Optics & Laser Technology 44 (2012) 954–959

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

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

Enhanced red-shifted radiation by pulse trapping in photonic crystal fibers with two zero-dispersion wavelengths

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ARTICLE INFO

Article history:
Received 24 January 2011
Received in revised form
11 October 2011
Accepted 1 November 2011
Available online 3 December 2011

Keywords:
Red-shifted radiation
Pulse trapping
Photonic crystal fibers

ABSTRACT

A theoretical investigation on the two pulses copropagation and the red-shifted radiation generation in a photonic crystal fiber with two zero-dispersion wavelengths are presented. It is found the intensity of the red-shifted radiation components can be enhanced when the fiber is pumped with two pulses and the pulse trapping occurs. As the input peak power of the pump pulse is increased under the phenomenon of pulse trapping, the intensity of the red-shift radiation can be further enhanced. The above effects can be explained by the energy transfer from the Raman soliton to the red-shifted radiation components due to the effect of pulse trapping and the effect of higher-order dispersion.

1. Introduction

Photonic crystal fibers (PCFs) commonly consist of a fused silica core surrounded by an ordered array of microscopic air holes that serves as a cladding [1]. PCFs possess numerous unusual properties, such as "endlessly sing-mode" behavior [2], novel group velocity dispersion characteristics at visible and near infrared wavelengths [3], and enhanced effective nonlinearity due to the reduced mode size in the core [4]. This combination of the unique dispersion properties and enhanced nonlinearities has made the PCFs to be a promising medium for the nonlinear interaction studies, such as supercontinuum generation [5–10] in PCFs, which have been used in a variety of applications [11–15]; side band generation by four-wave mixing [16,17]; soliton self-frequency shift (SSFS) due to Stimulated Raman scattering (SRS) [18]; blue-shifted radiation generation by Raman soliton in PCFs with a single zero-dispersion wavelengths (ZDW) and the blue-shifted radiation generation mechanism is mainly due to the positive third-order dispersion (TOD) [5,19–20]; red-shifted radiation generation [21] by Raman soliton in PCFs with two ZDW, which is typically not observed in fibers with a single-ZDW. In fibers with a single ZDW, only blue-shifted radiation called Cherenkov radiation [22] is observed because the TOD is always positive ($\beta_3 > 0$). However, in a PCF with two ZDW, TOD is positive near the first ZDW and TOD is negative near the second ZDW, in the case of $\beta_3 < 0$, the Raman soliton will emit the red-shifted radiation, this phenomenon firstly has been observed by Skryabin et al. in PCFs near the second ZDW [21], which achieved the suppression of SSFS; the phenomenon of pulse trapping by cross-phase modulation in PCFs with a single ZDW [23–24], which firstly has been observed by Nishizawa et al. in the conventional fibers [25]. When a soliton pulse in the anomalous dispersion region satisfies the group velocity matching condition with an optical pulse in the normal dispersion region across the ZDW, the soliton pulse will traps another pulse. That is to say, the two pulses do not walk off and copropagate together along the fiber. The above studies have mainly focused on the nonlinear propagation of a single pulse in PCFs. Less emphasis has been put on the nonlinear propagation of two pulses in a PCF with two ZDW (especially near the second ZDW). In this paper, we study the nonlinear copropagation of two optical pulses and the enhanced red-shifted radiation generation by pulse trapping in a PCF with two ZDW near the second ZDW.

2. Numerical model

To understand the enhanced red-shifted radiation generation by pulse trapping in photonic crystal fibers, we have numerically solved the strict coupled nonlinear Schrödinger equations using a

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doi:10.1016/j.optlastec.2011.11.002

standard split-step Fourier algorithm [26]:

$$\frac{\partial A}{\partial z}+\sum_{n=2}\beta_{nA}\frac{i^{n-1}}{n!}\frac{\partial^n}{\partial T^n}A=i\gamma_A\left(|A|^2A+2|B|^2A+\frac{i}{\omega_{0A}}\frac{\partial |A|^2A}{\partial T}-T_RA\frac{\partial |A|^2}{\partial T}\right) \quad (1)$$

$$\frac{\partial B}{\partial z}-d\frac{\partial B}{\partial T}+\sum_{n=2}\beta_{nB}\frac{i^{n-1}}{n!}\frac{\partial^n}{\partial T^n}B=i\gamma_B\left(|B|^2B+2|A|^2B+\frac{i}{\omega_{0B}}\frac{\partial |B|^2B}{\partial T}-T_RB\frac{\partial |B|^2}{\partial T}\right) \quad (2)$$

where A and B represent the amplitudes of the pulse envelopes for the pump pulse and the signal pulse, respectively. z is the longitudinal coordinate along the fiber. $T=t-\beta_{1A}z$ is the time in a reference frame traveling with the pump light, where t is the time and β_{1A} is the first-order dispersion for the pump pulse. β_n is the nth-order dispersion coefficient at the central frequency ω_0. $\gamma=n_2\omega_0/(cA_{eff})$ is the nonlinear coefficient, $n_2\approx 3.0\times 10^{-20}$ m^2/W is the nonlinear refractive index of fused-silica glass, and A_{eff} is the effective mode area of the fiber. ω_{0A} and ω_{0B} are the center angular frequencies for the pump and the signal pulses. $T_R=5$ fs is the coefficient for the Raman scattering. The parameter d is a measure of group-velocity mismatch between the two pulses. The left hand sides of the above equations represent the linear effects; the effects of the chromatic dispersions are included. The right hand sides correspond to the nonlinear effects; self-phase modulation (SPM), cross-phase modulation (XPM), self-steeping (SST), and intrapulse stimulated Raman scattering (ISRS) are considered.

We consider a PCF with two ZDW used in Ref. [27]. The ZDWs of the fiber are 760 nm and 1160 nm. The TOD is positive near the first ZDW (760 nm) and the TOD is negative near the second ZDW (1160 nm). The group velocity dispersion and relative group delay of the fiber are shown in Fig. 1. At a wavelength of 1056 nm, the nonlinear coefficient is estimated to be $\gamma=75.39$ (Wkm)$^{-1}$, and the up to sixth order dispersion coefficients are $\beta_2=-2.3086\times 10^{-5}$ fs^2/nm, $\beta_3=-8.3377\times 10^{-5}$ fs^3/nm, $\beta_4=6.6568\times 10^{-4}$ fs^4/nm, $\beta_5=-2.4\times 10^{-3}$ fs^5/nm, and $\beta_6=2.19\times 10^{-2}$ fs^6/nm. At a wavelength of 1240 nm, the nonlinear coefficient is estimated to be $\gamma=64.2$ (Wkm)$^{-1}$, and the up to sixth order dispersion coefficients are $\beta_2=3.2237\times 10^{-5}$ fs^2/nm, $\beta_3=-3.267\times 10^{-4}$ fs^3/nm, $\beta_4=-7.2225\times 10^{-4}$ fs^4/nm, $\beta_5=6.75\times 10^{-2}$ fs^5/nm, and $\beta_6=-1.7144$ fs^6/nm. $d=1/v_{gA}-1/v_{gB}=0$ fs/nm for the pump wavelength is 1056 nm and the signal wavelength is 1240 nm. The fiber loss is neglected since only a short length of the fiber is considered in the simulations.

The input pulses are assumed to have the forms:

$$A(z=0,T)=\sqrt{P_1}\,\mathrm{sech}(T/T_1) \quad (3)$$

$$B(z=0,T)=\sqrt{P_2}\,\mathrm{sech}((T-T_d)/T_2) \quad (4)$$

where $P_1=A_0^2$ and $P_2=B_0^2$ are the input peak powers of the pump pulse and the signal pulse, respectively. For the pump pulse and the signal pulse, 100 (i.e., $T_1=100$ fs) and 200 fs (i.e., $T_2=200$ fs) transform limited sech^2 pulses are assumed, where T_1 and T_2 are related to the initial full width at half maximum (FWHM) by $T_{FWHM1,2}\approx 1.763T_{1,2}$. T_d is the pulse delay.

3. Numerical results

First, a single pulse nonlinear propagation in a PCF has been simulated using the numerical modeling of Eq. (1) in Ref. [7]. Fig. 2 shows the Spectral (a) and time domain (b) evolution along the fiber pumped with an initially 100-fs (FWHM) linearly polarized pulse in the anomalous dispersion region at 1056 nm near the second ZDW for an input peak power of 500 W. As seen in Fig. 2, the pulse is initially compressed due to the combined

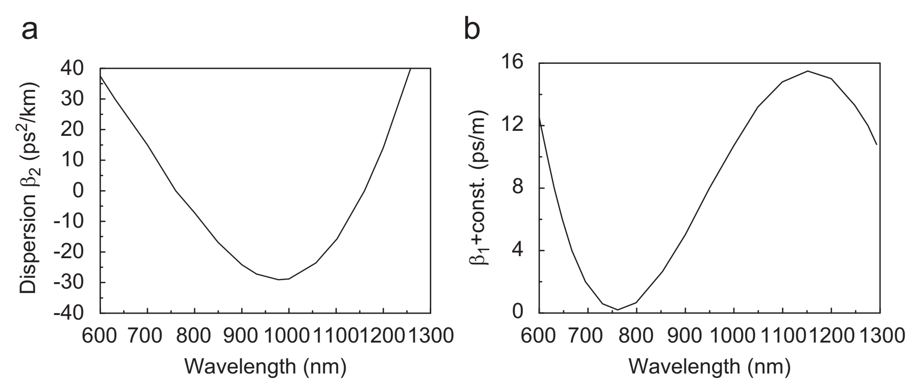

Fig. 1. (a) Group velocity dispersion of the photonic crystal fiber [27]; (b) relative group delay of the photonic crystal fiber [27].

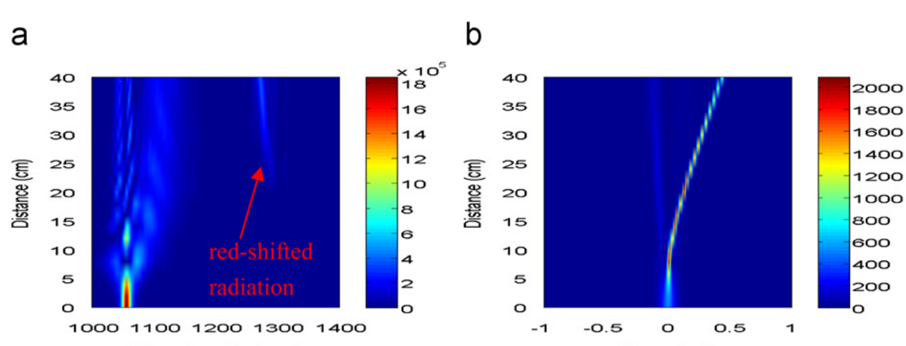

Fig. 2. Spectral (a) and time domain (b) evolution along the fiber pumped with a single pulse in the anomalous dispersion region. $\lambda_0=1056$ nm, $P_0=500$ W.