All-polarization-maintaining Er-doped ultrashort-pulse fiber laser using carbon nanotube saturable absorber

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Abstract: We present an all-polarization-maintaining Er-doped ultrashort-pulse fiber laser using a single-wall carbon nanotube polyimide nanocomposite saturable absorber. The maximum average power for single-pulse operation is 4.8 mW, and the repetition frequency is 41.3 MHz. Self-start and stable mode-locking operation is achieved. The RF amplitude noise is also examined and it is confirmed that the noise figure is as low as that of a solid-state laser. Using a polarization-maintaining anomalous dispersive fiber, a 314 fs output pulse is compressed to 107 fs via higher-order soliton compression. The peak power of the compressed pulse is up to 1.1 kW.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (320.7090) Ultrafast lasers

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1. Introduction

Passively mode-locked ultrashort-pulse fiber lasers are stable, compact, maintenance-free, practical ultrashort-pulse light sources, and they have attracted a great deal of attention lately. Ultrashort-pulse fiber lasers are promising practical pump sources for ultrashort-pulse applications, such as optical frequency combs, 3D optical memory, and supercontinuum sources. The figure-eight scheme, nonlinear polarization rotation, and semiconductor saturable absorption mirrors (SESAMs) have been used in ultrashort-pulse fiber lasers for passive mode-locking [1]. Environmental stability is one of the key issues for fiber lasers. The sigma cavity configuration and a Faraday rotator have been used in the demonstration of an environmentally stable fiber laser [1]. Recently, a few studies of all-polarization-maintaining (PM) fiber lasers have been reported, such as a figure-eight laser, an Yb laser with a SESAM, and so on [2–4]. Since the linear polarization state is always maintained in these PM fiber lasers, they are robust against environmental variations and have excellent long-term stability.

Recently, it was discovered that a single-wall carbon nano-tube (SWNT) has saturable absorption properties. The recovery time is ~1 ps, and a transparent saturable absorber can be formed so that it works as a useful mode-locker. A few groups have demonstrated passively mode-locked fiber lasers using SWNTs [5–13]. SWNT saturable absorbers are divided into three types: direct deposition [6,10], evanescent [9,11,12], and film [7,8,13]. The film type is a useful device because one can obtain passive mode-locking merely by setting the film between the fiber connectors [7,13]. In a PM fiber laser, generally it is necessary to align the birefringent axes of PM fibers precisely. However, if we use a film-type SWNT device in the fiber connector, the birefringent axes of the PM fibers are automatically aligned at the fiber connector, and passive mode-locking is achieved in a simple all-fiber ring cavity configuration without any polarization devices. Thus, the film type SWNT device is attractive for PM fiber lasers.

In this work, we have demonstrated an all-PM SWNT Er-doped ultrashort-pulse fiber laser for the first time. A polyimide film in which SWNTs are dispersed is used as a transparent saturable absorber, and stable passive mode-locking operation is achieved merely by setting the polyimide film between the fiber connectors in the cavity. The output pulses are compressed using a small-core PM fiber. The RF amplitude noise of this laser is also examined.

2. All-polarization-maintaining Er-doped ultrashort-pulse fiber laser using SWNTs

Figure 1 shows the configuration of our all-PM passively mode-locked Er-doped ultrashort-pulse fiber laser using SWNTs. A high-power laser diode (LD) with a wavelength of 980 nm was used as the pump laser. The pump beam was introduced into a 1.2 m long PM Er-doped fiber (EDF) through a PM wavelength division multiplexed coupler. The peak absorption of the EDF is 55 dB at a wavelength of 1550 nm. The PM-EDF was fusion spliced with a PM isolator and a 1:1 PM coupler to construct an all-PM fiber ring laser. The PM isolator and fiber coupler were connected mechanically using an angled polished FC/APC fiber connector. The total length of the cavity was 5.1 m.

A freestanding SWNT–polyimide nanocomposite film saturable absorber has been demonstrated as a mode-locker [13]. In our present work, we used a polyimide film containing SWNTs synthesized by the high pressure CO (HiPco) method. Figure 2 shows the

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absorption spectrum of the film. The film thickness was 17 μm. The film had a broad absorption spectrum, and the absorbance at a wavelength of 1.55 μm was about 0.3. The refractive index of the polyimide film was about 1.58. A small piece of the film with dimensions 2 mm × 2 mm was used as the saturable absorber.

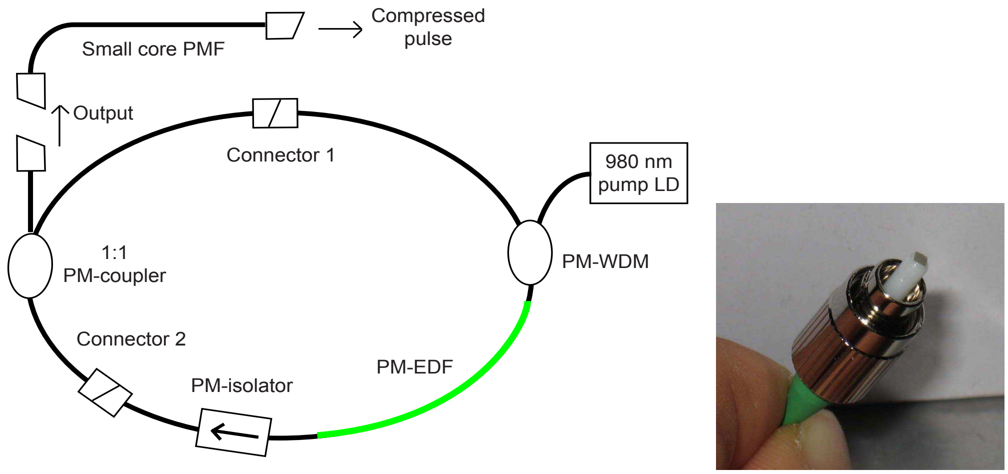

Fig. 1. Configuration of all-polarization-maintaining (PM) passively mode-locked Er-doped ultrashort-pulse fiber laser using SWNT–polyimide film. WDM, wavelength division multiplexed coupler; EDF, Er-doped fiber. Inset shows the fiber connector with the SWNT–polyimide film.

The SWNT–polyimide film was inserted in Connector 1. Since the polyimide film is robust and flexible, it was easily inserted between a pair of angled-polished FC/APC fiber connectors. Since the FC/APC connectors were used to suppress the effect of reflection, the

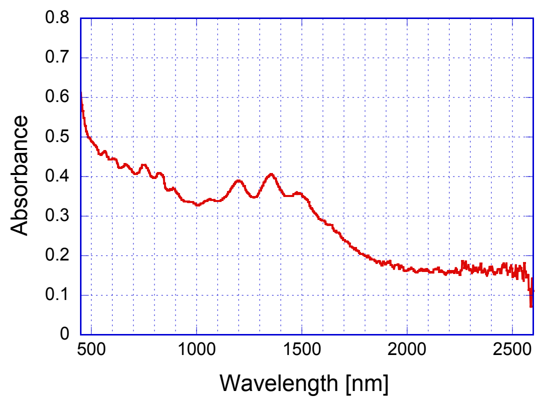

Fig. 2. Absorption spectrum of SWNT–polyimide film. This absorption is almost due to the semiconductor SWNT.

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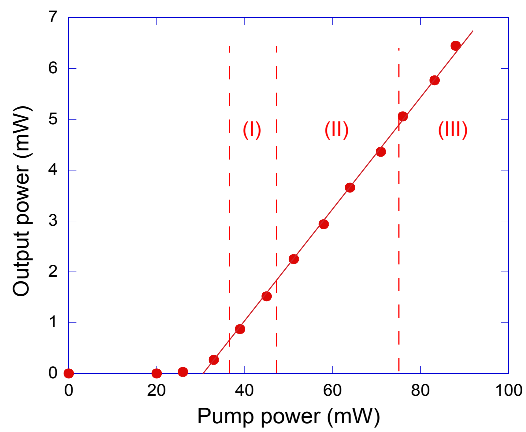

Fig. 3. Power and performance of the laser as a function of pump power. (I) Q-switching, (II) single-pulse oscillation, and (III) multiple-pulse oscillation.

index matching fluid was not used. The total insertion loss of SWNT film was ~33 % at a wavelength of 1.55 μm. The cavity length was adjusted to obtain high-power single-pulse operation. The net dispersion of the cavity was estimated to be –0.104 ps^2. Because the cavity exhibited anomalous dispersion, stable soliton mode-locking operation was achieved.

Figure 3 shows the output power as a function of the pumping power. As the pumping power was increased, the output power increased linearly, and the laser operation changed from cw lasing, to self-Q switching, and then single-pulse mode-locking. Self-start passive

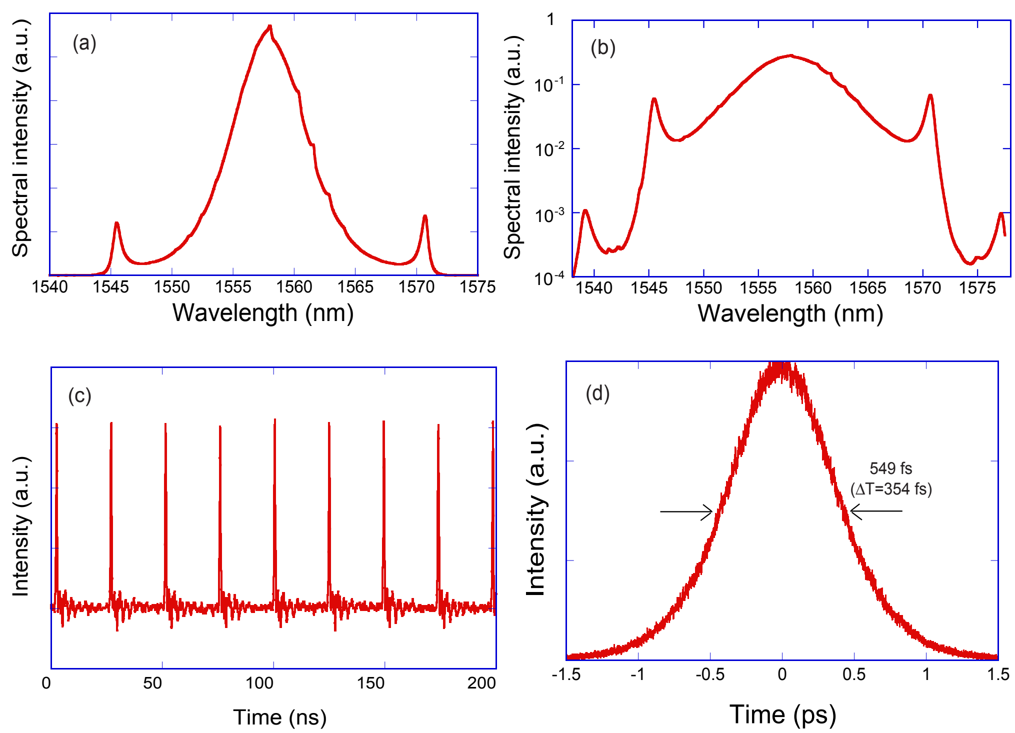

Fig. 4. Characteristics of output pulse from fiber laser when output power was 4.5 mW, showing optical spectra on (a) linear and (b) log scale, (c) pulse train, and (d) autocorrelation trace.

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mode-locking operation was achieved. As the pumping power was increased to more than 76 mW, additional pulses arose, resulting in multiple-pulse oscillation. The maximum average power in the single-pulse operation was 4.8 mW.

Figure 4 shows the characteristics of the output pulses from the fiber laser when the output power was 4.5 mW. For these measurements, we used an optical spectrum analyzer, a combination of a fast photodiode and a digital oscilloscope, and an SHG autocorrelator. The ultrashort pulses were generated stably at a repetition frequency of 41.3 MHz. The Kelly sidebands of soliton laser emission are clearly observed in the pulse spectra [1]. The spectral width was 7.2 nm full-width at half-maximum (FWHM). In the autocorrelation trace, a pedestal-free clear trace was observed. The temporal width of the autocorrelation trace was 549 fs, and the corresponding temporal width assuming a sech^2 pulse shape was 354 fs. The time–bandwidth product was 0.31, which is almost equal to that of the transform limited sech^2 pulse. The soliton order, N, was estimated to be about 1, meaning that the output pulse was the fundamental soliton pulse. When the output power was 4.8 mW, which was the maximum power of the single-pulse operation, the observed temporal width was 314 fs. The autocorrelation trace of the shortest pulse is shown in Fig. 6(b).

When the SWNT–polyimide saturable absorption film was set in Connector 1, the laser beam passed through the film after power division at the output fiber coupler. We also set the SWNT–polyimide film in Connector 2 and examined the effect. For Connector 2, since all of the laser power passed through the SWNT–polyimide film, mode-locking was achieved at lower pumping power, but the threshold power of multiple-pulse operation also decreased by about 20 %. As a result, the maximum power for single-pulse operation was obtained when we used Connector 1.

When we removed and reinserted the SWNT–polyimide film at the fiber connectors, the performance of the fiber laser was almost unchanged and showed good repeatability. This shows that the SWNT–polyimide nano-composite film has good uniformity, stability, and robustness. In this work, the polyimide film containing SWNTs prepared by the laser ablation (LA) method was also examined and the passive mode-locking was confirmed [13]. In terms of the power, however, we obtained higher output power for the HiPco SWNT film compared to the LA one. Thus we used HiPco SWNT film in this work.

Next, we examined the RF noise of the fiber laser using the single sideband method. A fast photodiode, bias-T, and RF spectrum analyzer were used for the measurement. We observed the RF noise shown in Fig. 5. There was no large noise component. The noise level was as low as that of a commercial ultrashort-pulse solid-state laser [14]. This result confirms that the our all-PM SWNT fiber laser was a low noise laser.

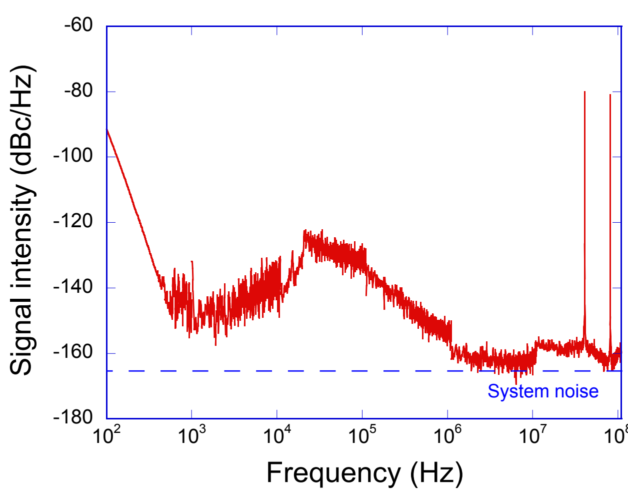

Fig. 5. Observed RF noise of our all-PM SWNT fiber laser.

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Since this laser is an all-PM type, the linearly polarized output pulses are obtained. The observed extinction ratio of the output pulse was 15 dB. This laser is also robust against environmental variations and operates stably. In this experiment, we confirmed continuous long-term stable operation up to 50 hours. After 50 hours, the characteristics of the SWNT film were slightly changed and the multiple pulse operation occurred. We re-adjusted the pump power and then we observed stable single pulse operation up to 140 hours. The thermal effect and the oxidation of SWNT are the possible candidates to cause the characteristic change of SWNT film [15].

3. Pulse compression

Next, the output pulse from the fiber laser was compressed using a small-core polarization-maintaining fiber (PMF). The mode field diameter was 6 μm, and the second-order dispersion was $\beta_2 = -16$ ps^2/km. When the output pulse was coupled into this PMF, pulse compression occurred due to the higher-order soliton compression effect [16]. First, we conducted a numerical simulation of the pulse compression using the nonlinear Schrödinger equation to estimate the optimum fiber length. Then, we demonstrated the pulse compression experimentally.

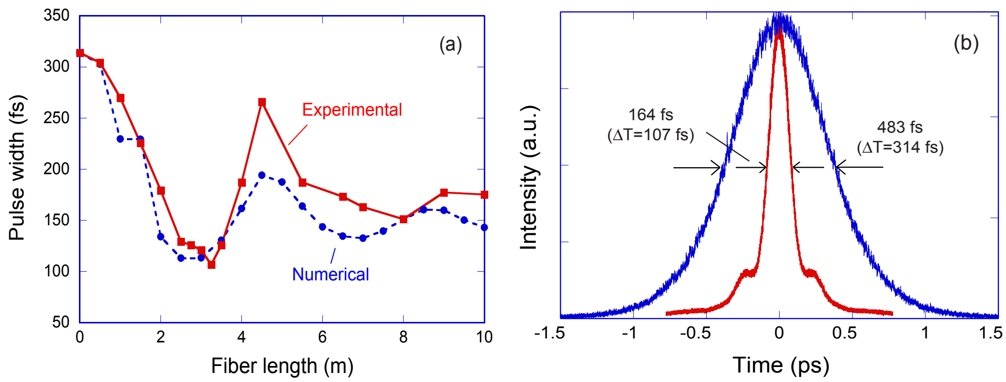

Fig. 6. (a). Variation of temporal width of compressed pulse as a function of fiber length, and (b) observed autocorrelation traces of output pulse from fiber laser and achieved shortest pulse after compression.

Figure 6(a) shows the variation of temporal width of the output pulse from the pulse compression fiber. The output power from the fiber laser was set to the maximum level of 4.8 mW. In the experiment, the temporal width was obtained from measurements taken with an autocorrelator. Owing to the self-phase modulation and anomalous dispersion, higher-order soliton compression occurred in the pulse compression fiber. The temporal width changed periodically along the fiber length, and the shortest pulse width was obtained when the length of the pulse compression fiber was 3.25 m. The experimental results showed similar behavior to the numerical ones.

Figure 6(b) shows the observed autocorrelation trace of the compressed pulse. The autocorrelation trace of the output pulse from the fiber laser is also shown for comparison. Although a small pedestal component arose, clean compressed pulses were stably obtained. The temporal width of the autocorrelation trace of the compressed pulse was 164 fs, and the corresponding pulse width assuming a sech^2 pulse shape was 107 fs. The corresponding peak power was estimated to be up to 1.1 kW. From the numerical analysis, if we could increase the output power from the fiber laser, we should be able to obtain a narrower pulse using the same fiber. We would be able to increase the maximum single pulse output power by the optimization of the cavity, such as the dispersion map and the branching ratio of the output coupler, etc. Since the whole system consisted of all-PM fiber devices, it showed stable operation.

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4. Conclusion

We have demonstrated an all polarization-maintaining (PM) passively mode-locked Er-doped ultrashort-pulse fiber laser using a polyimide film with dispersed single wall carbon nanotubes. A 314 fs ultrashort soliton pulse was stably generated from the fiber laser at a repetition frequency of 41.3 MHz, and the maximum output power was 4.8 mW for single-pulse operation. We also examined the RF noise of the fiber laser and confirmed that the noise level was as low as that of a commercial ultrashort-pulse solid-state laser. The output pulse was compressed using an anomalous-dispersion small-core PM fiber, stably producing a 107 fs ultrashort pulse. Since this soliton fiber laser consisted of all PM type fiber devices and a robust SWNT–polyimide film, it showed stable and self-start operation.

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