{2\hbar\omega_c}(|A_c(z,t)|^2\cdot A_{cAeff}^{-1})^2+\frac{\beta_{ddTPA}}{2\hbar\omega_d}(|A_d(z,t)|^2\cdot A_{dAeff}^{-1})^2\\&+\frac{\beta_{cdTPA}}{\hbar\omega_d}(|A_d(z,t)|^2\cdot A_{cAeff}^{-1})^2+\frac{\beta_{dcTPA}}{\hbar\omega_c}(|A_c(z,t)|^2\cdot A_{dAeff}^{-1})^2\end{aligned} \quad (6)$$

To observe the characters of ultrafast dark generated, the Eqs. (1)~(6) can be solved numerically with determined boundary conditions. In the following section, the detailed simulation investigations will be presented.

3. Simulation results and discussion

According to literatures [6, 9], the simulation parameters adopted are shown in Table 1.

Table 1. Simulation parameters

Parameter	Definition	Value
n_2	Nonlinear coefficient	$6\times10^{-18}\ m^2.W^{-1}$
β_{c1}	The first-order dispersion at CW wavelength	1.353×10^{-8}s.m^{-1}
β_{c2}	The second-order dispersion at CW wavelength	$0.2ps^2.m^{-1}$
β_{c3}	The third-order dispersion at CW wavelength	$3.8\times10^{-3}ps^3.m^{-1}$
β_{d1}	The first-order dispersion at dark pulse wavelength	1.351×10^{-8}s.m^{-1}
β_{d2}	The second-order dispersion at dark pulse wavelength	0
β_{d3}	The third-order dispersion at dark pulse wavelength	$4.0\times10^{-3}ps^3.m^{-1}$
$\alpha_{cl,\ dl}$	Waveguide linear loss coefficient	$0.22dB.cm^{-1}$
β_{TPA}	Two-photon absorption coefficient	$0.8cm.GW^{-1}$
W	Rib waveguide width	$900nm$
H	Rib height	$780nm$
h	Slab height	$390nm$
$S,S^{'}$	Effective surface recombination velocity	$80m.s^{-1}$
D	Diffusion coefficient	$16cm^2.s^{-1}$
$\hbar$	Reduced Planck constant	$1.06\times10^{-34}J.s$

The pump pulse is assumed to be Gaussian in shape as $A_d(0,\ T)=(P_{d0})^{1/2}exp[-1/2.(T/T_{d0})^2]$, and the input CW signal is expressed as $A_s(0,\ T)=(P_{s0})^{1/2}$. In this paragraph, we will focus on the influence of initial pump energy on the contrast of dark pulse generated. Fig. 2 shows the profiles of formed dark pulse at the end of 5-mm-long SOI waveguide with different input pump power. The system parameters adopted were shown in Table 1, and other coefficients such as T_{d0}=100fs, and P_{s0}=1mW, and to ignore the influence of group velocity dispersion (GVD), i.e., second-order dispersion, on the pump pulse, we make the GVD be zero.

As can be seen from the Fig. 2, the ultrafast dark pulse is generated after pump pulse and CW passing together through the waveguide, and the contrast of dark pulse is increased gradually with the increase of launch pump power, i.e., when the launch pump power varies from 4 W to 8 W, the contrast of dark pulse is increased from 4.13 dB to 7.37 dB.

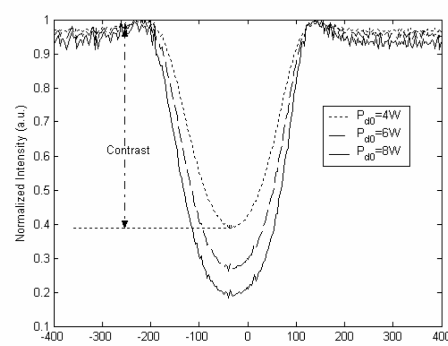


Fig.2 The profiles of dark pulse generated at the end of 5-mm-long waveguide for different input pump power: P_{d0}=4W, contrast=4.13dB; P_{d0}=6W, contrast=5.83 dB; P_{d0}=8W, contrast=7.37 dB.

The physical mechanism of dark pulse generation can be described that when pump pulse and CW are co-propagating along the silicon waveguide, the CW will be modulated by the pump pulse by means of non-degenerate TPA process, where the combined energy of one pump photon and one CW photon will exceed the band gap energy of silicon so that the CW energy of the overlapping region between both of optical fields will reduced quickly owing to the non-degenerate TPA as a result that the CW is modulated invertedly. As a consequence, the ultrafast dark pulse can be achieved at the end of SOI waveguide. In addition, the contrast of generated pulse is 4.13dB in the case of P_{d0}=4W, nevertheless, which may be improved by increasing the launch pump power. The behave can be explained that with the increase of pump power, the process of non-degenerate TPA will also become strong comparing to the case of lower pump power, which will lead to that more CW energy is absorbed due to non-degenerate TPA, namely, CW is modulated further. For example, in the cases of P_{d0}=6W and 8W, the pulse contrasts are increased to 5.83dB and 7.37dB, respectively. In the figure, another noticeable issue is that pulsewidth of dark pulse is equal to ~200fs at full width of half contrast, or so, which is large comparing with the input pulsewidth of pump pulse because of the effect of GVD. Based on the above analysis, we may be increase the initial pump power for obtaining higher pulse contrast when other parameters are fixed. In fact, the waveguide length is also very important parameter for improving the pulse contrast. In the following part, various waveguide lengths will be attended.

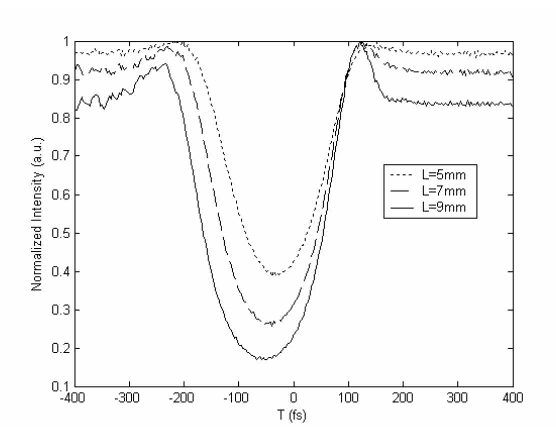


Fig. 3. The profiles of dark pulse generated with P_{d0}=4W for different waveguide length: L=5mm, contrast=4.13dB; L=7mm, contrast=5.89dB; L=9mm, contrast=7.69dB.

Fig. 3 plots the profiles of generated dark pulses with three cases of *L*=5mm, 7mm, 9mm, respectively. From the figure, it is clearly shown that the contrast and pulsewidth of generated pulse is increased proportionally as extending the waveguide length. Originations of these phenomena are that the nonlinear interaction distance is remarkably extended with increase of waveguide length as a result that more energy will be absorbed for CW due to non-degenerate TPA process so that the pulse contrast is also improved, i.e., when the waveguide length varies from 5mm to 9mm, the pulse contrast can be increased from 4.13dB to 7.69dB. In addition, because the group velocity of pump pulse is larger than that of CW in waveguide, the generated dark pulse, i.e., invertedly modulated pulse, will shift forward in time window. The pulsewidth will also obtain spread due to the combined effects of GVD and group velocity mismatch between both of optical fields, which can be broadened to ~250fs in the case of *L*=9mm. Therefore, to improve the pulse contrast, we can extend the waveguide length when other parameters are determined.

4. Conclusions

To generate ultrafast dark pulse, we have proposed and demonstrated a novel modeling device based on the integrated SOI optical waveguide. The ultrafast dark pulse can be achieved by utilizing the nonlinear process of non-degenerate TPA. By means of numerically solving the system equations, simulation results show that the contrast of generated pulse is dependent strongly on the initial pump power and waveguide length that may be increased for obtaining higher pulse contrast. In addition, the pulsewidth will also be extended because of the combined effects of GVD and group velocity mismatch.

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