A 40 GHz, 770 fs regeneratively mode-locked erbium fiber laser operating at 1.6 μm

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Abstract: We report a 40-GHz harmonically and regeneratively FM mode-locked erbium fiber laser with a phase-locked loop (PLL) circuit operating in the 1.6 μm region. The oscillation wavelength was extended to the L-band by using a 15 m erbium-doped fiber with an Er^{3+} concentration of 3500 ppm as a gain medium. As a result, a 770 fs transform-limited Gaussian pulse with a 14 mW output power was successfully generated with a timing jitter as low as 88 fs. The wavelength is tunable over 20 nm between 1583 and 1603 nm.

Keywords: mode-locked laser, erbium fiber laser

Classification: Integrated optoelectronics

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1 Introduction

To meet the growing demand for higher transmission capacity, the telecommunication band has been expanding from the C-band (1530–1565 nm) to the L-band (1570–1625 nm) [1, 2, 3]. Consequently, an ultrafast mode-locked laser operating at a repetition rate of 10~40 GHz in the 1.6 μ m region is an attractive light source as an L-band high-speed transmitter. It is also useful as a control pulse source for demultiplexing and switching ultrahigh-speed optical signals in the C-band. This is because, as a symbol rate increases or the pulse width is shortened, the signal bandwidth itself becomes as broad as the entire C band. For example, a 300 fs Gaussian pulse (a typical pulse width for a 1 Tbaud symbol rate) has a 3 dB spectral width of 11.7 nm, and the 20 dB spectral width is extended to 30 nm. This bandwidth is comparable to the entire C-band. This makes it very difficult to accommodate both the signal and control pulses within the C-band, and therefore a control pulse in the L-band becomes indispensable. A 1 GHz amplitude-modulated (AM) mode-locked erbium fiber laser has already been demonstrated as a GHz pulse source in the L-band [4]. The pulse width was 2.5 ps and was linearly compressed to 580 fs with external chirp compensation. However, the timing jitter was 700 fs. An ultrashort pulse laser at a repetition rate of >10 GHz and with a low jitter has not yet been realized in this wavelength region.

Among many high-speed pulse sources such as mode-locked laser diodes [5, 6], an actively mode-locked fiber laser (MLFL) with harmonic and regenerative mode-locking is an attractive pulse source with which to generate a transform-limited picosecond pulse to subpicosecond pulse at 10~40 GHz with a low timing jitter [7]. Using this laser as a basis, we have realized various advanced types of

MLFL including a mode-hop-free optical frequency tunable 40 GHz MLFL [8], and a C₂H₂ or HCN frequency-stabilized and repetition-rate-stabilized MLFL at 10~40 GHz [9, 10]. These lasers have been successfully applied to ultrahigh-speed digital coherent and non-coherent transmission experiments at bit rates of 1 Tbit/s and faster [11, 12].

In this paper, we present the first 40 GHz harmonically and regeneratively frequency-modulated (FM) mode-locked erbium fiber laser operating in the L-band. We introduce a 15 m-long EDF with an Er³⁺ doping concentration of 3500 ppm, which was bi-directionally pumped with two laser diodes (LDs), to achieve a high optical gain in this wavelength region. As a result, we successfully obtained a 770~780 fs transform-limited Gaussian output pulse at a wavelength between 1583 and 1603 nm. The repetition rate was locked to an external synthesizer clock with a phase-locked loop (PLL) circuit [13], and the timing jitter was as low as 88 fs.

2 Configuration of a 40 GHz harmonically and regeneratively MLFL in L-band

The configuration of our 40 GHz harmonically and regeneratively FM MLFL in the L band is shown in Fig. 1. As a gain medium, we used an erbium-doped fiber (EDF) whose gain was shifted to the L-band. Fig. 2(a)–(c) show the gain characteristics of 5, 15, and 25 m EDFs, respectively, which were obtained for a pump power of 300 mW and an input signal power of –10 dBm. Here, the Er concentration was 3500 ppm and the absorption was about 36.2 dB/m at 1530 nm. With a 5 m EDF, a gain of more than 30 dB was obtained in the C band but the gain decreased rapidly for a longer wavelength, and it was reduced to 15 dB at 1.6 μm as shown in Fig. 2(a). As the EDF length increases, the wavelength dependence of the gain shifts to a longer wavelength, and at 15 m a gain of more than 24 dB was obtained over a wavelength of 1560~1600 nm with a gain variation of <1.5 dB as shown in Fig. 2(b). However, the gain variation increased for a 25 m EDF as shown in Fig. 2(c) although the average gain increased slightly. Therefore, we used 15 m EDF. Here, taking account of the absorption caused by the increased EDF length, we adopted a bi-directional pumping configuration, in which two 1.48 μm LDs were used for forward and backward pumping, and the pump power of 300 mW in Fig. 2(b) is given by the total power from the two LDs. With forward pumping alone, the gain was less than 10 dB at 1570 nm for a single pump power of 300 mW.

As a mode locker, we used a 40 GHz LiNbO₃ (LN) phase modulator, which was driven by a 40 GHz RF signal at 30 dBm. The 40 GHz clock signal was obtained through a regenerative feedback loop consisting of a 40 GHz clock extraction circuit and a phase controller [7]. This makes long-term stable operation possible because the free-running clock signal always represents the change in the cavity length. As a next step, the repetition rate was stabilized to an external synthesizer clock with a PLL technique, in which the error signal for the repetition rate stabilization was fed back to the fiber cavity via a piezoelectric transducer (PZT) [13] on which part of the fiber cavity was wound.

The average dispersion of the laser cavity is shown in Fig. 3. The fiber cavity included a 70 m dispersion-shifted fiber (DSF), and by installing a 0.6 m dispersion-

Fig. 1. Cavity configuration of 40 GHz L-band harmonically and regeneratively MLFL

Fig. 2. Gain characteristics of (a) 5, (b) 15, and (c) 25 m long EDFs (input signal power: -10 dBm, pump power: 300 mW).

Fig. 3. Average dispersion of fiber cavity.

compensating fiber (DCF) with a dispersion of -148 ps/nm/km, the average dispersion was reduced to ~ 1 ps/nm/km at 1590 nm. The total cavity length was 87.7 m, which corresponds to a fundamental mode spacing of 2.3 MHz. The relatively long cavity length enables the cavity Q value to increase, which can help to reduce the timing jitter of the output pulse. The cavity also includes a 10 nm tunable optical filter. All the fibers in the cavity were polarization maintaining to remove the fluctuations caused by polarization rotation.

3 Output characteristics of 40 GHz L-band MLFL

Fig. 4 shows the output pulse characteristics of a 40 GHz L-band MLFL vs. the pump power, which were measured at 1593 nm. Here the pulse width was estimated from an autocorrelation waveform assuming a Gaussian pulse. As shown in Fig. 4(a), the threshold pump power was 80 mW, and an output power of 14 mW was obtained for a pump power of 500 mW. As shown in Fig. 4(b), the pulse width was 765~790 fs and almost uniform for a pump power of 300~500 mW.

Fig. 5(a) and (b) show an auto-correlation waveform and the optical spectrum of the MLFL, respectively. The pump power was 440 mW. The output pulse width

Fig. 4. Laser output characteristics versus pump power. (a) Output power, (b) pulse width (wavelength: 1593 nm).

Fig. 5. Auto-correlation waveform (a) and optical spectrum (b) of the laser output pulse (wavelength: 1593 nm, pump power: 500 mW).

Fig. 6. RF characteristics of 40 GHz harmonically and regeneratively MLFL. (a) 40 GHz electrical clock signal and (b) SSB phase noise spectrum.

was 1.5 ps, and after compensating for the chirp externally with a dispersion of -0.3 ps/nm using a dispersion-compensating fiber, it was reduced to 770 fs as shown in Fig. 5(a). The spectral shape shown in Fig. 5(b) is well fitted with a Gaussian profile as shown by the black curve. The spectral width was 4.8 nm, corresponding to a time-bandwidth product (TBP) of 0.44. This indicates that a transform-limited Gaussian pulse was successfully generated. Here, a Gaussian pulse rather than a sech pulse was generated by the MLFL output, indicating that the laser operates in a linear regime and nonlinearities do not play a major role. This will be investigated later with numerical simulations.

Fig. 6(a) shows an RF spectrum of a 40 GHz clock measured over a 100 MHz span. Only one clock component can be observed, and the supermode noise was suppressed by 75 dB. In Fig. 6(a), the repetition rate was set at a standard clock frequency of 39.81312 GHz for applications to 40 Gbit/s communication systems. It is also possible to tune the repetition rate within a bandwidth of the electrical filter (~ 40 MHz) in the 40 GHz clock extraction circuit. Fig. 6(b) shows a single sideband (SSB) phase noise power density vs. an offset frequency at the 40 GHz carrier frequency. By integrating the SSB phase noise spectrum from 10 Hz to

Fig. 7. Pulse width and TBP as a function of wavelength (pump power: 440 mW).

1 MHz, the timing jitter was estimated to be 88 fs, while the jitter of a reference synthesizer was 70 fs.

We also measured the wavelength dependence of the output characteristics by tuning the optical bandpass filter in the cavity. The pulse width and TBP as a function of wavelength are shown in Fig. 7. A pulse width of 770~780 fs and a TBP of 0.44 were simultaneously obtained over a 20 nm bandwidth in the L-band. A laser oscillation was not obtained for wavelengths outside this regime, which was limited by a wavelength tunability of the optical filter.

4 Numerical analysis of 40 GHz L-band MLFL

To evaluate the influence of nonlinearities in the fiber cavity, we carried out a numerical simulation of the transient waveform evolution and steady-state pulse propagation inside the cavity. The pulse propagation in the fiber cavity is described by the nonlinear Schrödinger equation

$$-i \frac{\partial u}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 u}{\partial t^2} + \gamma |u|^2 u \quad (1)$$

where $u(z, t)$ is the complex amplitude of the pulse, β_2 is dispersion, and γ is a nonlinear coefficient. We used a split-step Fourier method for calculating Eq. (1). The gain is given by $g = g_0 / (1 + P/P_s)$ where g_0 is the small-signal gain, P is the input power and P_s is the saturation power. The simulation also includes a sinusoidal phase modulation at 40 GHz, assuming a modulation index of 10π , and an optical filter. The present analysis is based on our previous work reported in [14, 15].

Fig. 8(a) shows the evolution of the pulse from amplified spontaneous emission (ASE) noise to steady-state oscillation, and Fig. 8(b) and (c) show a waveform and its optical spectrum in the steady state, respectively, when the output power was 14 mW. Fig. 8(a) shows that a steady state was achieved after ~80 circulations, in which the pulse width was 1.5 ps. After chirp compensation with a dispersion of -0.32 ps/nm, a pulse width of 790 fs and a spectral width of 4.4 nm were obtained as shown in Fig. 8(b) and (c), corresponding to a TBP of 0.44. These results are in

Fig. 8. Numerical results for 40 GHz L-band MLFL. (a) transient evolution from ASE noise, (b) pulse waveform and (c) optical spectrum in a steady state.

Fig. 9. Numerical result of the change in the pulse width inside the fiber cavity in a steady state.

good agreement with the experimental results shown in Fig. 5. We also observed how the pulse width varies inside the fiber cavity under a steady state, which is shown in Fig. 9. SMFs corresponding to fiber pigtailed components are not shown as they are sufficiently short and do not affect the pulse propagation. The pulse width changes dynamically between 790 fs and 1.5 ps within the cavity, and such a large and rapid variation implies that any nonlinearities are sufficiently weak.

The pulse width obtained for various powers is shown in Fig. 10. A pulse width of 780~790 fs was obtained independently of the signal power after chirp com-

Fig. 10. Signal output power vs. pulse width (after chirp compensation) in a steady state.

Fig. 11. Pulse width and TBP vs. average dispersion of the fiber cavity.

pensation. We also confirmed that the numerical result was almost identical even when we neglected the nonlinear effects by setting $\gamma = 0$ in Eq. (1). These results indicate that the laser operates in a linear regime and nonlinearities do not play an important role, which validates the experimental results.

Fig. 11 shows a numerical result for the relationship between pulse width, TBP, and the average dispersion of the fiber cavity, where the average dispersion was varied by changing the DCF length. By reducing the average dispersion, the pulse width decreases gradually, and there is a possibility of obtaining a 600 fs pulse at an average dispersion of 0.2 ps/nm/km. In addition, the TBP decreases from 0.44 as the average dispersion decreases, which indicates that the pulse is getting closer to a sech shape due to larger nonlinearity.

5 Conclusion

We presented the first demonstration of a 40 GHz subpicosecond pulse source operating in the L-band using a harmonically and regeneratively MLFL with a low jitter and long-term stability. A 770 fs transform-limited Gaussian pulse was successfully generated over a 20 nm bandwidth in the 1.6 μm region, with an output power of 14 mW and a timing jitter as low as 88 fs. This laser is expected

to be an attractive pulse source for ultrahigh-speed pulse transmission, optical metrology, and optical comb generation in the L-band.

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