Optics & Laser Technology 71 (2015) 50–54

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Spectral–temporal description of dispersive wave emission and soliton trapping in micro-nano silicon-on-insulator waveguides

Jin Wen*, Chengju Ma, Wei Fan, Haiwei Fu

School of Science, Xi'an Shiyou University, Xi'an 710065, China

ARTICLE INFO

Article history:
Received 13 November 2014
Received in revised form
19 January 2015
Accepted 12 February 2015

Keywords:
Dispersive wave
SOI waveguide
Supercontinuum

ABSTRACT

We numerically investigate the dispersive wave emission and soliton trapping in the process of femtosecond soliton propagation in silicon-on-insulator (SOI) waveguide. The cross-correlation frequency resolved optical gating (X-FROG) technique is employed to analyze the spectral–temporal dynamics of the soliton at different propagation distances. The numerical results show that dispersive wave emission can be blue-shifted (around 1300 nm) or red-shifted (around 1900 nm), which is determined by the dispersion slope for the pump wavelength (1550 nm). In addition, it can be found that red-shifted dispersive wave can supply contribution to the flatness of the supercontinuum generation. Through increasing the peak power of the soliton to 100 W, the soliton trapping can be observed by the edge of dispersive wave, which can be visualized in the form of multi-peak oscillation structure in the spectrogram when not considering the two-photon absorption (TPA). This work opens up the possibility for the realization of dispersive wave emission device in highly integrated circuit.

1. Introduction

Supercontinuum has important potential applications in the fields such as optical communication, spectroscopy, and optical coherence tomography [1–5]. In the process of supercontinuum generation, a high-order soliton breaks into fundamental components by soliton fission, which plays a crucial role in formation of supercontinuum [6]. The resonant dispersive wave emission originates from the fundamental soliton propagation perturbed by high order dispersion, which is of the key importance in blue-shifted supercontinuum generation [7]. In order to realize the efficient resonant dispersive emission, the phase matching condition between the propagating fundamental solitons and dispersive waves must be satisfied due to the cooperation of the dispersion and nonlinearity [8]. Considerable efforts have been devoted to investigating the dispersive wave emission in highly nonlinear fibers [9,10]. The conventionally points indicate that dispersive wave emission is the caused by the amplification of linear wave. In 2013, Webb et al. have demonstrated that dispersive wave emission in nonlinear fiber optics is not limited to soliton-like pulse propagating in anomalous dispersion regime [11]. Their results provide the significant insights into the initial stage of supercontinuum generation.

SOI waveguides are promising candidates for supercontinuum generation owing to their advantages of employing an emerging silicon integrated photonics platform and large nonlinear coefficient in broadband wavelength range [12]. The SOI waveguide has a smaller transverse dimension governing the dispersion properties so that the dispersion properties can be tailored flexibly by designing the transverse dimension properly [13,14]. Meanwhile, the optical intensity used is a moderate input power due to high optical confinement in waveguide caused by the high index contrast, therefore the nonlinear optical effects are enhanced intensely [15,16]. Currently, the dispersive wave emission in SOI waveguide is significant due to the practical application in supercontinuum generation. In 2014, Lau et al. reported the first demonstration of octave-spanning supercontinuum generation on a silicon chip, which is characterized by soliton fission and dispersive radiation across two zero group-velocity dispersion wavelengths [17].

In this paper, the dispersive wave emission and soliton trapping in micro-nano SOI waveguide is investigated based on the generalized nonlinear Schrödinger equation (GNLSE). The numerical results show the wavelength of the dispersive wave emission can be blue-shifted or red-shifted depending on the dispersion slope for the central wavelength of the pump, which is directly related to the third-order dispersion coefficient. The X-FROG technique is used to describe the spectral–temporal characteristics of dispersive wave emission. With the increase of peak power, the soliton trapping can be observed from the numerical X-FROG

* Corresponding author.
E-mail address: wenjin@opt.ac.cn (J. Wen).

http://dx.doi.org/10.1016/j.optlastec.2015.02.009
0030-3992/

trace. The shape of the soliton trapping can be visualized in the form of multi-peaks oscillation structure in spectrogram when the TPA effect is not considered. Specially, the red-shifted dispersive wave emission can supply contribution to the flatness supercontinuum generation.

2. Numerical modeling

For the numerical model of the femtosecond soliton propagation in SOI waveguide, a well-known GNLSE can be used by [18],

$$\frac{\partial A}{\partial z}=\sum_{m=2}^{\infty}\frac{i^{m+1}\beta_m}{m!}\frac{\partial^m A}{\partial t^m}-\frac{1}{2}(\alpha_l+\alpha_f)A$$

$$+i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)A(z,\ t)\times\int_{-\infty}^{t}R(t-\tau)\left|A(z,\ \tau)\right|^2 d\tau. \quad (1)$$

where $A=A(z, t)$ is the pulse time domain envelope, t is the time in a reference frame moving at the group velocity of the input pulse, z is the longitudinal coordinate along the SOI waveguide. The α_l and α_f account for the linear losses and the free-carrier absorption (FCA) of the waveguide, respectively; β_ms are dispersion coefficients at center frequency ω_0, γ denotes the nonlinear coefficient of the waveguide, which is defined as $\gamma=n_2k_0/a_{eff}+i\beta_{TPA}/a_{eff}$, n_2 is the nonlinear refractive index parameter of SOI waveguide, the parameter k_0 is the wave vector, and a_{eff} is the effective area; β_{TPA} is the TPA coefficient. The influence of the FCA is from the nonlinear loss $\alpha_f=\sigma N_c(z, t)$, where $N_c(z, t)$ is the density of free carriers. The density of free-carrier $N_c(z, t)$ can be obtained by solving the following: [13]

$$\frac{\partial N_c(z,\ t)}{\partial t}=\frac{\beta_{TPA}}{2h\nu_0}\frac{\left|A(z,\ t)\right|^4}{a_{eff}^2}-\frac{N_c(z,\ t)}{\tau}, \quad (2)$$

where τ is the effective carrier life time [19], h is Plank constant and ν_0 is the central frequency. All of the parameters above have been considered in our numerical model, the initial injected soliton is assumed to have a hyperbolic secant field profile

$$A(0,\ T)=\sqrt{P_0}\mathrm{sech}\left(\frac{t}{T_0}\right), \quad (3)$$

here P_0 is the peak power of the input soliton. The order of input soliton N satisfies the condition of the following:

$$N^2=\mathrm{Re}(\gamma)P_0T_0^2/\beta_2, \quad (4)$$

The right-hand side of Eq. (1) represents the nonlinear response of the SOI waveguide with the response function of $R(t)$, which can be written as

$$R(t)=(1-f_R)\delta(t)+f_Rh_R(t). \quad (5)$$

where the value of $f_R=0.043$, which is smaller than that of silica fibers. $\delta(t)$ is the delta function, which is used to express corresponding nonlinear process. The function of h_R can be written as [20]

$$h_R=\frac{\tau_1^2+\tau_2^2}{\tau_1^2\tau_2^2}\exp\left(-\frac{t}{\tau_2}\right)\sin\left(\frac{t}{\tau_1}\right). \quad (6)$$

where $\tau_1=10$ fs and $\tau_2=3.03$ ps.

It is well known that Soliton fission and dispersive wave emission is the basic mechanism of the supercontinuum generation in SOI waveguide. A phase matching condition between the soliton and dispersive wave must be satisfied in the process of dispersive wave emission [21]

$$\beta(\omega_R)-\beta(\omega_s)-\beta_1(\omega_s)(\omega_R-\omega_s)=\sum_{m\geq 2}\frac{\beta_n(\omega_s)}{m!}(\omega_R-\omega_s)^m=\frac{\gamma_0(\omega_s)P_0}{2} \quad (7)$$

where $\beta(\omega_s)$ and $\beta(\omega_R)$ are the frequency dependent wave vector of the soliton and dispersive wave, respectively. In Eq. (7), the sign of P_0 has the same meaning as in Eq. (3), which denotes the input soliton peak power. γ_0 is the nonlinear coefficient calculated at ω_s, which can be written as $\gamma_0=n_2k_0/a_{eff}$. The discrete solution of the Eq. (7) can give the prediction of the frequencies of the dispersive waves. To visualize the results exactly, we consider the pulse propagation simultaneously in time and spectral domain using the well-known X-FROG spectrograms [24]. In this research, the numerical X-FROG traces were numerical computed with a window Fourier transform of the field envelope

$$S(t,\ \omega)=\left|\int_{-\infty}^{+\infty}dt' A_{ref}\left(t'-t\right)A\left(t'\right)e^{-i\omega t}\right|^2. \quad (8)$$

where A_{ref} is the envelope of the reference pulse and A is the envelope of the field inside the SOI waveguide, respectively. Commonly, we use the pump pulse as the reference pulse. In addition, we plot the spectrograms on the logarithmic color scale normalized to $S_0(t, \omega_0)$.

3. Numerical results and discussion

The waveguide used in simulation is straight slab waveguide as shown in Fig. 1(a). Correspondingly, the TE mode profile and TM mode profile distribution of the SOI waveguide are shown in Fig. 1(b). The dispersion properties of the waveguide play an important role in the process of femtosecond soliton propagation. The zero-dispersion wavelength (ZDWL) must be designed to be around the central wavelength of the pump (1550 nm). We have shown that ZDWL of such waveguide can be tailored to fall in this regime with a suitable design. The ZDWL of the TE mode and TM mode can be tailored to below the pump wavelength for straight waveguide as shown in Fig. 2 when both the width and height of the waveguide are close to 0.8 μm. The width and height of waveguide are assumed as $W=0.8$ μm and $H=0.6$ μm, respectively.

As shown in Fig. 2, the effective refractive index of the TE mode (n_{effTE}) and TM mode (n_{effTM}) are calculated using the full-vector finite difference mode solver [22]. Furthermore, the second dispersion

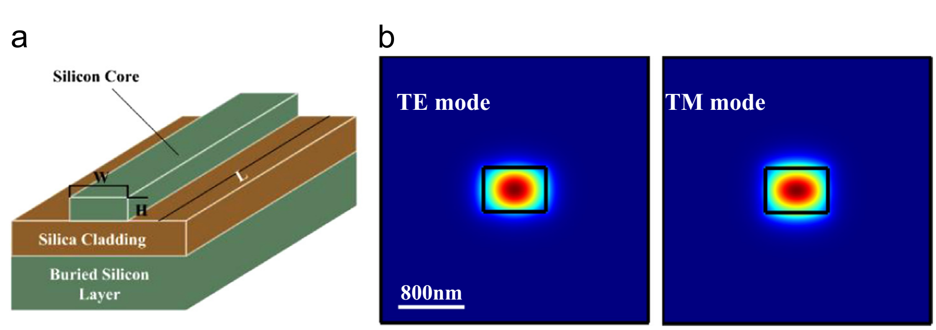

Fig. 1. (a) SOI waveguide schematic. The lower cladding material is SiO_2 and the upper cladding material is air. $W=$ 0.8 μm denotes the width of the waveguide, and $H=0.6$ μm is the height of the waveguide. L is the length of the waveguide. (b) TE mode profile and TM mode profile.