Generation of High-Power Femtosecond Pulse and Octave-Spanning Ultrabroad Supercontinuum Using All-Fiber System

Jun Takayanagi, Norihiko Nishizawa, *Member, IEEE*, Hiroyuki Nagai, Makoto Yoshida, and Toshio Goto, *Fellow, IEEE*

***Abstract*—We present the all-fiber system for amplification of high peak power femtosecond pulses. The 260-fs pulses are generated in the passively mode-locked Er-doped fiber (EDF) laser and amplified using the EDF amplifier system. The average and peak powers of the generated pulses are 215 mW and 43.2 kW, respectively, and the pulsewidth is 42.3 fs. Then the amplified pulses are coupled into polarization-maintaining highly nonlinear dispersion-shifted fiber and octave-spanning supercontinuum is generated. The spectral range is widely expanded from 980 to 2570 nm. To the best of our knowledge, this bandwidth is the maximum one in this wavelength region.**

***Index Terms*—Nonlinear optics, optical fiber amplifiers, optical fiber lasers, optical pulse amplifiers, optical pulses.**

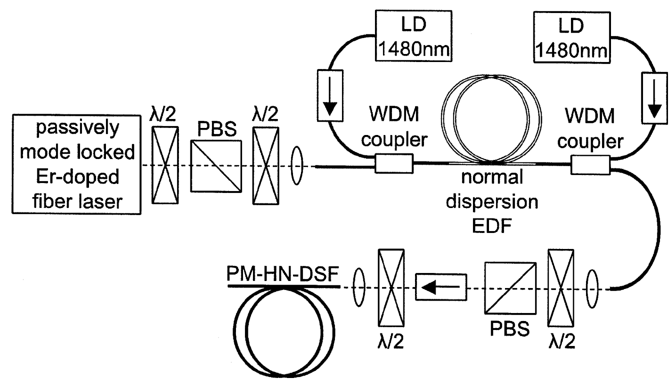

Fig. 1. Experimental setup for generation of high-power femtosecond pulse and ultrabroad SC.

I. Introduction

ULTRASHORT pulse source is important source for a lot of applications, such as ultrafast optelectronics, ultrafast spectroscopy, or three-dimensional microfabrication, etc. The techniques of the femtosecond laser have been developed rapidly and today we can generate the femtosecond pulses in many ways. One of these remarkable techniques is the fiber laser that uses rare-earth doped optical fibers [1]–[3]. This laser has a compact system and can output stable pulses compared with the other solid-state lasers represented by Ti : sapphire laser because it consists of only optical fibers and can eliminate spatial couplings. And it has other advantages, such that we can use cheap and compact diode lasers for excitation or that it does not need the delicate maintenance.

Recently, the supercontinuum (SC) with broad spectral bandwidth attracted concern of many researchers [4], [5]. It is expected for application to ultrafast spectrometry, frequency metrology, optical coherence tomography, and extreme-short pulse generation [6]–[8]. For these applications, the magnitude of bandwidth is the important factor. The SC can be generated by use of high peak power ultrashort pulses and special fibers with high nonlinearity. So far, we have demonstrated 1.1–2.2 μm widely broadened SC using Er-doped fiber (EDF) laser and polarization-maintaining highly nonlinear dispersion-shifted fiber (PM-HN-DSF) [9]. Using the fiber laser as a pump light source, the system becomes very compact and stable compared with the Ti : sapphire laser and the photonic microstructure fiber systems. The wavelength region of SC covers the entire band that used for optical communication so it is attractive for practical application. For these reasons, several SC generations using a fiber laser were reported until now [3], [9]–[11].

In this letter, we present the widely broadened SC sources from the fiber laser system. To broaden the bandwidth of SC, we used the high peak power ultrashort pulses produced by EDF amplifier system. This amplifier system consists of only one fiber and has no excessive spatial couplings. The difference of group-velocity dispersion (GVD) between EDF and single-mode fiber (SMF) enables effective amplification and pulse compression. The octave spanning SC is generated using PM-HN-DSF.

II. Experimental Setup and Results

The experimental setup is shown in Fig. 1. The passively mode-locked fiber laser generates the 260-fs sech^2-like femtosecond pulses at repetition frequency of 48 MHz. The center wavelength is 1.56 μm and the average power is 8 mW. After power modulation by use of a half-wave plate and a polarization beam splitter (PBS), the pulses are coupled into the 8-m-long EDF. For the characteristics of the EDF, the dispersion parameter and the mode field diameter are 6.18 $\mathrm{ps}^2/\mathrm{km}$ and 8.0 μm, respectively. It shows that the pulses operate in normal dispersion regime. Two laser diodes excite the EDF through two wavelength-division-multiplexing (WDM) couplers spliced

Manuscript received June 3, 2004; revised August 30, 2004.
J. Takayanagi, N. Nishizawa, and T. Goto are with the Department of Quantum Engineering, Nagoya University, Nagoya 464-8603, Japan (e-mail: J_takaya@nuee.nagoya-u.ac.jp).
H. Nagai and M. Yoshida are with the Business Planning Office Optics Annex, AISIN SEIKI Co., Ltd., Kariya 448-0003, Japan.
Digital Object Identifier 10.1109/LPT.2004.837741

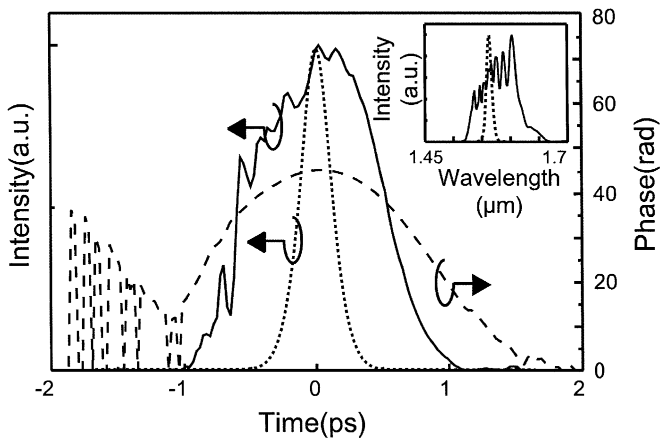

Fig. 2. Temporal and spectral waveform (solid line) and phase (broken line) of the pulses after propagation of normal dispersive EDF. Dotted line represents incident pulses.

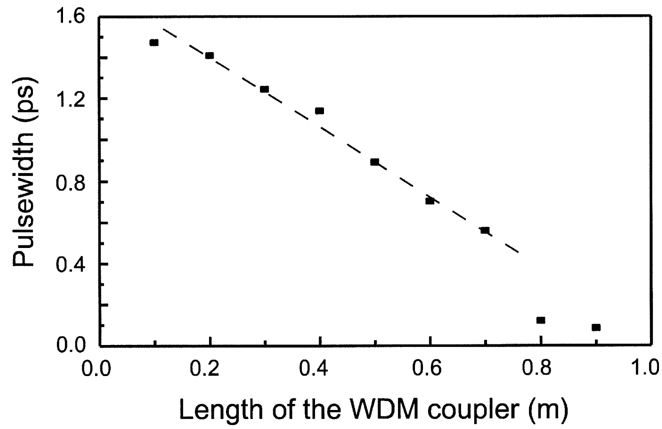

Fig. 3. Observed compressed pulsewidth measured by the autocorrelator as a function of the length of the WDM coupler.

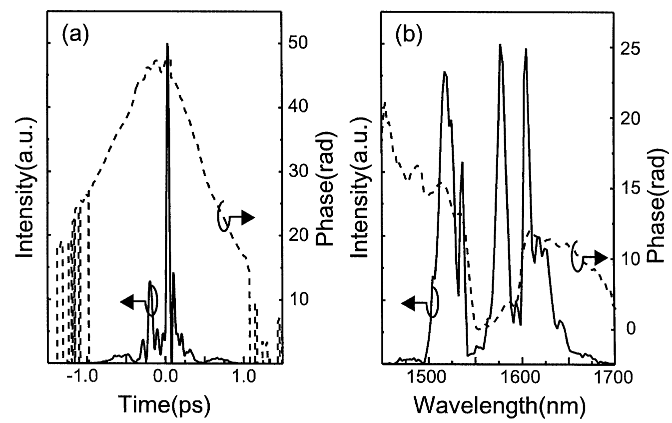

Fig. 4. Reconstructed (a) temporal waveform and (b) optical spectrum of generated high peak power femtosecond pulses.

with both edges of the EDF. The fiber type of the WDM couplers is SMF-28, of which dispersion parameter β_2 is -21.4 ps^2/km. The oscillation wavelength of the pump LD is 1480 nm and the output power is 400 mW. The pulses broaden their temporal width while propagating the EDF so that their energy is amplified with keeping their peak power low. Thus, the excessive nonlinear effects can be avoided. The WDM coupler spliced at the output port compensates the chirping with its anomalous dispersion property and the amplified pulses experience the higher order soliton compression. In this all-fiber system, the splicing loss can be suppressed to be about zero. By adjusting the length of the WDM coupler, we find out the optimized condition (the shortest pulsewidth and the highest peak power). Finally, the half-wave plate and the PBS are used to pick off only linearly polarized components from the output pulses.

The characteristics of the output pulses are observed using power meter, autocorrelator, optical spectrum analyzer, and second-harmonic generation (SHG)-type frequency-resolved optical gating (FROG) system. In the FROG system, 0.5-mm-thick BBO crystal is used for the nonlinear crystal. The generated sum frequency signals are observed using monochromator, photomultiplier tube, and lock-in amplifier.

Fig. 2 shows the temporal waveforms (solid line) and the phase (broken line) of the output pulses from the EDF observed by SHG-FROG system. The inset shows the spectrum. The dotted lines are waveforms of the incident pulses. The pulses get linear chirps almost over all. The spectral bandwidth is broadened by the self-phase modulation (SPM) and the oscillatory structure arises in the spectral waveform. The SPM broaden the spectrum symmetrically around 1560 nm. The asymmetry of the spectral broadening seen in Fig. 2 is caused by the filter used to eliminate the residual pump light source. The filter cuts the short wavelength component of the amplified pulses as well as the pump light. In this experiment, the excessive nonlinear effects such as Raman shift did not occur.

Fig. 3 shows the temporal width of the autocorrelation trace of the output pulses as a function of the length of the WDM coupler at the output side. First, the pulses are compressed linearly because of the negative dispersion of the fiber. When the length becomes longer than 0.7 m, the pulses are compressed below 100 fs rapidly. This is because the strengthened peak power by dispersion compensation causes the higher order soliton compression. The still longer fiber length leads to the pulse splitting.

Fig. 4 shows the temporal waveform and spectrum of the observed narrowest pulses. The solid curves represent pulse intensity and the broken lines show phase. The central peak of the temporal waveform has the pulsewidth as narrow as 41.3 fs at full-width at half-maximum and the flat phase. The average power of the output pulses is 215 mW so that we derived the fact that the peak power amounts to 42.3 kW by integrating the temporal waveform. Because of the inherent nature of higher order soliton compression, the small components before and behind the central peak remained without compression. The spectrum consists of three components mainly.

Then we have generated the ultrabroad SC using obtained high peak power pulses and the PM-HN-DSF. For the characteristics of the PM-HN-DSF, the dispersion parameter, the mode field diameter, and the nonlinear refractive index are 1.0 ps/km/nm, 3.7 μm, and 21 $\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$, respectively. In this experiment, we have observed the generated pulse spectrum in PM-HN-DSF by the monochromator and the optical spectrum analyzer. Fig. 5 shows the spectrum of the SC by use of the 5-m-long PM-HN-DSF. The spectrum expands over one octave at least from 980 to 2570 nm. There is the possibility that the spectrum is much broadened to longer wavelength side because

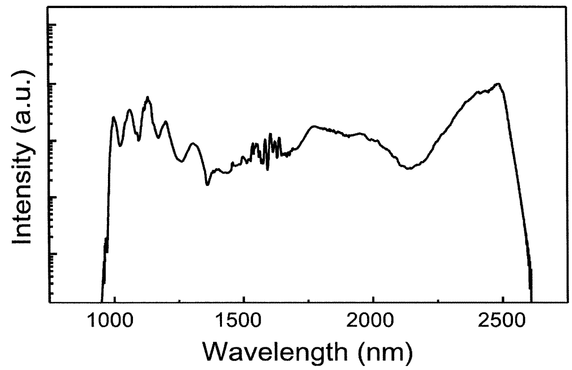

Fig. 5. Optical spectrum of generated ultrabroad SC.

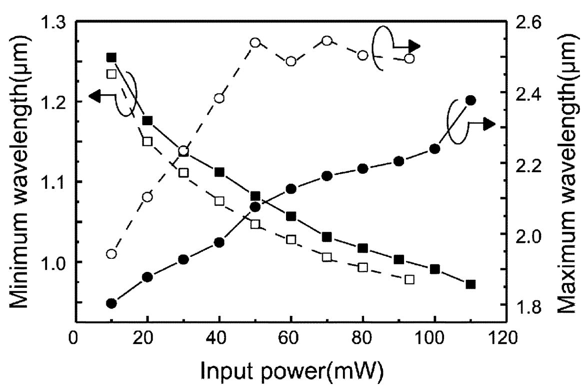

Fig. 6. Wavelength of the longest (circles) and the shortest (squares) wavelength edge of generated SC in 20-cm-long (filled data points and solid line) and 2-m-long (open data points and broken line) PM-HNL-DSFs as a function of the input average power.

our experimental setup does not have sensitivity in a longer wavelength region. The average power of the SC is 78 mW. The bandwidth is as large as 1590 nm at −20-dB level. To the best our knowledge, this bandwidth is the maximum one in this wavelength region.

Fig. 6 shows the wavelength of the shortest and longest wavelength edge of the SC generated in the 20-cm and 2-m-long PM-HN-DSF as a function of the input average power. The shortest wavelength shifts to shorter wavelength side monotonously in both two fibers of different length as the input power increases. In 2-m-long fiber, the longest wavelength saturates with a certain input power, while it shifts to longer wavelength side monotonously in 20-cm-long fiber. It shows the fact that the large fiber loss, which is caused mainly by infrared absorption, degrades the wavelength shift toward the longer wavelength side by soliton self-frequency shift in long fiber. And it shows that the spectral broadening by SPM in the short fiber is not influenced by the fiber loss. So we think that the higher peak power pulses and the fiber with short length enable us to produce more broadened SC.

III. Conclusion

We have demonstrated a very compact and stable system without excessive spatial couplings for generation of SC around 1.55 μm. We have realized the broad SC by amplifying laser pulses using the EDF amplifier system. This amplifier system enables us to attain high peak power efficiently by combining positive GVD of the EDF and negative GVD of the SMF. The pulsewidth and the peak power of obtained pulses are 41.3 fs and 42.3 kW, respectively. By use of the high peak power pulses and the PM-HNL-DSF, we have generated the ultrabroad SC. The spectrum ranges over one octave from 980 to 2570 nm, and the wavelength bandwidth is over 1590 nm and, to the best of our knowledge, this bandwidth is the maximum one in this wavelength region.

We think that it is difficult to generate much broadened SC because of the large fiber loss. At 2.6 μm, the loss of the silica fiber is over 300 dB/km under the influence of infrared absorption. But we think that using higher peak power ultrashort pulses and shorter length fiber make it possible to generate much broadened SC.

References

[1] A. Galvanauskas, G. C. Cho, A. Hariharan, M. E. Fermann, and D. Harter, "Generation of high-energy femtosecond pulses in multimode-core Yb-fiber chirped-pulse amplification system," *Opt. Lett.*, vol. 26, pp. 935–937, 2001.

[2] M. Hofer, M. E. Fermann, A. Galvanauskas, D. Harter, and R. S. Windeler, "Low-noise amplification of high-power pulses in multimode fibers," *IEEE Photon. Technol. Lett.*, vol. 11, no. 6, pp. 650–652, Jun. 1999.

[3] F. Tauser and A. Leitenstorfer, "Amplified femtosecond pulses from an Er:fiber system: Nonlinear pulse shortening and selfreferencing detection of the carrier-envelope phase evolution," *Opt. Exp.*, vol. 11, pp. 594–600, 2003.

[4] J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," *Opt. Lett.*, vol. 25, pp. 25–27, 2000.

[5] V. V. Ravi Kant Kumar, A. K. George, W. H. Reeves, J. C. Knight, and P. S. J. Russell, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation," *Opt. Exp.*, vol. 10, pp. 1520–1525, 2002.

[6] I. Hartl, X. D. Li, C. Chudoba, R. K. Ghanta, T. H. Ko, and J. G. Fujimoto, "Ultrahigh-resolution optical coherence tomography using continuum generation in an air-silica microstructure optical fiber," *Opt. Lett.*, vol. 26, pp. 608–610, 2001.

[7] S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, T. Udem, and T. W. Hänsch, "Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb," *Phys. Rev. Lett.*, vol. 84, pp. 5102–5104, 2000.

[8] L. Li, S. Kusaka, N. Karasawa, R. Morita, H. Shigekawa, and M. Yamashita, "Amplitude and phase characterization of 5.0 fs optical pulses using spectral phase interferometry for direct electric-field reconstruction," *Jpn. J. Appl. Phys.*, vol. 40, pp. L684–L687, 2001.

[9] N. Nishizawa and T. Goto, "Widely broadened super continuum generation using highly nonlinear dispersion shifted fibers and femtosecond fiber laser," *Jpn. J. Appl. Phys.*, vol. 40, pp. L365–L367, 2001.

[10] J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum," *Opt. Lett.*, vol. 28, pp. 643–645, 2003.

[11] J. H. V. Price, W. Belardi, T. M. Monro, A. Malinowski, A. Piper, and D. J. Richardson, "Soliton transmission and supercontinuum generation in holy fiber, using a diode pumped Ytterbium fiber source," *Opt. Exp.*, vol. 10, pp. 382–387, 2002.