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Optimized amplification of femtosecond optical pulses by dispersion management for octave-spanning optical frequency comb generation

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A B S T R A C T

We report a method for optimizing the amplification of femtosecond optical pulses by using dispersion management. The amount of dispersion provided to the seed optical pulse of an erbium-doped fiber (EBF) has an optimal region that enhances the output power of an amplifier. The power enhancement is accompanied by spectral broadening, which originates from adiabatic narrowing in the erbium-doped fiber. The amplified optical pulses can be used to generate an octave-spanning optical frequency comb (OFC) by employing a highly nonlinear fiber (HNLF).

1. Introduction

Mode-locked fiber lasers (MLFLs) with an erbium-doped fiber (EDF) operating in the 1.5 μm wavelength region are versatile and reliable devices [1,2]. Ultrashort optical pulses from MLFLs require amplification using an erbium-doped fiber amplifier (EDFA) for many applications in frequency metrology, telecommunication technology and optical imaging because the output from an MLFL is generally less than 10 mW.

EDFAs have been studied for long distance optical communication [3,4]. Pumping with a laser-diode (LD) was achieved in 1989 [5]. Subsequently, many excellent studies have been undertaken on ultrashort optical pulse amplification with EDFAs. For example, there have been reports of the adiabatic gain narrowing of optical pulses with an EDFA [6], optical soliton amplification [7,8] and the spectral narrowing of ultrashort optical pulses by self-phase-modulation (SPM) in optical fibers [9].

At the same time, research on octave-spanning optical frequency comb (OFC) generation with a mode-locked Ti:sapphire laser and photonic crystal fiber (PCF) [10] received considerable attention in 2000 owing to its important contribution to frequency metrology [11,12]. In 2003, optical frequency combs based on the MLFL were broadened with an EDFA and a highly nonlinear fiber (HNLF) [13] or a PCF [14]. Furthermore, optical frequencies have been measured by using fiber-based frequency combs [15]. Recently, a long-term measurement of more than 1 week was reported that used a fiber-based frequency comb has been reported [16]. An MLFL with an EDFA as an optical frequency comb has become a key technology in frequency metrology. Therefore, the optimization of both amplification efficiency and quality are significant issues.

The pre-chirp of a seed pulse input into an EDFA has always been important as regards the optimization of femtosecond pulse amplification. The dependence of EDFA output power on the amount of chirp has already been described [6,13]. According to these reports, spectral broadening is induced by adiabatic narrowing when optical pulses with a slightly negative chirp are launched into an EDFA. In 2004, it was reported that the output power could be increased or reduced by changing the chirp of the seed pulses [17]. The output power decreased with spectral broadening and increased with spectral narrowing.

In the present paper, we report a detailed study of the EDFA characteristics and clarify the optimal conditions for octave-spanning optical frequency comb generation. The amount of dispersion provided to the seed optical pulse of an EDF has an optimal region that enhances the average output power of an EDFA. In the optimal dispersion region, the seed optical pulse from an MLFL is amplified with a high average power and is accompanied by spectral broadening in an EDF. This is the first report to point out the existence of an optimal amount of dispersion enhancing the output power from an EDFA. Furthermore, we found that the optimized amplification

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of an optical pulse is suitable for octave-spanning optical frequency comb generation by using an HNLF.

2. Experimental setup

Fig. 1 is a schematic diagram of our experimental setup. The erbium fiber oscillator is a ring resonator MLFL that employs nonlinear polarization rotation (NPR) as a mode-locking mechanism [2]. The oscillator is pumped by an LD at 980 nm via a wavelength division multiplexing (WDM) coupler. The laser delivers 5 mW of fiber-coupled output average power at a repetition rate of 50 MHz, a pulse width of 70 fs, a spectral full width at half maximum (FWHM) of 40 nm, and a central wavelength of 1560 nm. The net dispersion of the oscillator cavity is estimated to be 0.002 ps^2 at 1550 nm. The pump power is typically 200 mW. We classify the laser as a stretched-pulse oscillator owing to the positive net cavity dispersion, the high laser output power and the broad spectrum [18]. The pulses from the oscillator (at A) are launched into an EDF (at B) via a single-mode fiber (SMF), half and quarter wave plates, and a polarization independent isolator (PII). The SMF has a group velocity dispersion (GVD) $\beta_2 = -0.0223\ ps^2/m$ at 1550 nm. In this report, we call the SMF between the oscillator and an amplifier as a dispersion shifter (DS).

In the amplifier, a 4 m length of EDF, with a peak absorption of 20 ± 2 dB/m at 1530 nm and a mode field diameter (MFD) of 6.5 ± 0.5 μm, is pumped by a 980 nm LD from its output side with a power of 510 mW (at C). We estimated the GVD of the EDF to be approximately +0.019 ps^2/m from the spectral FWHM of our custom made oscillators and the GVD of SMF.

In addition, the output of the EDFA was launched into an HNLF via an SMF between C and D (dispersion compensator: DC). The HNLF broadens the spectrum of the optical pulses as a result of such nonlinear optical effects as SPM.

3. Optimal amplification of femtosecond pulses

This section describes the influence of the chirp of the seed optical pulses on the amplification characteristics. First, we measured the pulse width at B as we changed the length of the DS to normalize the amount of dispersion provided to the pulses from the oscillator (Fig. 2(a) inset). The amount of dispersion providing the smallest pulse width was set at zero. Then, we measured the optical power and spectra of the amplified pulses at D as we changed the amount of chirp of the seed pulses by using the DS. In addition, we set the input power of the EDFA at 5, 1.2 mW, 430 and 40 μW using optical fiber couplers between A and B, and then measured the EDFA output power. We employed a wavelength independent power meter to obtain accurate measurements of the powers of the broadened and changing spectra of the amplified pulses.

Fig. 2(a) shows the input pulse width and the EDFA output power as a function of the DS dispersion. These results showed that the amplifier has an optimal dispersion ϕ_{optimal} region (shaded area in Fig. 2(a)), which enhances the EDFA output power. When input power of the EDFA was 5 mW, its output power was 94 mW when the dispersion was far from its optimal value ϕ_{optimal}. However, the EDFA output power was enhanced to 130 mW when the dispersion was optimal. In this case, the EDFA output power increased approximately 1.4 times. When the input average powers of the EDFA were 1.2 mW and 430 μW, the output powers of the EDFA were similarly enhanced. The optimal amount of dispersion ϕ_{optimal} was approximately $-0.1\ ps^2$ for any input average power of the EDFA. When the input power of the EDFA was 40 μW, the EDFA output power was not enhanced at the optimal amount of dispersion. In this case, the optical pulse was not amplified properly because the spectrum of the amplified pulses was accompanied by a continuous wave (CW) component. To investigate where or not the amplifier output was saturated, we amplified the optical pulses with backward and forward pumping (bidirectional), and increased the total pump power to approximately 1 W. A large increase in the EDFA output power at the optimal value ϕ_{optimal} was also observed as in the previous experiments, and the output power did not saturate.

Fig. 2(b) shows the spectra of the amplified pulses as a function of the dispersion of the DS, which was measured at D in Fig. 1, and the oscillator. The shapes of these spectra strongly depended on the dispersion of the DS, which was reported in [13,17]. This spectral broadening is referred to as adiabatic narrowing in an EDF [6]. It is difficult to determine the spectral and the pulse width of the EDFA output because the spectral and the pulse shape are complicated by the nonlinear optical effects in optical fiber. In this experiment, the increase in the output power of the EDFA was accompanied by spectral broadening ((γ) in Fig. 2(b)). The EDFA exhibited spectral narrowing and output power reduction when the anomalous dispersion was provided to the input pulses of the EDFA ((α and (β) in Fig. 2(b)). Furthermore, we used an LD operating at 1480 nm as pump sources to investigate the difference from the results obtained with an LD operating at 980 nm. An increase in the EDFA output power and spectral broadening of the amplified pulses were also observed when using a 1480 nm LD as a pump source. This result means that the increase in the output power the EDFA does not depend on the pump wavelength.

We believe that ϕ_{optimal} exists for the following reason. In the optimal amplification region, the negatively chirped optical pulse is compressed while it is being amplified. The optical pulse is compressed almost to a Fourier transform limited (FT) pulse, and then positively chirped. Under this condition, the spectrum of the opti-

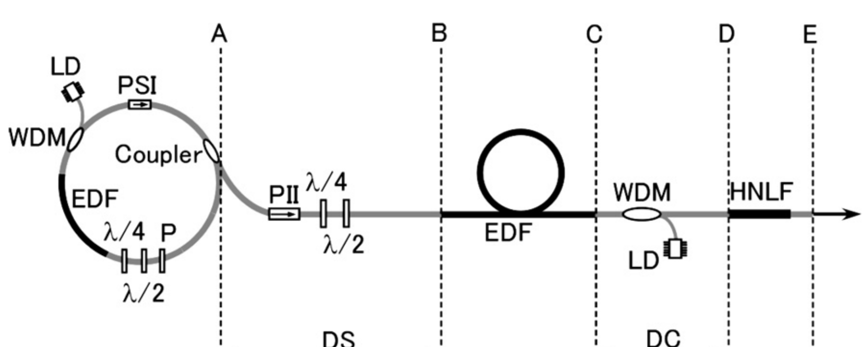

Fig. 1. Schematic diagram of experimental setup. DS: Dispersion shifter between the oscillator and an EDFA, DC: Dispersion compensator between an EDFA and a HNLF, WDM: Wavelength division multiplexing coupler, PSI: Polarization sensitive isolator, PII: Polarization independent isolator, λ/4 and λ/2: quarter and half lambda wave plates, P: Polarizer, HNLF: Highly nonlinear fiber.