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Performance Comparison Between Harmonically Mode-Locked Ring and Figure-of-Eight Type Fiber Lasers

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We report on comparative results obtained from harmonically mode-locked laser operations of ring-type and figure-of-eight(F8) type erbium-doped fiber lasers by using a directional-coupler type electro-optic modulator as an active mode-locker. The mode-locked and transform-limited pulses of 10.6 ps width were obtained at harmonics of the fundamental cavity frequency with the F8 type laser while mode-locked laser pulses greater than 15 ps were achieved with the ring type laser.

I. Introduction

Recently passive mode-locked laser operations from erbium-doped fiber lasers(EDFLs) have been demonstrated to generate ultrashort laser pulses at the communication wavelength of 1.55 μm.[1-8] Even though the passive mode-locking mechanism has a superior property of very short pulse generation, its major disadvantages are a relatively poor synchronization property of the mode-locked pulse output and the limited laser pulse repetition rate. The mode-locked laser output is self-initiated by noise fluctuation under polarization controller movements or by evolution of a particular polarization state, and the repetition rate is determined by the given cavity length. On the other hand, actively harmonic mode-locked laser schemes using an external modulator have advantages on these problems even though the output laser pulses of these schemes typically have longer pulse lengths than the passively mode-locked laser schemes do.[9-18] In order that optical pulses can be used in high-capacity optical communications with a combined time- and wavelength-division-multiplexing scheme, the pulses must be transform-limited at pulse lengths longer than 10 ps.[19] Thus, the actively mode-locked fiber laser schemes are good choices for such application.

The actively mode-locked fiber lasers of ring-type geometry are usually limited to deliver mode-locked laser pulses whose pulse length is in the range of 15 ps or longer, if there is no external pulse compression mechanism applied and no extremely high modulation frequency (of greater than several GHz) is used. Thus, in this paper we report on the comparatively measured laser outputs of the harmonically mode-locked erbium-doped fiber lasers of both ring-type and F8 type laser geometries in order to achieve transform-limited laser pulses of relatively long pulse lengths and to find out how the nonlinear amplifier loop mirror (NALM) in the F8 type fiber lasers can be used to change the pulse length.

II. Experimental Methods and Results

The experimental setup used to demonstrate the harmonically mode-locked erbium-doped fiber laser of ring-type geometry is shown in Fig. 1. It was composed of two polarization controllers(PCs), a 5-m long erbium-doped fiber(EDF) of about 700 ppm Er^{3+}-ion concentration pumped by a 980-nm laser diode(LD) and a 1480-nm LD at both ends, an optical isolator, a Ti-dif-

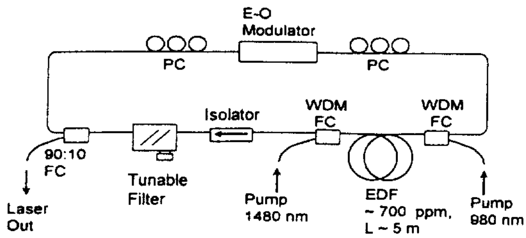

Fig. 1. Schematic diagram of the ring-type harmonically mode-locked fiber laser setup.

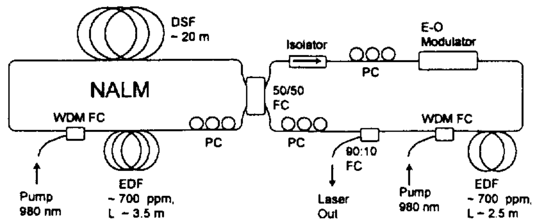

Fig. 3. Schematic diagram of the figure-of-eight type harmonically mode-locked fiber laser setup.

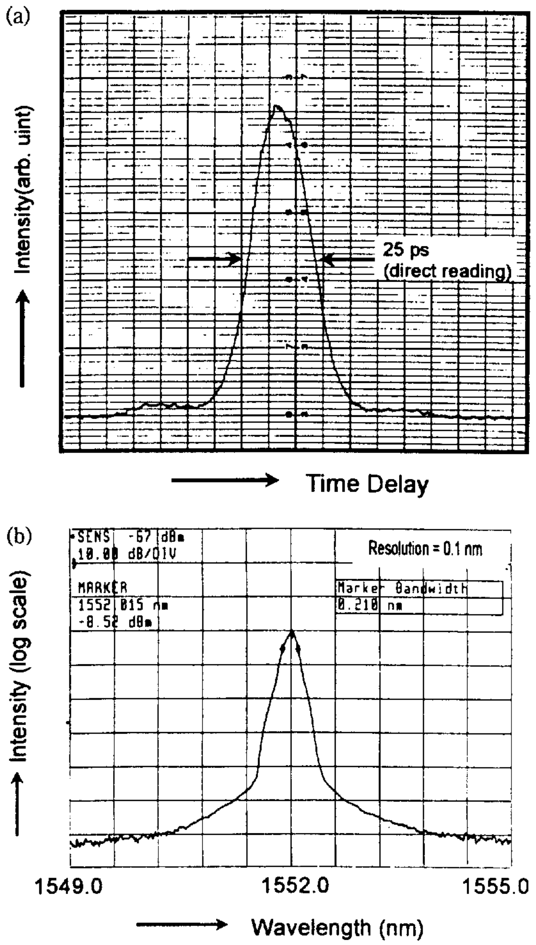

Fig. 2. (a) The autocorrelator measurement and (b) optical spectrum of the harmonically mode-locked laser outputs of the ring-type fiber laser.

fused $LiNbO_3$ directional coupler type electro-optic(E-O) intensity modulator, a tunable filter and a 90:10 fiber coupler(FC). The bandwidth of the tunable filter was larger than 2 nm. The mode-locked laser output was taken from the 10% output port of the 90:10 FC, and its temporal and spectral characteristics were measured with an optical spectrum analyzer, an autocorrelator, and a high-speed opto-electric lightwave converter whose electrical output is connected to a sampling oscilloscope.

Figs. 2(a) and (b) show the measured autocorrelator curve and pulse spectrum, respectively, when the pump powers of 52 mW at 980 nm wavelength and of 39 mW at 1480 nm wavelength were launched to the EDF and the E-O modulator was driven at a frequency of 2 GHz. This modulation frequency was determined to be as high as we could have with our experimental equipments, since it was a typically known phenomenon that the actively mode-locked laser pulses in a ring-type laser geometry become short as the modulation frequency increases. The measured autocorrelation pulse length and the line width was about 25 ps and 0.21 nm, respectively. The pulse length corresponds to 17.7 ps for assumption of a Gaussian pulse shape. We obtained the time-bandwidth product of 0.46, which is close to that for the transform-limited Gaussian-type pulses. The total laser cavity length was about 26 m since the fundamental frequency was measured to be 8 MHz.

Fig. 3 shows a harmonically mode-locked fiber laser setup in a F8 geometry utilizing a pulse shaping and saturable absorber mechanism of nonlinear amplifying loop mirror (NALM). The laser was basically composed of a NALM and a linear loop. The NALM consisted of a PC, a 3.5-m long EDF of about 700 ppm Er^{3+}-ion concentration pumped by a 980-nm LD and a 20-m long dispersion-shifted fiber(DSF) of $|D| \leq 3.5$ ps/km/nm at 1.5 μm. An optical isolator, two PCs, a Ti-diffused $LiNbO_3$ directional coupler type E-O intensity modulator, a 2.5-m long EDF gain section pumped

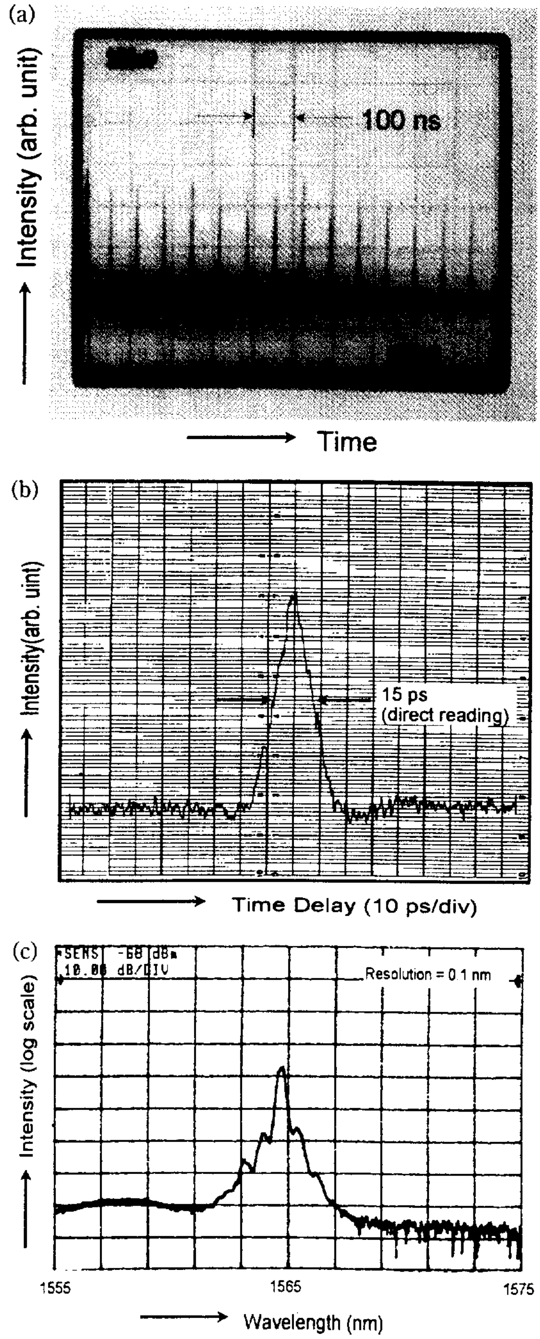

Fig. 4. (a) The oscilloscope trace, (b) autocorrelator measurement and (c) optical spectrum of the harmonically mode-locked laser outputs of the figure-of-eight type fiber laser.

by a single 980 nm LD and a 90:10 fiber coupler(FC) were used in the linear loop.

The harmonically mode-locked condition of the F8 type fiber laser requires a precise PC adjustment as well as a fine adjustment of the modulation frequency at the harmonics of the cavity fundamental frequency. In our experimental setup the optimum mode-locked condition was found at a RF modulation frequency of 14.5 MHz, as shown in Fig. 4(a), which corresponds to 4th harmonic of the fundamental cavity frequency of 3.6 MHz. The corresponding cavity length was about 56.7 m. The 980-nm pump power entering the EDF in the NALM was about 55 mW, and that in the linear loop was about 28 mW. Figs. 4(b) and (c) show the measured temporal and spectral output characteristics of the harmonically mode-locked laser outputs. The measured autocorrelation pulse length was about 15 ps, which corresponds to the calibrated pulse length of 10.6 ps on the assumption of Gaussian pulse shape. The average laser power and peak pulse power were about 0.92 mW and 6.0 W, respectively. The measured spectral width(FWHM) was about 0.33 nm. This yields the time-bandwidth product to be 0.43, and indicates that the pulses were almost transform-limited to the Gaussian pulse shape.

From the comparison of the results of Figs. 2(a) and 4(b) it is observed that the addition of the NALM to the ring-type fiber laser cavity plays a role of pulse shortening mechanism in the mode-locked laser outputs. However, the repetition rate of the laser pulse output is significantly limited by the saturation power of the optical amplifier in the NALM. It was also observed both experimentally and theoretically that the increase of the optical amplifiers saturation power in the NALM allowed the increase of the repetition rate and the Gaussian-type pulse output was changed to soliton pulses when the amplifiers gain was sufficiently high. [20] In the soliton generation using typical mode-locked F8 type fiber lasers the relationship of the repetition rate with respect to the optical amplifiers saturation power in the NALM is obtained from a simple power analysis as follows [20]

$$f_{\max}=\frac{2\cdot P^{aver}_{EDFA\ Sat.}\cdot C_{13}\cdot L_{NALM}\cdot \pi^2 C n_2 \tau}{\{\pi^2 C\tau^2\lambda+1.552\,C_{14}\lambda^3|D|L_{NALM}\}\cdot A_{eff.}}. \quad (1)$$

$P^{aver}_{EDFA\ Sat.}$ is the average saturation power of the optical amplifier in the NALM, L_{NALM} is the fiber length of the NALM, n_2 is the nonlinear refractive index of the silica fiber, τ is the solitons pulse length, λ is the wavelength of the light propagating the NALM, $|D|$ is the chromatic dispersion of the fiber, and c is the speed of light. C_{13} and C_{14} are the fiber coupler's coupling ratios of the input light into the two opposite arms of the NALM. The large optical gain caused by the high saturation power needed for the high repetition rate results in the generation of soliton pules of long pulse lengths according to the following relation[20]

$$\tau^2 = \frac{1.552\,\lambda^2\,|D|\,L_{NALM}(GC_{13}-C_{14})}{\pi^2 c} \qquad (2)$$

This trade-off properties of the repetition rate and the pulse length on the optical gain may be solved by choosing the unequal coupling ratios, C_{13} and C_{14}, of the fiber coupler into the two arms of the NALM or by repositioning the asymmetrically located optical amplifier toward the middle of the NALM (but not at the exactly the middle of it). This subject is left for future investigation. In addition, the stability problem related to the harmonically mode-locked laser operation in the ring-type and F8 type laser geometries with an amplitude modulator is also an issue to be resolved. Dynamic polarization fluctuations due to environment changes, periodic perturbation due to optical gain in the loop, and external modulators instability, can be some of the causes affecting the instabilities of the laser output.

III. Conclusion

We have successfully demonstrated harmonically mode-locked fiber laser operation in each of ring-type and figure-of-eight type laser geometries by using a directional-coupler type electro-optic modulator as a active mode-locker. By comparing the mode-locked laser outputs of the two schemes we have found that the NALM plays an important role in the pulse shortening mechanism. The laser pulse lengths obtained from each scheme were 17.7 ps and 10.6 ps, respectively. This means that the actively mode-locked fiber lasers of ring-type geometry without any external pulse compression mechanisms are good to deliver the laser pulses of equal to or longer than 15 ps, and those of figure-of-eight type geometry are good to generate laser pulses shorter than 15 ps at relatively high repetition rates compared to the limited repetition rate of the passively mode-locked fiber lasers.

Acknowledgments

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