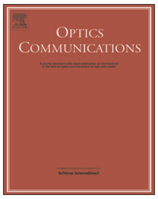
Optics Communications 344 (2015) 134–138

Contents lists available at ScienceDirect

Optics Communications

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



Pulse-by-pulse near 800-nm band power stabilization using all-optical limiter based on self-phase modulation

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ARTICLE INFO

Article history:
Received 7 November 2014
Received in revised form
14 January 2015
Accepted 16 January 2015
Available online 17 January 2015

Keywords:
Nonlinear optics
Optical limiter
Optical stabilizer
Self-phase modulation
Photonic crystal fiber

ABSTRACT

We demonstrate a near 800-nm range all-optical limiter to stabilize pulse-by-pulse peak power fluctuations of near 800-nm optical pulses. The all-optical limiter proposed here relies on intensity-dependent spectral pattern change by self-phase modulation (SPM) under zero-dispersion condition by using a photonic crystal fiber (PCF). The experimental result shows the successful output power stabilization less than 0.36 dB against the 2.0 dB input power fluctuation.

1. Introduction

Optical-pulse-induced ultrafast nonlinear optical effects have been widely used for various photonic applications in academic and industrial fields [1–8]. In the near 800-nm band, ultrafast nonlinear optical effects have often been used for optical fabrication, bio-imaging, and so on with free-space optical systems [5–8], because a number of transparent materials including biological samples have a very low absorption in the near 800-nm band [6,7]. Since nonlinear optical effects are very sensitive to the pulse peak power, a very stable laser sources are strongly required to avoid unexpected damages due to pulse peak power fluctuations. To generate optical pulses for the free-space optical systems using nonlinear optical effects, solid-state lasers such as 800-nm Ti: sapphire lasers and 1064-nm Nd:YAG lasers have been well-developed [8]. To stabilize power fluctuations in laser sources, several techniques have been reported [9–13]. In the near 800-nm band, photo-detector feed-back systems have been generally adopted to stabilize power fluctuations of laser systems and such feed-back systems focus on relatively slow fluctuations (i.e., slower fluctuations than the response speed limit that can be controlled with state-of-the-art electronics). In addition, since they monitor only pulse average power fluctuations, they cannot completely avoid unexpected damages due to pulse peak power fluctuations. In the communication band, several techniques for pulse-by-pulse all-optical limiting have been proposed and demonstrated based on pulse-peak-power-dependent spectral pattern change by self-phase modulation (SPM) in a high nonlinear fiber (HNLF) [9,11,13]. Since SPM can be induced in the near 800-nm band, they would be expected to effectively work on the near 800-nm band too.

In this paper, we investigate a near 800-nm range all-optical limiter based on SPM for pulse-by-pulse power stabilization. We introduced a photonic crystal fiber (PCF) as a substitute of a HNLF in a communication band so that a SPM-based optical limiter could effectively work on the near 800-nm band too. We used a coupling lens for coupling a collimated spatial beam from free space to a PCF. Since the fiber coupling with lenses can cause the unexpected performance of the SPM-based all-optical limiter with a PCF, we carefully examined the behavior of SPM-based spectral change. This examination is important for not only the all-optical limiter but also all the fiber-based systems when the fiber-based systems are applied to the free-space optical systems.

2. Theoretical background

Fig. 1 shows a schematic diagram of an all-optical limiter based on self-phase modulation (SPM). As described in Fig. 1, the function is performed in the following three steps: (i) dispersion adjustment by a dispersion controller, (ii) generation of a SPM-based power-dependent spectral pattern change in a HNLF, and (iii) filtering of power-stationary spectral components by an optical band-pass filter (OBPF).

In the 1st step, a dispersive amplitude U at relative time T of an optical pulse after a dispersion controller is expressed as [15]

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http://dx.doi.org/10.1016/j.optcom.2015.01.046
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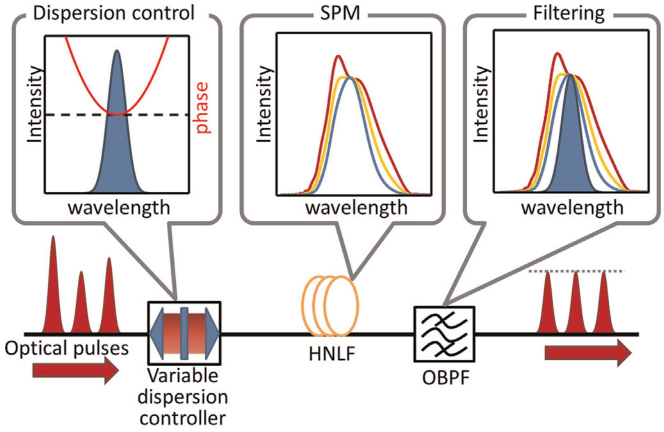

Fig. 1. All-optical limiter based on SPM.

$$U(T;\beta_2)=\frac{T_0}{(T_0^2-i\beta_2)^{1/2}}\exp\left(-\frac{T^2}{2(T_0^2-i\beta_2)}\right), \tag{1}$$

where T_0 is the half-width of the optical pulse at $1/e$-intensity, and β_2 is the group delay dispersion (GDD) given by a dispersion controller. In the 2nd step, the dispersive optical pulse is fed to a HNLF to generate a SPM-based power-dependent spectral pattern change. During propagation in a HNLF, an optical pulse experiences a certain amount of SPM-based phase shift ϕ, which is expressed as

$$\phi(z,T;\beta_2)=|U(0,T;\beta_2)|^2\left(\frac{L_{\rm eff}}{L_{\rm NL}}\right), \tag{2}$$

where z is the propagation distance, $L_{\rm eff}$ is the effective propagation distance related to a fiber loss α by

$$L_{\rm eff}=\frac{1-\exp(-\alpha z)}{\alpha}, \tag{3}$$

and $L_{\rm NL}$ is the nonlinear distance related to both the nonlinear parameter γ and optical pulse peak power P_0 by

$$L_{\rm NL}=(\gamma P_0)^{-1}. \tag{4}$$

From Eq. (2), SPM-based phase shift ϕ is proportional to $|U(0,T;\beta_2)|^2$ and it is a function of β_2 as well as T. Fig. 2 shows an apparatus of a SPM-based phase shift which results in changing a spectrum of a transform limited optical pulse. The instantaneous frequency component of an optical pulse changes according to its instantaneous power because it is given by a differential of a SPM-based phase shift ϕ as described by the following equation:

$$\delta\omega(T;\beta_2)=-\frac{\partial\phi}{\partial T}=-\frac{\partial\left(|U(0,T;\beta_2)|^2\right)}{\partial T}\frac{L_{\rm eff}}{L_{\rm NL}}. \tag{5}$$

From Eq. (5), a SPM-based power-dependent spectral pattern change of an optical pulse can be controlled by adjusting the initial value of GDD β_2 of an optical pulse.

In the 3rd step, the optical pulse after the spectral change is fed to an OBPF to extract the almost stationary power components out of the optical pulse spectral components. Since the output pulse after the OBPF could keep a certain stationary power with no reference to an input power change, the function of an all-optical limiter is completed. In general, an optical pulse in the near 800-nm band cannot effectively induce SPM in a conventional HNLF in the communication band because the zero-dispersion wavelength of such a HNLF is much longer one than the near 800-nm band and GDD is too large to induce SPM. To solve this issue, we examine a PCF in the near 800-nm band to see how it can serve as a substitute of a HNLF in a communication band. A PCF is a kind of a silica fiber with an array of microscopic air holes along its distance, and a specific characteristic of the structure is expected to provide zero-dispersion condition in the near 800-nm band [14]. However, the beam coupling with a coupling lens is essential for the usage of a PCF because a standard fiber connector generally does not well match to a bare PCF and an optical pulse in the near 800-nm band is mostly provided as a collimated spatial beam radiated from a solid state laser too. Fig. 3 shows the apparatus of the beam coupling and phase and pulse fronts of an optical pulse does not match after a coupling lens [16]. Since a coupling lens could lead to such a distortion of an optical pulse with spatially structured spatio-temporal dispersion, we need to carefully examine the behavior of SPM-based spectral change prior to the usage of PCF for optical limiting.

3. Simulation

We investigated the behavior of SPM-based spectral change in a PCF depending on an input pulse power. Fig. 4 shows the power spectrum of the input optical pulse used for simulation which is same as that in an experiment.

Here, we assumed its initial phase to be 0. For comparison, we used a HNLF in a communication band and a PCF in a near 800-nm band. The parameters of the HNLF used for simulation at 1550 nm were following: fiber length $L=20$ m, dispersion parameter $D=-0.04$ ps/nm/km (or -364.84 ps/nm/km at 790 nm), dispersion slope $Sl=0.48$ ps/nm^2/km, nonlinear parameter $\gamma=14.4$ W/km, loss $\alpha=0.19$ dB/km. The parameters of the PCF used for simulation at 790 nm were following: fiber length $L=3$ m, dispersion parameter $D=0$ ps/nm/km, dispersion slope $Sl=0.64$ ps/nm^2/km, nonlinear parameter $\gamma=75$ W/km, loss $\alpha=22.193$ dB/km. Fig. 5(a) and (b) is spectral changes for a HNLF and a PCF, respectively and effective SPM-based spectral changes were generated only for the PCF. While we can directly measure only a pulse average power, actual SPM-based spectral change certainly

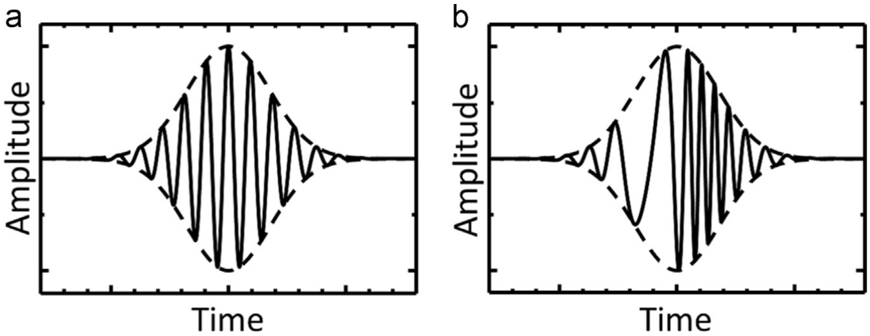

Fig. 2. Temporal phase in an optical pulse (a) before and (b) after SPM-based phase shift.