Control of Noiselike Pulse Generation in Erbium-Doped Fiber Lasers

Moshe Horowitz and Yaron Silberberg

***Abstract*— Noiselike generation in lasers can be controlled by changing the cavity in order to obtain pulses with unique properties. Intense noiselike pulses, as narrow as a few picoseconds, were obtained. These are two orders of magnitude narrower than pulses obtained in previous work. In long cavities, coherent and incoherent two-color noiselike generation were demonstrated. The wavelength difference between the generated pulses could be tuned in a wide wavelength range, which is much broader than the amplifier bandwidth. High-energy ≈16-nJ noiselike pulses with a broad-band spectrum and narrow intensity autocorrelation trace were also demonstrated.**

***Index Terms*—Mode-locked lasers, optical bier lasers, optical fiber polarization, optical variables measurement, pulsed lasers.**

I. Introduction

PASSIVELY mode-locked erbium-doped fiber lasers (EDFL's) [1] are compact, environmentally stable and can generate femtosecond light pulses with broad spectra. A wide range of potential applications require optical sources with broad spectra, and not necessarily with ultrashort pulse duration. For example, optical sources for coherence tomography and for gyroscopes should produce high-energy pulses with short coherence lengths. In previous work [2]–[4] it was demonstrated that noiselike generation in lasers can be used to obtain sources with a broad spectrum. The autocorrelation trace for the intensity contains a narrow peak, which is not strongly broadened by dispersion effects [2]. A theoretical model indicated that the noiselike mode of operation is due to the existence of birefringent fibers inside the laser cavity [5]. The noiselike mode has significant advantages over conventional short pulse mode: 1) its spectrum is smoother and broader; 2) its output maintains a narrow peak, a few hundred femtoseconds wide, in the autocorrelation trace of the pulse intensity even after the propagation through long dispersive media; and 3) its average powers is higher by up to 50% compared with conventional mode-locking. Although Q-switch operation can be used for obtaining high energy broadband pulses, the pulse train generated in the noiselike mode is periodic, stable, and its spectrum does not fluctuate in time. Recently, an application of the noiselike mode of operation for interrogating an array of fiber gratings [3] was reported.

Manuscript received April 13, 1998; revised June 10, 1998.

M. Horowitz is with the Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel.

Y. Silberberg is with the Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel.

Publisher Item Identifier S 1041-1135(98)07131-6.

In this letter, we investigate the effect of the cavity dispersion and length on the noiselike pulse generation and find out that one can control many parameters of the noiselike pulse by appropriate design of the cavity. In short cavities with low dispersion, we obtained an intense noiselike pulse with a width of a few picoseconds. In previous work [2]–[4], the pulses were about two orders of magnitude longer. The short noiselike pulses enable one to combine the advantages of the noiselike mode with a relatively high intensity as obtained in the short pulse mode. We also demonstrate a two color operation with two different types of autocorrelation curves, suggesting either coherent or incoherent relation between the different wavelength bands. Unlike the conventional short-pulse mode where the wavelengths of the two bands are determined by the amplifier gain profile, the wavelength difference between the bands in the noiselike mode could be adjusted in a wide-wavelength regime that exceeds the bandwidth of the optical amplifier. The cavity of the noiselike laser can be scaled to very long lengths, thereby generating high energy pulses without the complications of conventional short pulse EDFL [6]–[8]. We obtained noiselike pulses with energy of about 16 nJ, and with broad spectrum and short coherence length.

In our experiment, we used a ring fiber cavity, similar to those used for passive mode-locking through nonlinear polarization rotation [4], and added an additional pulse shaper (two polarization controllers and a polarizer) in order to smooth and to broaden the spectrum [2]. Noiselike mode of operation could be obtained for any type of fiber, which was inserted into the cavity, and the overall dispersion could be significantly positive or negative. When we add a 1.7-m normal dispersion fiber (NDF) with $d = 75$ ps/nm/km, the overall dispersion was close to zero and the lasers could be operated in three distinct modes. The switching between the modes was obtained by adjusting the polarization controllers. In the long duration noiselike mode, the laser generated pulses with a broad spectrum, 38-nm full-width at 3-dB point, and a narrow autocorrelation trace, with a peak width of about 130 fs. The ratio between the peak and the shoulders of the autocorrelation trace was about 2 : 1 as obtained in [2]. The pulselength was of the order of 100's of ps. The repetition rate (15 MHz) did not change when the pumping power was raised from 40 to 250 mW. In the short-pulse mode, the laser generated pulses as short as 220 fs (assuming sech profile) with a bandwidth of about 15 nm. Unlike the noiselike mode, when the pumping was increased, several pulses coexisted simultaneously in the cavity, and the spectral line-shape deteriorated.

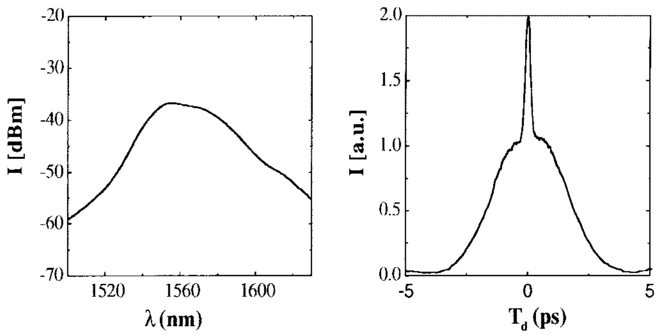

Fig. 1. Optical spectrum and the corresponding background free autocorrelation trace for a noiselike mode with short pulses.

The third operation mode was a noiselike mode with short pulses. Fig. 1 shows the spectrum and the intensity autocorrelation trace for this mode. The repetition rate was equal to the cavity round-trip time and the autocorrelation trace indicates that the pulse has a width of a few picoseconds. In order to verify that the peak in the autocorrelation trace is caused by a noiselike pulse (and not by a combination of a broad and a narrow pulses) we measured the dependence of the autocorrelation trace on dispersion. The width of the pulse envelope increased by 1.2 ps after propagating through 0.5 m in the NDF fiber, and by 2.4 ps after propagating through l m. Similar results are expected from a pulse with an optical spectrum of about 32 nm. The peak width in the autocorrelation trace increased only by a factor of 1.25 after propagating through 0.5 m of fiber and 1.35 after propagating through l m of the NDF fiber. Therefore, the effect of dispersion on the coherent peak is much smaller for the short noiselike pulse, compared to that of a conventional short pulse mode with the same autocorrelation width (200 fs). The ratio between the peak and the shoulders of the autocorrelation trace was close to 2. However, slightly higher ratios could be observed when the pulsewidth was minimum indicating the existence of some ordered structures caused due to the small ratio between the pulsewidth and the coherence time.

The results described below can be explained by considering the unique nonlinear element leading to the noiselike mode. This element, which is based on nonlinear polarization rotation in birefringent fibers, has a transmission that depends on the instantenous derivative (amplitude and phase) of the input wave, rather than only on its instantenous intensity [5]. When the input wave is approximately equally split between the two principle axes of the birefringent fiber, the transmissivity depends mainly on the derivatives of the input wave. However, when the input polarization is approximately parallel to one of the principle axes of the fiber, the pulse polarization does not change and the effect of the birefringence vanishes. In this case, a conventional short-pulse mode can be obtained if the required nonlinear polarization rotation is provided from nearly isotropic fibers inside the cavity. In the general case the polarization at the input of the nonlinear element is arbitrary, and the transmissivity depends on both the instantenous intensity and the derivative of the pulse amplitude. The dependence on the intensity is also enhanced by the second nonlinear element, which was added to the cavity and is based on nonlinear polarization rotation in isotropic fibers. Therefore, the laser generates short noiselike pulses (as shown in Fig. 1) in order to maximize both the pulse intensity and its derivatives.

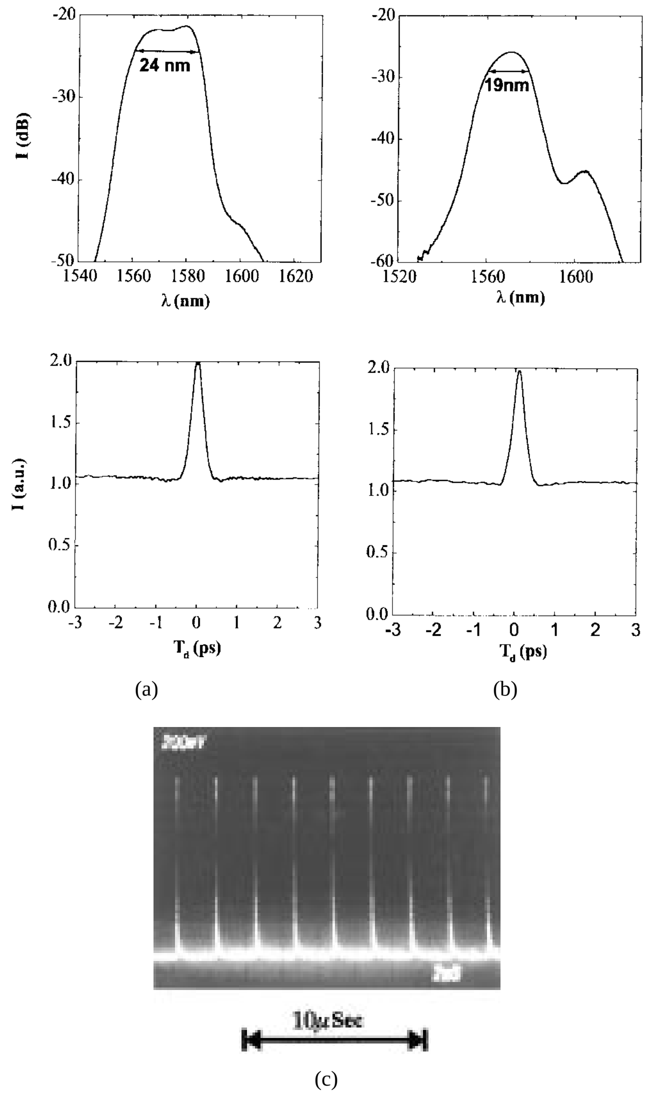

Fig. 2. Optical spectrum, the corresponding background free autocorrelation trace and the pulse train: (a) with 450-m dispersion shifted fiber added to the cavity and (b) with 450 m of a dispersive fiber (Corning SMF28) added.

We have also investigated noiselike operation of long cavity lasers. The long cavities enable one to obtain two-color mode of operation as well as high energy pulses. In our experiment, we added a section of a 450-mg-length fiber to the cavity that was either a dispersion shifted fiber ($d \cong 2$ ps/nm/km) or an anomalous dispersion fiber (Corning SMF28) ($d \cong 16$ ps/nm/km), which added a total dispersion of about 7 ps/nm. For both types of fibers, noiselike pulses with broad spectra and narrow autocorrelation peaks were obtained, as shown in Fig. 2(a) for the case where the dispersion shifted fiber was added to the cavity and in Fig. 2(b) where a dispersive fiber (Corning SMF28) was added. The width of the peak in the autocorrelation traces was about 350 fs. The laser could be adjusted to generate pulses with a periodicity that equals to the cavity round-trip time of 2.3 μs. The pulsewidths for both types of fibers were of the order of a few nanoseconds and it

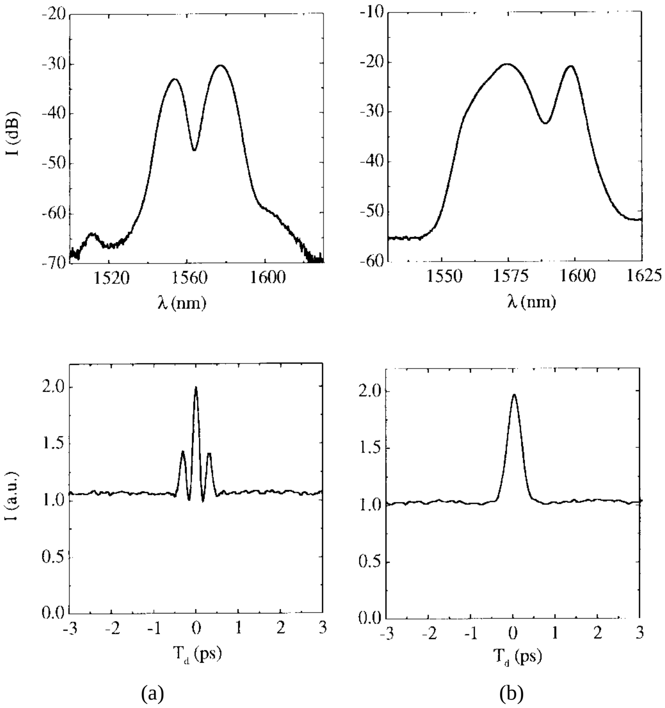

Fig. 3. Optical spectrum and the corresponding background free autocorrelation trace in a two-color operation mode (a) for the coherent mode and (b) for the incoherent mode. For both modes a dispersion shifted fiber was used.

increased as the pump power was raised. The results indicate that the noiselike mode is not significantly affected by the cavity dispersion due to the small affect of the dispersion on the pulse properties, as measured in our previous work [2]. High pulse energies of about 16 nJ were obtained. The average power was about 7 mW compared to 10 mW in short cavities.

We found out that in certain cases the long-cavity laser could be adjusted to operate in a two-color mode. We attribute this to the large birefringence introduced by these long fibers, which were spooled on a drum. The birefringence imposed additional wavelength-dependent modulation on the loss of the cavity. Its effect could be emphasized by adjusting the polarization controller that was located near the input end of the long fiber. The optical spectrum of the laser was split into two separate bands in order to match the wavelength-dependent modulation of the loss. The frequency of the longer wavelength peak could be tuned over a wide range of more than 20 nm, by adjusting the polarization controllers. Fig. 3 shows the spectrum and the background-free autocorrelation traces for the two-color mode. The autocorrelation traces indicate that two types of operation could be obtained. In the first mode [Fig. 3(a)] the two frequency bands are mutually coherent. The noise burst has a strong component at the beat frequency, and therefore, the autocorrelation trace contains several peaks (up to seven different peaks were measured). In the incoherent case, shown in Fig. 3(b), the frequency dependence of the transmission caused the generation of two burst trains with different wavelengths. The different trains were usually synchronized, however relative motion of the different trains was also observed, similar to that obtained in Ti:sapphire lasers [9]. In those cases, we could observe on the oscilloscope two independent trains of pulses with the same repetition rate, which slide along each other.

In long cavities, the noiselike pulses are preferred over conventional short pulses because of nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and Raman, which become dominant. These effects tend to broaden the spectrum and deteriorate the structure of a smooth pulse. On the other hand, noiselike pulses are less affected by dispersion, and similarly, by nonlinear effects. The nonlinear effects may also significantly broaden the spectrum of the generated noiselike pulse behind that of the amplifier gain bandwidth (as can be observed in Fig. 3). However, the pulse-to-pulse correlation in this case is expected to be lower than that in short cavities due to the strong dependence of the nonlinear effects on the instantaneous intensity, and, therefore, the optical spectrum became more noisy.

In cases when the polarization mode delay (PMD) of the birefringent fiber is less than the minimum pulsewidth, which can be generated by the laser, the optical bandwidth is determined by the PMD. In long lasers, the PMD is usually large and therefore the bandwidth is smaller than in short cavities. The measured bandwidth in our laser is in accordance to the PMD induced by a 450-m fiber, which are rounded on a 20-cm drum. In the case when the average dispersion is low and the PMD is large, pulses that are shorter than the PMD can be generated. The birefringence in this case splits each of the short pulses into two pulses. The splitting of the pulses causes the bunching of many short pulses into a long noiselike pulse and the bandwidth of the optical spectrum may not be strongly affected by the PMD.

Acknowledgment

The authors would like to thank Dr. I. N. Duling, III, from the Navy Research Laboratory for stimulating discussion and Y. Barad for his invaluable help.

References

[1] M. E. Fermann, "Ultrashort-pulse sources based on single-mode rare earth-doped fibers," *J. Appl. Phys. B,* vol. 58, pp. 197–209, 1994.
[2] M. Horowitz, Y. Barad, and Y. Silberberg, "Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser," *Opt. Lett.,* vol. 22, pp. 799–801, 1997.
[3] M. A. Putnam, M. L. Dennis, I. N. Duling, III, C. G. Askin, and E. J. Friebele, "Broadband square-pulses operation of passively mode-locked fiber laser for fiber Bragg grating interrogation," *Opt. Lett.,* vol. 23, pp. 138–140, 1998.
[4] V. J. Matsas, D. J. Richardson, T. P. Newson, and D. N. Payne, "Characterization of a self starting, passively mode-locked fiber ring laser that exploits nonlinear polarization rotation," *Opt. Lett.,* vol. 18, pp. 358–360, 1993.
[5] M. Horowitz and Y. Silberberg, "Nonlinear filtering using intensity dependent polarization rotation in birefringent fibers," *Opt. Lett.,* vol. 22, pp. 1760–1762, 1997.
[6] A. B. Grudinin, D. J. Richardson, and D. N. Payne, "Energy quantization in figure eight fiber laser," *Electron. Lett.,* vol. 28, pp. 67–68, 1992.
[7] S. M. J. Kelly, "Characteristic sideband instability of periodically amplified average soliton," *Electron. Lett.,* vol. 28, pp. 806–807, 1992.
[8] M. L. Dennis and I. N. Duling, III, "Experimental study of sideband generation in femtosecond fiber lasers," *IEEE J. Quantum Electron.,* vol. 30, pp. 1469–1477, 1994.
[9] R. R. Dykaar, S. B. Darack, and W. H. Knox, "Cross-locking dynamics in a two-color mode-locked Ti-sapphire laser," *Opt. Lett.,* vol. 19, pp. 1058–1060, 1994.