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Gain Dependent Optimum Pulse Generation Rates of a Hybrid-Type Actively and Passively Mode-Locked Fiber Laser

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ABSTRACT

We have experimentally observed and theoretically analyzed the gain dependent optimum repetition rates of a hybrid-type active and passive mode locked laser pulses in an erbium-doped fiber laser of the figure-of-eight geometry by utilizing a nonlinear amplifier loop mirror (NALM) as a saturable absorber and a directional-coupler type electro-optic modulator as an active mode locker. Transform-limited mode-locked pulses of about 10 ps width were obtained at repetition rates which correspond to harmonics of the cavity fundamental frequency and depend on the optical amplifier gain in the NALM.

I. INTRODUCTION

Technology of ultrashort pulse generation with mode-locked erbium-doped fiber lasers (EDFLs) at the communication wavelength of 1.55 μm has rapidly advanced in recent years. Especially passive mode-locking schemes of the EDFLs in the figure-of-eight geometry with a nonlinear amplified loop mirror (NALM) or in the ring-type geometry with nonlinear polarization rotation (NPR) or with stretched-pulse additive pulses have been demonstrated to deliver optical pulses of a few hundred femtosecond [1]-[8]. One of the primary disadvantages of the passively mode-locked EDFLs is that the repetition rate of the mode-locked pulses is usually limited to the cavity's fundamental mode frequency which depends on the cavity length. Another distinct disadvantage is the relatively poor synchronization property of the mode-locked pulses because the lasing conditions are typically self-initiated by noise fluctuation due to polarization controller movements or by evolution of a particular polarization mode. The repetition rate and pulse synchronization properties can be improved with directly amplitude or phase modulated active mode-locking schemes of the EDFLs. However, the actively mode-locked laser pulses typically have longer pulse widths than the passively mode-locked laser pulses do unless any pulse compression methods are applied [9]-[14]. Thus, hybrid-type passively and actively mode-locked erbium-doped fiber ring lasers have been pursued to utilize the merits of each scheme, that is, short pulse generation from the passive mode-locking schemes and the relatively high repetition rate and easy pulse synchronization from the active mode-locking schemes [11], [15]-[17]. Numerical modeling for such a hybrid-type fiber laser has also been reported [18]. In this paper we report, for the first time to our knowledge, experimental observation and theoretical analysis on the optical gain dependency of the optimum soliton pulse generation rates in a hybrid-type actively and passively mode-locked erbium-doped fiber ring laser of a figure-of-eight geometry with a NALM.

II. THEORETICAL ANALYSIS

The operation of the NALMs is based on the nonlinear phase shift difference between two counterpropagating lights in a Sagnac loop as shown in Fig. 1. The nonlinear phase shift difference of the two counterpropagating pulses is written as

$$\delta\phi_c - \delta\phi_{cc} = \frac{2\pi}{\lambda} n_2 I_{in} L_{NALM} (GC_{13} - C_{14}), \quad (1)$$

where $\delta\phi_c$ and $\delta\phi_{cc}$ are the phase changes of the lights propagating clockwise and counterclockwise, respectively [19]. n_2 is the nonlinear refractive index of the silica fiber ($\approx 3.2 \times 10^{-20}$m^2/W at 1.5 μm) [20], λ is the wavelength of the light propagating the NALM, L_{NALM} is the fiber length of the NALM, G is the gain of the optical amplifier located asymmetrically in the NALM, and I_{in} is the input light intensity. C_{13} and C_{14} are the coupling ratios of the input light to the fiber coupler's outputs as shown in Fig. 1, where $C_{14} = 1 - C_{13}$.

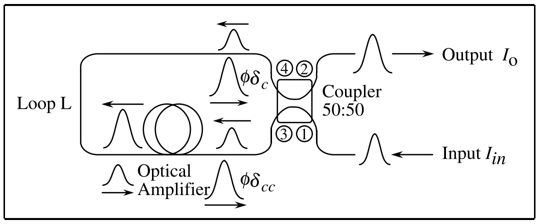


Fig. 1. Nonlinear amplified loop mirror.

The switched light intensity I_o of the NALM is written as

$$I_0 = I_{in} G \sin^2\left[(\delta\phi_c - \delta\phi_{cc})/2\right]. \qquad (2)$$

Since the switched light intensity is the maximum for $\delta\phi_c - \delta\phi_{cc} = \pi$, the input intensity for the maximum switched output becomes, from (1),

$$I_{in,\pi} = \frac{\lambda}{2 n_2 L_{NALM} (G C_{13} - C_{14})}. \qquad (3)$$

Then, the corresponding peak input and output light powers are written as

$$P^{peak}_{in,\pi} \cong I_{in,\pi} \cdot A_{eff} = \frac{\lambda A_{eff}}{2 n_2 L_{NALM} (G C_{13} - C_{14})} \qquad (4)$$

and

$$P^{peak}_{o,\pi} = P^{peak}_{in,\pi} \cdot G, \qquad (5)$$

respectively, where A_{eff} is the fiber's effective core area.

When the NALM is used in a laser cavity, a detailed analysis of the pulse propagation along the fiber may be very complicated. A theoretical analysis has been reported by Duling *et al* [21]. In this paper we attempt a simple analysis of the laser power propagation in a hybrid type mode-locked laser scheme with a NALM and an optical modulator as shown in Fig. 2. The light powers after each optical components can be written as

$$P_A = P_o \cdot \alpha_I \cdot \alpha_m \qquad (6)$$

$$P_B = g \cdot P_A = g \cdot P_o \cdot \alpha_I \cdot \alpha_m \qquad (7)$$

$$P_C = P_B \cdot (1 - C_o) = g \cdot P_o \cdot \alpha_I \cdot \alpha_m \cdot (1 - C_O), \qquad (8)$$

where α_I and α_m are the optical losses at the isolator and modulator, respectively. g is the light gain of the optical amplifier in the linear loop, and C_o is the coupling ratio of the fiber coupler at laser output. By neglecting the extra losses due to the splicing, polarization controllers (PCs) and all other components in (8) we can write, for a steady state laser operation,

$$P_{in} = P_C = P_o \cdot g \cdot \alpha_I \cdot \alpha_m \cdot (1 - C_o). \qquad (9)$$

Substitution of P_o of (5) into (9) gives

$$P_{in} = P_{in} \cdot G \cdot g \cdot \alpha_I \cdot \alpha_m \cdot (1 - C_o) \qquad (10)$$

and thus,

$$G \cdot g \cdot \alpha_I \cdot \alpha_m \cdot (1 - C_o) = 1. \qquad (11)$$

This equation indicates the typical laser oscillation requirement that the entire gain in the fiber laser cavity is needed just as much as the total optical losses in the cavity.

The peak power of the fundamental soliton and the soliton period are

$$P^{peak}_1 = \frac{0.776 \lambda^3 |D| A_{eff}}{\pi^2 c n_2 \tau^2} \qquad (12)$$

and

$$z_o = \frac{0.322 \pi^2 c \tau^2}{\lambda^2 |D|}, \qquad (13)$$

respectively [22], where c is the speed of light, $|D|$ is the chromatic dispersion of the fiber, and τ is the soliton's pulse length.

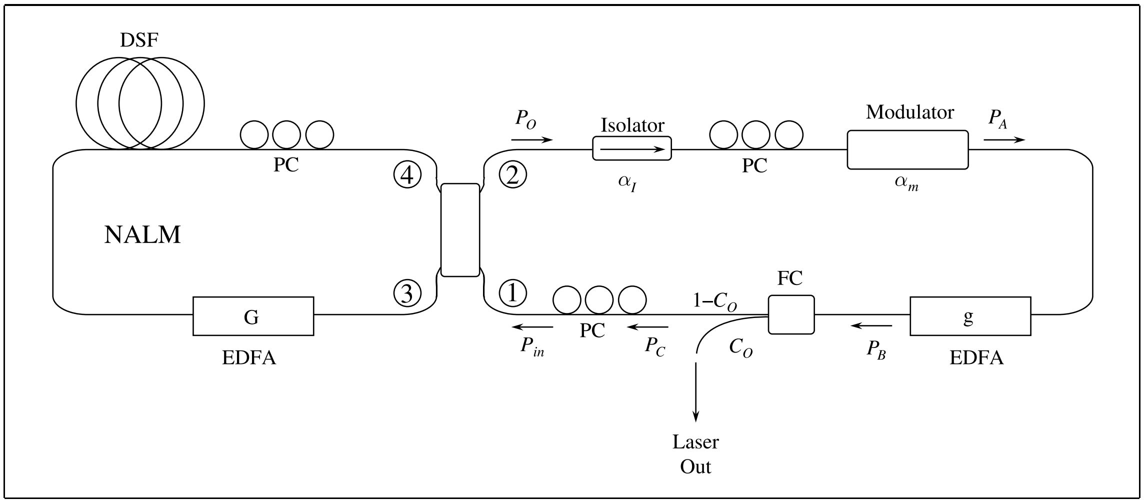


Fig. 2. Figure-of-eight type fiber laser.

If we assume that P_{in} should be the same as P_1^{peak} for the stable soliton operation, we can have, from (4) and (12), that

$$\frac{\lambda A_{eff}}{2n_2 L_{NALM}(GC_{13}-C_{14})} = \frac{0.776\lambda^3|D|A_{eff}}{\pi^2 c n_2 \tau^2} \tag{14}$$

and

$$\tau^2 = \frac{1.552\lambda^2|D|L_{NALM}(GC_{13}-C_{14})}{\pi^2 c}. \tag{15}$$

This equation indicates that the pulse length is proportional to the chromatic dispersion, fiber length and the optical amplifier's gain.

From $P_{in} = P_1^{peak}$, (5) can be rewritten as

$$P_o^{peak} = P_1^{peak} \cdot G\,. \tag{16}$$

The average output power of the NALM is

$$P_o^{aver.} = P_o^{peak} \cdot \tau \cdot f, \tag{17}$$

where f is the repetition rate of the soliton pulses. Since this average output power cannot be greater than the saturation output power of the optical amplifier, $P_{EDFA\ Sat.}^{aver.}$, in the NALM, we can have the output power relation as

$$P_o^{aver.} \leq P_{EDFA\ Sat.}^{aver.} \tag{18}$$

Combining (17) with (18) leads one to

$$P_o^{peak} \cdot \tau \cdot f_{\max.} = P_{EDFA\ Sat.}^{aver.} \tag{19}$$

and

$$f_{\max.} = \frac{P_{EDFA\ Sat.}^{aver.}}{P_o^{peak} \cdot \tau}. \tag{20}$$

Then, we obtain, from (16) and (20),

$$f_{\max.} = \frac{P_{EDFA\ Sat.}^{aver.}}{P_1^{peak} \cdot G \cdot \tau}. \tag{21}$$

By using P_1^{peak} of (12) and solving (15) for G, (21) can be rewritten as

$$\begin{aligned} f_{\max.} &= \frac{P_{EDFA\ Sat.}^{aver.}}{G} \cdot \frac{\pi^2 c n_2 \tau}{0.776\lambda^3|D|A_{eff}} \\ &= \frac{P_{EDFA\ Sat.}^{aver} \cdot C_{13}}{\left(\dfrac{\pi^2 c \tau^2}{1.552\lambda^2|D|L_{NALM}} + C_{14}\right)} \end{aligned}$$

$$\cdot\frac{\pi^2 c n_2 \tau}{0.776\lambda^3|D|A_{eff}} \tag{22}$$
$$= \frac{2\cdot P^{aver}_{EDFA\ Sat.}\cdot C_{13}\cdot L_{NALM}\pi^2 c n_2\tau}{\{\pi^2 c\tau^2\lambda + 1.552 C_{14}\lambda^3|D|L_{NALM}\}A_{eff}}.$$

This relation indicates that the maximum repetition rate of the soliton pulse generation is proportional to the saturation power of the optical amplifier. In order to have the maximum repetition rate, $P^{aver.}_{EDFA\ Sat.}$ should be kept as large as possible.

The average saturation power of Er-doped fiber amplifiers (EDFAs) can be calculated as

$$P^{aver.}_{EDFA\ Sat.} = \frac{Nh\nu}{\tau_{lifetime}} = \frac{(\rho\cdot A_{eff}\cdot L_{EDFA})\cdot h\frac{c}{\lambda}}{\tau_{lifetime}}, \tag{23}$$

where N is the total number of Er^{3+}-ions, h is Planck constant, $\tau_{lifetime}$ is the upper state lifetime, ρ is Er^{3+} concentration, and L_{EDFA} is the length of Er-doped fiber.

By using (7) the laser output at the output fiber coupler is written as

$$P^{peak}_{laser-out} = P^{peak}_B\cdot C_o = P^{peak}_o\cdot g\cdot\alpha_I\cdot\alpha_m\cdot C_o. \tag{24}$$

Solving (9) for P_o and inserting it into (24), we obtain

$$P^{peak}_{laser-out} = P^{peak}_1\cdot\frac{C_o}{1-C_o}, \tag{25}$$

where we used $P^{peak}_{\mathrm{in}} = P^{peak}_1$.

III. EXPERIMENTAL SETUP

The experimental setup used to demonstrate the hybrid-type mode-locked erbium-doped fiber ring laser is shown in Fig. 3(a). It consists of a NALM and a linear loop. The NALM consists of a polarization controller (PC), an erbium-doped fiber (EDF) of about 700 ppm Er^{3+}-ion concentration pumped by 980 nm and/or 1480 nm laser diodes (LDs) at both ends and a 20-m long dispersion-shifted fiber (DSF) of $|D| \le 3.5$ ps/km/nm at 1.5 μm. Various lengths of the EDF from about 2.5 m to 9 m were used for both-side pump and single-side pump cases. An optical isolator, two PCs, a Ti-diffused LiNbO$_3$ directional coupler type electro-optic (E-O) intensity modulator, an EDF gain section and a 90:10 fiber coupler (FC) were used in the linear loop. The gain section in the linear loop was also removed or changed from 2.5 m to 9 m to compare its role in performing the hybrid-type mode-locked laser generation.

Figure 3(b) shows the passively mode-locked EDFL scheme, which is the same setup as the one shown in Fig. 3(a) except direct splicing of the optical isolator output end to the input end of the 90:10 fiber coupler (FC) without the E-O modulator and one PC in the linear loop. This setup was used to test its passively mode-locked laser performance before performing the hybrid-type mode-locking scheme.

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.

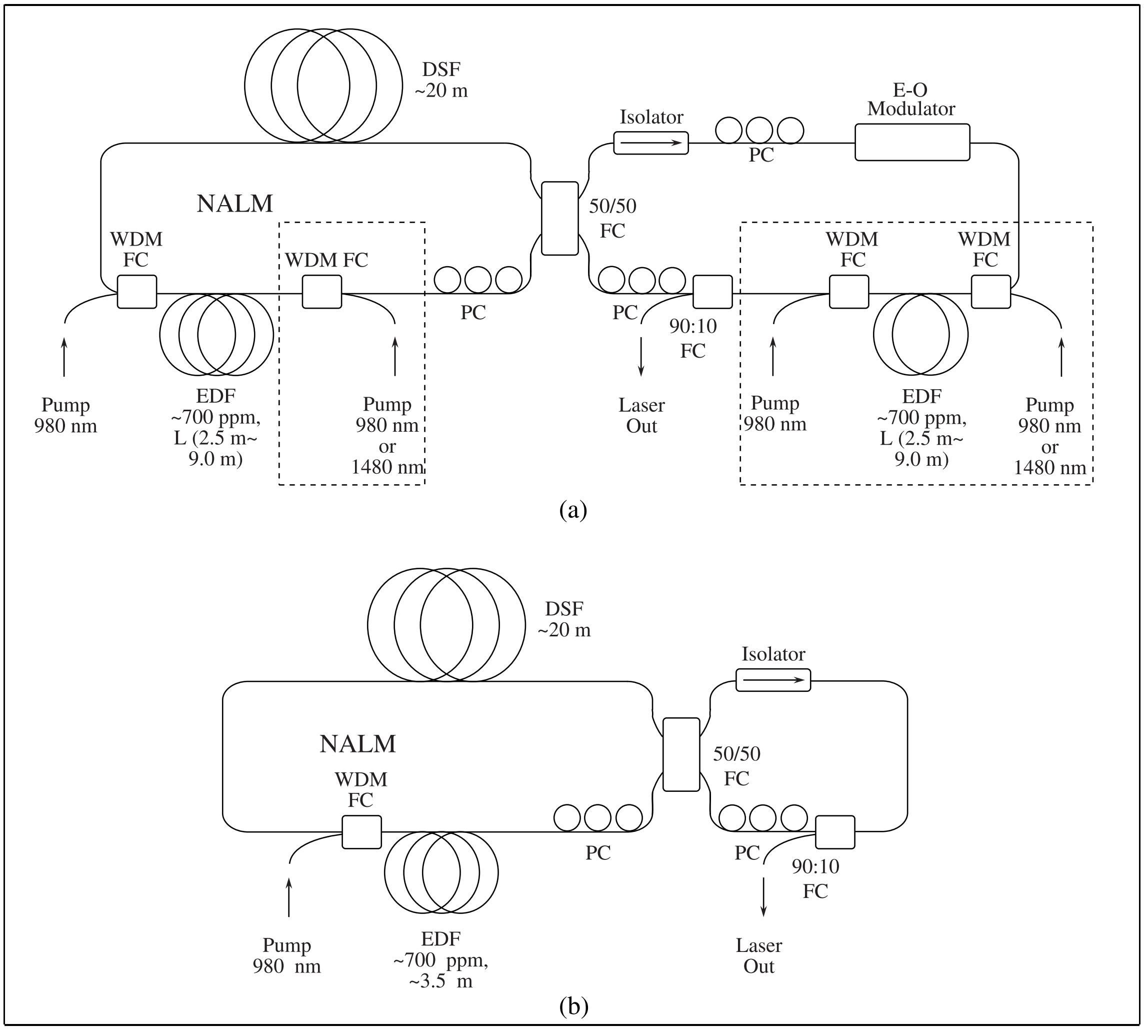


Fig. 3. Schematic diagrams of (a) the hybrid-type mode-locked fiber laser experiment, and (b) the passively mode-locked fiber laser experiment.

IV. RESULTS AND DISCUSSION

In the passively mode-locked EDFL experiment with the experimental setup of Fig. 3(b) a precise PC adjustment initiated the mode-locked laser oscillation. Figures 4(a) and (b) show the spectral and temporal output characteristics of the passively mode-locked laser outputs obtained with a 3.5-m long EDF and a single pump LD. The 980-nm pump power entering the EDF was about 44 mW. The spectral width(FWHM) of the mode-locked pulses was 2.8 nm, and the autocorrelation width was about 2.2 ps. The corresponding calibrated

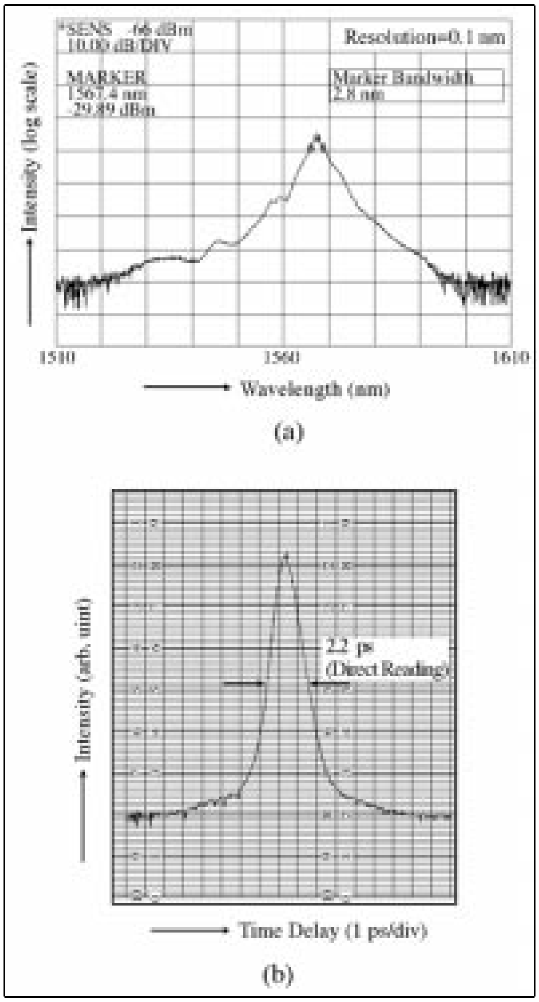
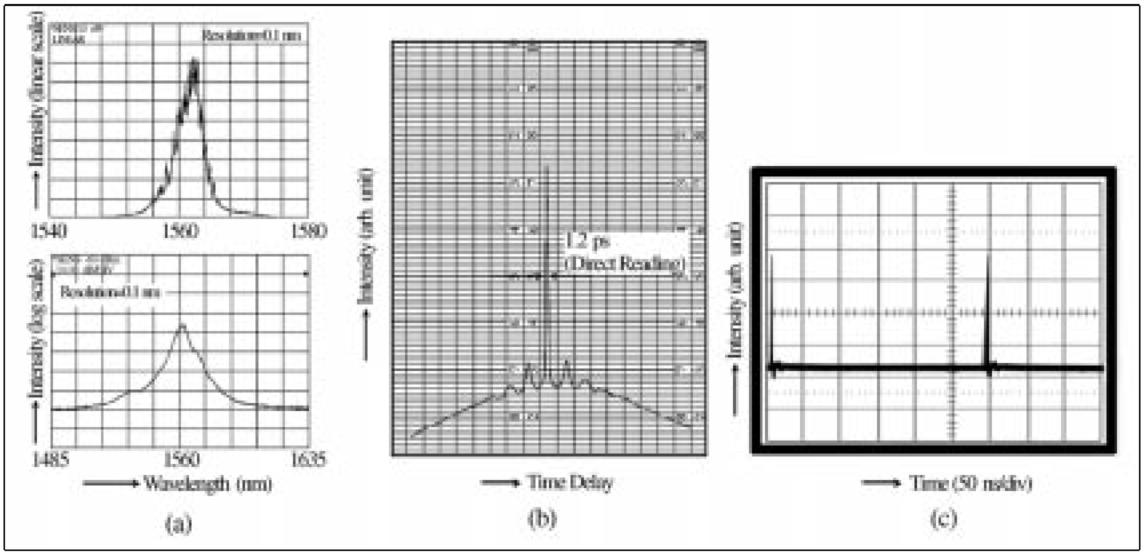


Fig. 4. (a) The optical spectrum and (b) autocorrelator measurement of the passively mode-locked laser pulses.

pulse width on the assumption of hyperbolic sech pulse shape is about 1.4 ps. Since the time-bandwidth product is about 0.48, the output laser pulses are not fully transform-limited. The repetition rate of the mode-locked pulses was 4.6 MHz, and the corresponding ring cavity length was about 44 m.

The hybrid type mode-locked condition with the simultaneous operation of passively and actively mode-locked lasing also requires a precise PC adjustment as well as a fine adjustment of the modulation frequency at around the harmonic frequencies of the cavity fundamental mode in the experimental setup shown in Fig. 3(a). The initiation of the mode-locking condition in this scheme is relatively easy compared to the passively mode-locking condition of Fig. 3(b) because of the externally driven modulation. The pulse pattern of the mode-locked laser output critically depends on the PC adjustment. The passive mode-locking mechanism is a dominant mechanism in the hybrid-type mode-locking condition since for a particular PC adjustment position the mode-locked laser output appears only at the fundamental cavity frequency even under the intensity modulation of the E-O modulator operating at high-order harmonic frequencies. The hybrid-type mode-locked laser operation to achieve the laser pulses at the entire E-O modulation frequency requires a precise adjustment of the PCs to another optimum position.

Figures 5(a)-(c) show the measured spectral and temporal output characteristics of the mode-locked laser pulses when the passive mode-locking mechanism is dominant in the hybrid-type mode-locked laser geometry with a double-side pumping of a 9-m long EDF in the NALM. One 980-nm LD and one 1480-nm LD were used to pump the EDF in the NALM at both ends and their optical powers



(a) (b) (c)

Fig. 5. (a) The optical spectra, (b) autocorrelator measurement and (c) oscilloscope trace of the passive mode-locking dominant mode in the hybrid-type mode-locked laser scheme.

launched to the EDF were 51 mW and 27 mW, respectively. A 2.5-m long EDF pumped with a 980-nm LD of the launched optical power of about 15 mW was used in the linear loop. As shown in Fig. 5(c) strong mode-locked laser pulses appear only at the cavity fundamental frequency of 3.4 MHz. The corresponding cavity length was about 60 m. The measured autocorrelation pulse width was about 1.2 ps, which corresponds to the calibrated pulse width of 800 fs on the assumption of hyperbolic sech pulse shape (Fig. 5(b)). The pulse spectra of linear and logarithmic scales shown in Fig. 5(a) have a linewidth of about 3 nm. Thus, the time-bandwidth product ($\Delta t \cdot \Delta \upsilon$) is about 0.29, which is very close to that of the transform-limited hyperbolic sech pulses. The small spikes shown on the pulse envelop of the linear scale pulse spectrum do not seem to be the soliton resonance sidebands which is described by Dennis and Duling [23], because their separation is very narrow and they seems to respond sensitively to the polarization states of PCs. For the given PC position the laser output does not show the same spectral and temporal pulse shapes as those of the typical soliton pulses, but rather have a very wide spectral distribution as shown in the logarithmic plot of Fig. 5(a) delivering strong and short pulses. The average laser power and peak pulse power were measured and calculated to be about 0.44 mW and 167.1 W, respectively. The autocorrelation measurement shows strong side lobe structures beside the central strong peak pulse, which are the typical structures of high power pump cases for the nonlinear loop [2], [24], and are attributed to the soliton reshaping process by the periodic perturbation in the feedback loop of the laser [21]. The measured laser output powers were much higher than those required for fundamental powers since the peak pulse power for the 800-fs long fundamental solitons and the average power for the 3.4 MHz repetition rate are calculated to be about 4.8 W and 13 μW for an estimated total average chromatic dispersion of $D \approx 2$ ps/nm.km of the fiber laser used in our experiment. This fact may explain the observed spectral and temporal laser output characteristics different from the soliton pulse output case's. In addition, the passive mode-locking dominant operation appeared to be unstable when the gain in the linear loop was increased further.

Figures 6(a) and (b) show the measured spectral distribution and temporal pulse shape of the mode-locked laser pulses when the PCs were adjusted in such a way that the fiber laser delivered the hybrid-type mode-locked laser pulses at the entire modulation frequency of 68.4 MHz as shown in Fig. 6(c). This modulation frequency corresponds to 20th harmonics of the cavity's fundamental frequency. The pump powers for the EDF in the NALM were kept the same as the passive mode-locking dominant case, but the 980-nm LD power used to pump the EDF in the linear loop was increased to 39 mW. The measured spectral width(FWHM) was about 0.25 nm. The measured autocorrelation pulse width was about 15 ps, which corresponds to the calibrated pulse width of 10 ps on the assumption of hyperbolic sech pulse shape. Since $\Delta t \cdot \Delta \upsilon = 0.30$, the pulses were almost transform-limited to hyperbolic sech pulse shape. The average laser power and peak pulse power were about 1.2 mW and 1.8 W, respectively. Even though the time-bandwidth product is close to that of the transform-limited hyperbolic sech pulses', the autocorrelation measurement of the temporal pulse shape shown in Fig. 6(b) does not present an exact hyperbolic sech pulse shape. It rather indicates that there must be some pulse reshaping processes taking place in forming the hybrid-type mode-locked laser output pulses, because the transform-limited Gaussian-shape laser pulses of about 17 ps pulse length were obtained in a separate experiment of active mode-locked ring-type fiber lasers [25].

We have tested the hybrid-type mode-locked laser operation in the setup shown in Fig. 3(a) with various combinations of the erbium-doped fiber amplifier (EDFA) gain sections in both the NALM and the linear loop. When the EDFA gain sections of the NALM and linear loop used in the above measurement were switched, the passive mode-locking dominant operation was possible only with relatively low power pumping in the linear loop but keeping high power pump powers introduced in the NALM. However, the hybrid-type mode-locked operation was difficult to achieve. Even when it was achieved, the laser output was unstable and the pulse length was very long. When the EDF length was increased to 3.5 m with a single-side pumping in the NALM and a single-side pumped 2.5-

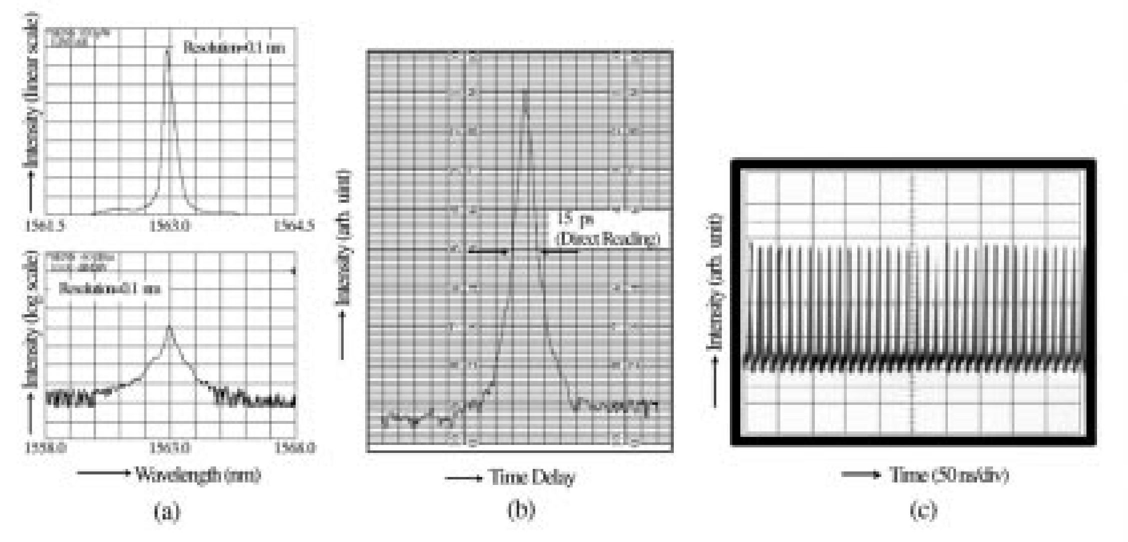


Fig. 6. (a) The optical spectra, (b) autocorrelator measurement and (c) oscilloscope trace of the hybrid-type mode-locked laser output.

m EDFA was used in the linear loop, we also observed both types of the passive dominant and hybrid-type mode-locking operations. For the 980-nm pump powers of 83 mW and 42 mW used for the EDFAs in the NALM and linear loop, respectively, the optimum repetition rate of the hybrid-type operation was 14.5 MHz, which corresponds to the forth harmonics of the cavity's fundamental frequency. In this case the measured autocorrelation pulse width was about the same as that of Fig. 6(b), but the pulses are not fully transform-limited to the hyperbolic sech pulse shape possibly due to insufficient signal gains. The transition from passive mode-locking to active harmonic mode-locking has been also observed by others in a ring type fiber laser with the nonlinear polarization rotation previously [16].

Figures 7(a) and (b) show the calculated results of the maximum repetition rates of the harmonically mode-locked soliton operation and the optical amplifier's gains in the NALM, respectively, as functions of the pulse length for various dispersion parameters and for various NALM's gain sections and loop lengths. (15) and (22) with the laser parameters used in our experiments were applied for this calculation, and the core diameter of 3 μm for the Er-doped fibers of 700 ppm concentration and the upper state lifetime $\tau_{lifetime}$ of 10 ms were used in the calculation of the saturation power of the EDFA. The saturation powers of 9, 3.5, and 2.5 m long EDFs were about 12.4, 4.8, and 3.4 mW, respectively. Figure 7(a) shows that the maximum repetition rate is mainly limited by the EDFA gain in the NALM. Our experimen-

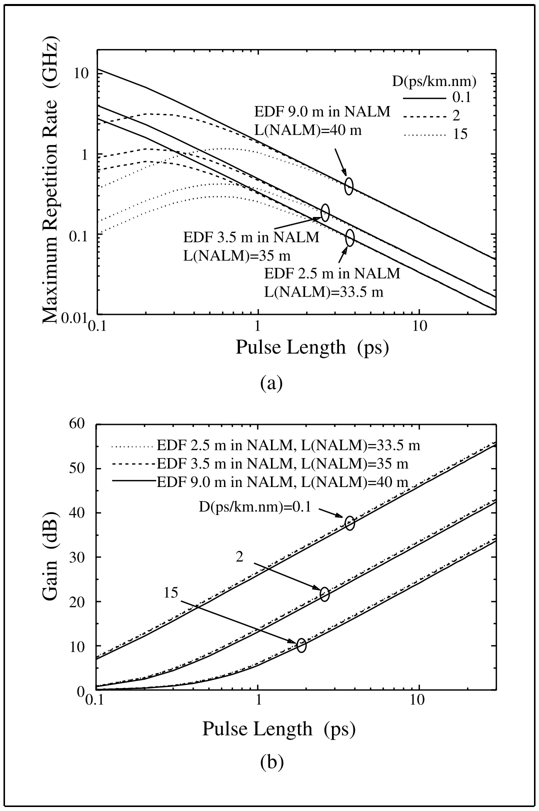


Fig. 7. (a) The Maximum repetition rate and (b) optical gain needed in the NALM as functions of pulse length for fibers of various dispersion coefficients and various EDF lengths.

tal results agree with this. It is also shown in Fig. 7(a) that the pulse length for the maximum repetition rate depends on the fiber's dispersion coefficient in the cavity and optical gain in the NALM, and appears to be below 1 ps. Since the large optical gain increases the repetition rate as well as the soliton pulse length as shown in Figs. 7(a) and (b), there must be an optimum gain requirement in achieving high repetition rates of transform-limited soliton pulses with the hybrid-type mode-locked laser configuration.

The hybrid-type active and passive mode-locked laser operation in our figure-of-eight laser geometry was observed to be highly sensitive to the environment, probably due to polarization state changes and cavity length variation, but once the lasing condition was established, the laser output appeared to be stable, as shown in Fig. 6(c), until it was perturbed again by the environment. On the other hand, the laser output of the passive mode-locking dominant operation appeared to be relatively more stable than that of the hybrid type operation, but the stable condition was also difficult to sustain for a long time. Various schemes, such as cavity length control or optical feedback circuitry, were previously reported as means to stabilize the laser outputs against environmental changes [18], [26]-[28]. The stability problems related to the hybrid-type fiber laser operation must be investigated further down the road.

V. CONCLUSIONS

We have observed experimentally and analyzed theoretically, for the first time to our knowledge, that the optimum soliton pulse generation rates of a hybrid-type passively and actively mode-locked fiber laser utilizing a NALM as a saturable absorber and a directional-coupler type E-O modulator as an active mode locker depend on the optical gain in NALM. The polarization dependent operations of both passive dominant and hybrid-type mode-locking were also observed with the figure-of-eight type fiber laser. The hybrid type mode-locked lasers delivered transform-limited laser pulses of about 10 ps width at the external modulation frequencies which were limited to harmonics of the cavity fundamental frequency and to the optical saturation powers of the optical amplifier in the NALM.

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