Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser

M. Horowitz, Y. Barad, and Y. Silberberg

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

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An erbium-doped fiber laser that produces a train of intense noiselike pulses with a broadband spectrum and a short coherence length is reported. The noiselike behavior was observed in the amplitude as well as in the phase of the pulses. The maximum spectral width obtained was 44 nm. The high intensity and the short coherence length of the light were maintained even after propagation through a long dispersive fiber. A theoretical model indicates that this mode of operation can be explained by the internal birefringence of the laser cavity combined with a nonlinear transmission element and the gain response of the fiber amplifier.

During the past few years, lasers based on erbium-doped fiber amplifiers have been intensively investigated. Such lasers are compatible with semiconductor pump lasers and can generate light in a well-confined diffraction-limited mode. Several laser configurations were suggested and demonstrated for ultrashort pulse sources[1] as well as narrow-band cw lasers.[2] For several important applications, in particular in optical metrology, light sources with short coherence lengths are essential. LED's, which generate broadband noise, are commonly used for such applications; however, the power of LED's is limited. Optical amplifiers such as erbium-doped fibers have been as spontaneous-emission sources or as light amplifiers to LED's. However, the power of such sources is limited because of the continuous mode of operation of the device. A further increase in the optical power could improve the performance of optical systems that use such sources. In this Letter we report a pulsed erbium-doped fiber laser that generates a train of high-intensity, broadband, noiselike pulses. A theoretical model indicates that this mode of operation can be explained by the internal birefringence of the laser cavity combined with a nonlinear transmission element and the gain response of the fiber amplifier.

Figure 1 shows the laser configuration schematically. We used a modified ring fiber cavity, similar to those used for passive mode locking through nonlinear polarization rotation,[3] which contained an erbium-doped fiber, two polarization controllers, a polarizer, and an isolator. We found that a second polarizer between the polarization controllers was needed to control and to broaden the spectrum of the laser. This element provides additional intracavity pulse shaping[4] and helps to produce a smooth and broad spectrum. We achieved noiselike generation in a long cavity ($\approx$15 m) with a significant birefringence that was caused by the erbium-doped fiber and by winding some of the cavity fibers. In most of our experiments the overall dispersion was significantly positive because of inclusion of a 3-m section fiber with positive group dispersion [$d = 75$ ps/(nm/km)]. Although noiselike behavior could have been achieved without it, we found that positive dispersion improved the stability of the laser. The laser was pumped with a master-oscillator power-amplifier laser with a wavelength of 985 nm.

When the laser was pumped above threshold, we observed a train of pulses with a repetition rate of 6.7 MHz and a pulse duration of the order of 100 ps by using a fast detector and a sampling scope. The laser output was polarized and had an average power of ~10 mW and a peak power of ~15 W. We could change the pulse width by adjusting the polarization controllers or by changing the pump power. However, long and noiselike pulses were generated, even at pump powers close to the threshold. We could obtain shorter noiselike pulses with widths of the order of tens of picoseconds by changing the length of the positive dispersion fiber. The optical spectrum, shown in Fig. 2(a), was broad and smooth. The background-free second-harmonic autocorrelation trace shown in Fig. 2(b) consisted of a 190-fs peak riding upon wide and smooth shoulders that extended over the entire width of our measurement window of 20 ps. The ratio between the peak intensity and the shoulder level of the autocorrelation trace was close to 2. The maximum spectrum width obtained was 44 nm [Fig. 2(c)]. We stress that broad and smooth spectra were obtained only after we inserted the additional intracavity pulse shaping.

The optical spectrum and the autocorrelation trace indicate that the laser generates noiselike pulses with

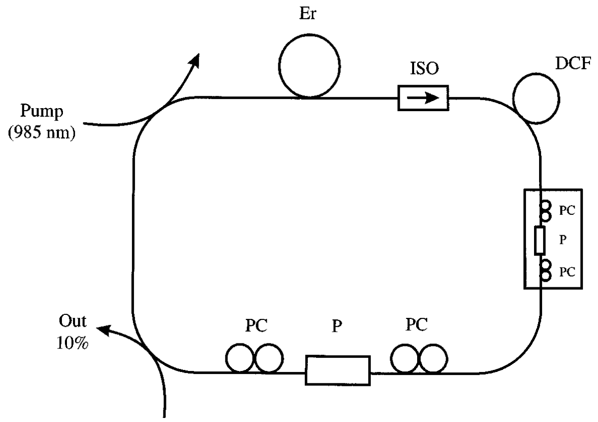

Fig. 1. Schematic setup of the laser: PC's, polarization controllers; P's, polarizers; ISO, isolator; DCF, positive-dispersion fiber; Er, erbium-doped fiber amplifier.

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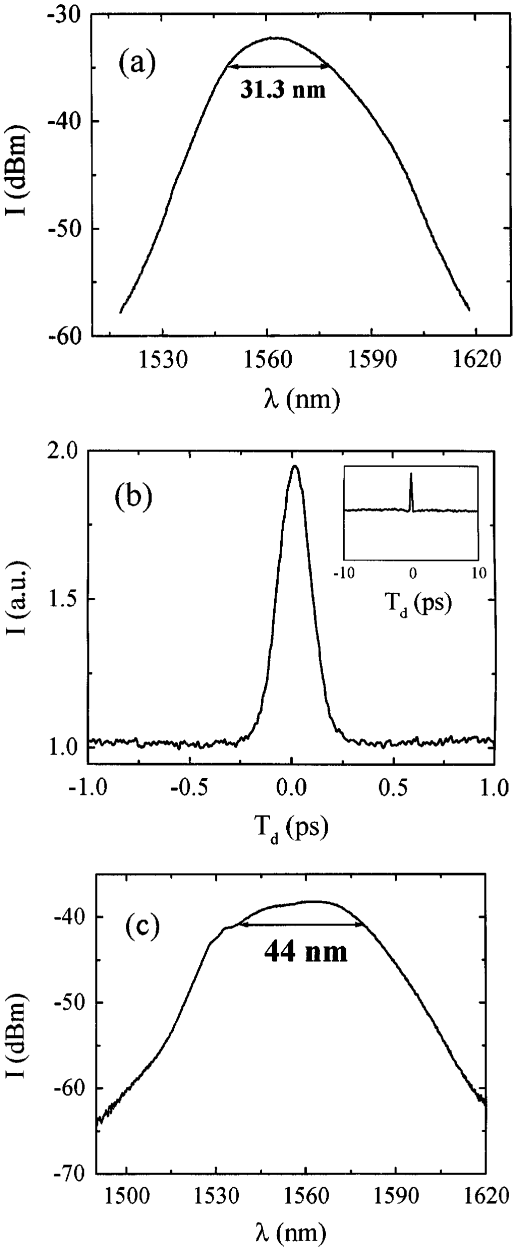

Fig. 2. (a) Optical spectrum and (b) the corresponding background-free autocorrelation trace of the laser output. (c) Spectrum with the maximum spectral width that was obtained.

low coherence lengths and broad spectra. The autocorrelation measurement was noncollinear and therefore was affected only by the intensity of the light and not by its phase. The ratio of 2 between the peak intensity and the shoulder level of the autocorrelation trace indicates that the power of the noiselike part of the pulse intensity is similar to the average pulse power. Therefore we can conclude that most of the pulse amplitude consists of noise and does not have a significantly ordered structure. We believe that the phase of the pulse has noiselike behavior similar to that measured for the amplitude. Indeed, the maximal spectral width that was measured corresponds to a coherence time of ~50 fs. Note that a figure-8-shaped fiber laser was reported to operate in a long-pulse mode,[5] which was attributed to modulational instability. However, modulational instability normally leads to structured spectra and autocorrelation traces, which we did not observe in our experiments.

The narrow peak in the autocorrelation trace was maintained even after the pulses propagated through a long dispersive medium. For example, after a pulse passed through 700 m of a standard fiber [$d = -16$ ps/(km/nm)], the half-width of the autocorrelation peak increased from 190 to 380 fs and the peak value decreased by approximately a factor of 2. A transform-limited pulse with a similar bandwidth is expected to broaden by more than 3 orders of magnitude after propagating through a similar fiber, and the maximum intensity of the autocorrelation trace would be attenuated by 6 orders of magnitude. We believe that the phase distortion caused by the fiber dispersion is relatively weak compared with the initial noise of the pulses and therefore has only a small effect on the coherence. This property could be important for optical measurements that need to be carried out through long fibers.

An interesting question is: What are the pulse-to-pulse changes in this laser or, equivalently, to what extent are the modes of this laser locked? The fixed repetition rate and the constant pulse envelope suggest at least partial mode locking. The transition from cw to pulsed operation is sudden; the spectrum becomes wide and continuous, suggesting the onset of mode locking.

In cavities in which the overall dispersion was small we could switch between a noiselike mode of operation and a single-pulse mode by adjusting the polarization controllers. We verified that for noiselike operation the polarization controllers were set at midrange between maximal and minimal transmissivity of the polarizers for low-power signals.

The birefringence in our laser was significant. The effect of the birefringence combined with the gain response of the amplifier could be experimentally observed when the laser was operated in a continuous mode. In this case we could control the laser frequency over a wide range, between 1541 and 1565 nm and near 1535 nm, by adjusting the polarization controllers. The birefringence of fiber lasers was analyzed and used for controlling the frequency of a cw laser.[6] Because the birefringence inside our laser cavity is not uniform, the frequency dependence of the linear transmissivity of the cavity has a complex behavior. We estimate the average birefringence of our laser to be $\Delta n = 5 \times 10^{-6}$.

To explain the formation of the pulsed noiselike operation mode we modeled a laser that comprised three elements: a fiber (with dispersion and Kerr effect), an optical amplifier, and a nonlinear transmission element. The total dispersion was ~0.2 ps/nm. To analyze the nonlinear element we used a simplified model for nonlinear polarization rotation in a birefringent fiber.[7,8] The power of linearly polarized light transmitted through a birefringent fiber and a polarizer is given by[8]

$$P_t = P_0 \sin^2[(\phi_{\mathrm{NL}} + \phi_0)/2]\sin^2(2\theta), \qquad (1)$$

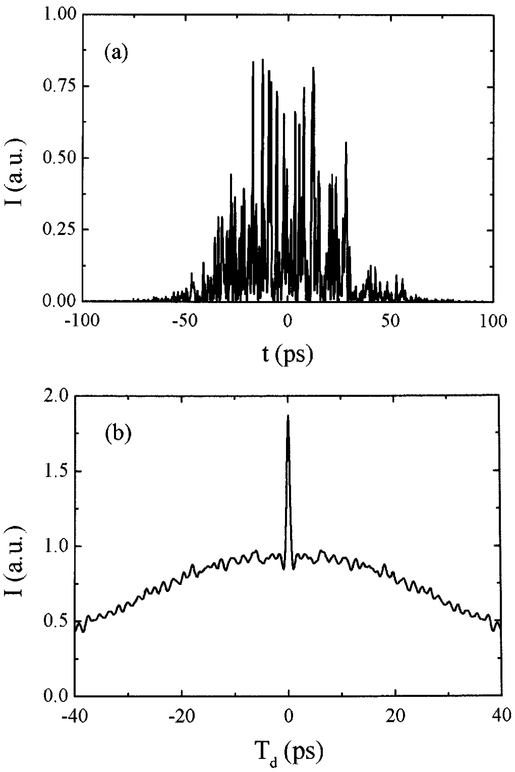

Fig. 3. (a) Calculated time-dependent intensity and (b) autocorrelation trace obtained by numerical solution of the theoretical model after 300 iterations.

where P_0 is the input power; θ is the angle between the polarization of the incident wave and one of the principal axes of the fiber (denoted x and y); $\phi_0 = k_0(n_x - n_y)l$ is the phase difference induced by the fiber birefringence, where n_x and n_y are the refractive indices for light polarized along the x and the y axes, respectively; k_0 is the wave number in vacuum; l is the fiber length; and $\phi_{\mathrm{NL}} = \gamma l(P_x - P_y)/3$ is the nonlinear phase difference, where P_x and P_y are powers of the light components polarized along the x and the y axes and is γ the nonlinear coefficient. Assuming a peak intracavity power of $P = 150$ W and a nonlinear coefficient of $\gamma = 4\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$, the interaction length needed for a nonlinear phase shift of π between the two polarization components is ~15 m.

In our laser the birefringence is significant, and polarization-dependent delay (PDD) should be included. We included it in the frequency domain, where each frequency component was assigned a different bias phase delay ϕ_0. The model also included the spectral dependence of the amplifier. We took these effects into account by transforming the nonlinear transmissivity into the frequency domain, adding the frequency dependence of the transmission, and then transforming the result back into the time domain. The nonlinear phase shift was calculated in the time domain, but, to simplify our calculations, we did not include the PDD. A more precise model, which includes a more accurate modeling of the nonlinear polarization rotation,[9] has been described. We expect the same general behavior to be reproduced.

Figure 3 shows the time-dependent intensity and the calculated autocorrelation trace obtained by integration of the laser equations numerically. We used spontaneous emission, modeled as white noise, to initiate the oscillation. Noiselike behavior, similar to that measured in the experiments, was obtained after a few iterations. Our calculations reproduce the noiselike intensity, which leads to an autocorrelation trace with a narrow coherent peak and wide shoulders. Note that the noise is leading to nearly full modulation of the laser intensity. To simplify the calculations, we chose the pulse duration in the simulations to be shorter than those measured in the experiments.

Our laser cannot support short pulses because of the strong positive dispersion and the significant birefringence, which introduces significant PDD. Dispersion tends to broaden short pulses, and birefringence splits them through PDD. However, our laser does not support long, narrow-band pulses because of the frequency dependence of the nonlinear element transmissivity as caused by the birefringence and by the gain response of the amplifier. Long, narrow-band pulses tend to be unstable owing to the growth of noise components that are added to the pulses and have a bias phase (ϕ_0) that causes high nonlinear differential gain. Hence the only stable mode of operation available is the formation of noiselike bursts, as we have observed experimentally and theoretically.

We have reported a new erbium-doped fiber laser that produced a train of long noiselike 100-ps pulses with a unique broad spectrum as wide as 44 nm. Such a wide spectrum is useful in many applications in metrology for which low coherence is required. Unlike most other sources for low-coherence light, this laser output is produced with relatively high peak power in well-defined pulses. We believe that this new source will offer these advantages for many applications in fiber-optics measurements and other fields.

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