Ultralow-repetition-rate pulses with ultralow jitter generated by passive mode-locking of an optoelectronic oscillator

Alexander Sherman* and Moshe Horowitz

Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel
**Corresponding author: sh.alexander@gmail.com*

Received July 19, 2013; revised September 23, 2013; accepted September 26, 2013; posted September 27, 2013 (Doc. ID 193748); published October 25, 2013

We demonstrate the generation of an ultralow-repetition-rate pulse train with a repetition rate of 19.6 kHz by passive mode-locking of an optoelectronic oscillator. The pulse-to-pulse timing jitter equals 0.06 ppm of the repetition time of the pulses. No significant dependence of pulse duration, pulse waveform, and timing jitter was observed when the cavity length was changed from 150 to 10,400 m. A simple theoretical model for calculating the dependence of the jitter on the cavity length is given.

OCIS codes: (230.0250) Optoelectronics; (140.4050) Mode-locked lasers; (230.4910) Oscillators; (320.5550) Pulses.

http://dx.doi.org/10.1364/JOSAB.30.002980

1. INTRODUCTION

Generation of ultralow-repetition-rate pulses with very low jitter is important for various applications of radar systems [1]. In particular, such pulses are required to accurately measure the position and velocity of long-distance targets. While a train of short pulses with ultralow jitter can be generated by mode-locked lasers, decreasing the pulse repetition rate of fiber lasers by increasing their cavity length causes the formation of multiple low-power pulses [2–4]. Alternatively, low-repetition-rate noise-like pulses can be generated in ultralong mode-locked fiber lasers [5–7]; however, the jitter performance of such pulses is limited. Ultralow-rate, high-power, picosecond optical pulse trains can also be generated by using a single-wall-carbon nanotube saturable absorber in an all polarization-maintaining (PM) mode-locked fiber laser with a length of 1.3 km [8]. However, the pulse duration and its repetition rate limit the application of such sources for microwave applications. Ultrawideband pulse trains can be obtained from electronic oscillators by connecting the oscillator output to a step-recovery diode [9] or an integrated electronic circuit [10,11]. However, the jitter of such systems is limited in comparison with mode-locked oscillators.

In a previous work, we demonstrated a new pulsed optoelectronic oscillator (OEO) that generates short electrical pulses by using a passive mode-locking technique [12]. In this paper, we demonstrate that such a technique can be utilized to overcome the formation of multiple low-power pulses in long passively mode-locked fiber lasers. By using a mode-locked OEO with a cavity length of about 10,400 m, the generation of pulses with a repetition rate of about 19.6 kHz is demonstrated. We have studied the performance of the mode-locked OEO for four different cavity lengths: $L_c = 150$, 2200, 5370, and 10,400 m. For all four cavity lengths, the pulse duration was about 580 ps and the pulse-to-pulse jitter was about 3 ps. Hence, the pulse duration, pulse waveform, and pulse-to-pulse timing jitter did not change significantly when the cavity length was increased from 150 to 10,400 m. Since an increase in the cavity length did not change the jitter, whereas the repetition rate of the pulses decreased, we could obtain a pulse-to-pulse jitter of only about 6×10^{-8} of the pulse repetition period for the OEO with a cavity length of 10,400 m. Stable operation of the device was obtained without the use of PM fibers as in Ref. [8]. A simple theoretical model given in the paper indicates that when noise due to changes in environmental conditions can be neglected, the jitter does not depend on the cavity length. Ti:sapphire lasers are used to generate ultrashort high-energy optical pulses with a kilohertz repetition rate by using cavity dumping [13,14] or by using a pulse picker outside the laser cavity. In the mode-locked OEO described in this paper, noise was added by radio-frequency (RF) amplifiers and hence we observed that the jitter did not change significantly when we decreased the repetition rate of the device by increasing its cavity length. If a pulse picker outside the mode-locked OEO is used to decrease the repetition rate, the jitter will increase as the repetition rate is decreased.

2. EXPERIMENTAL SETUP

The experimental setup, depicted in Fig. 1, is similar to that described in Ref. [12]. However, to enable operation of the system at a very low repetition rate, several modifications had to be made to the setup. In particular, the sensitivity and the dynamic range of the feedback system that determine the RF amplification had to be improved significantly, as described below. A continuous-wave (CW) semiconductor laser with an optical power of about $P_0 = 15$ dBm that operates at a wavelength of 1550 nm and has a spectral width of about 1 MHz is amplitude-modulated by a Mach–Zehnder modulator (MZM) having an insertion loss of $\alpha = 6$ dB, a dynamic extinction ratio of 13 dB, $V_{\pi,\mathrm{DC}} = 6$ V, $V_{\pi,\mathrm{AC}} = 5.5$ V, and a 3 dB electro-optical bandwidth of about 8 GHz. The MZM bias

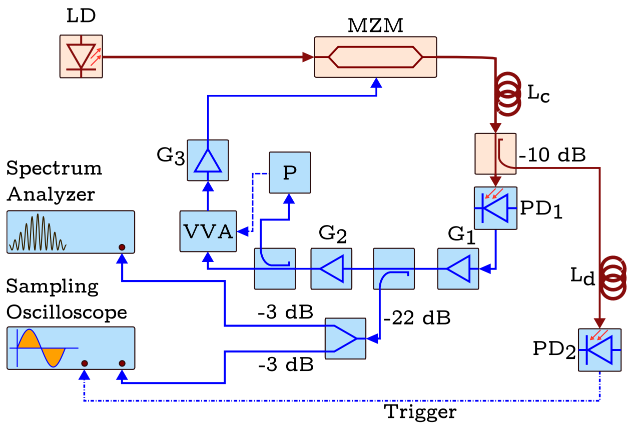

Fig. 1. Schematic description of the experimental setup. LD is a CW semiconductor laser; MZM is a Mach–Zehnder amplitude modulator; G_1, G_2, and G_3 are similar RF amplifiers with a small signal gain of 16 dB and 3 dB cutoff frequencies of 30 kHz and 4 GHz; PD_1 is a photodetector; L_c is a long fiber that determines the repetition rate; P is an RF power meter; and VVA is a voltage-controlled variable RF attenuator. To measure the pulse-to-pulse timing jitter by using a sampling oscilloscope (Agilent DCA-J 86100C), a fiber of length L_d that is slightly shorter than L_c and a second photodetector PD_2 are added to obtain a trigger signal to the sampling oscilloscope.

was set to $V_{b,\mathrm{DC}} = 12.8$ V and hence the small signal transmission of the modulator was close to its minimal value. To decrease the repetition rate of the device, we added to the cavity a long fiber (Corning SMF-28) of length up to about 10.4 km. A photodetector (PD_1) converts the optical signal into an RF signal, which is fed into two identical RF amplifiers. Each amplifier has a small signal gain $G = 16$ dB, a 3 dB amplification spectrum of 30 kHz–4 GHz, a noise figure $NF = 3$ dB, and saturation power $P_{1\,\mathrm{dB}} = 23$ dBm. The output of the amplifiers is fed into a voltage-controlled variable attenuator (VVA) with an attenuation that can be changed in the region 1.5–32 dB. The VVA is controlled by a slow RF feedback that contains an RF power detector with an integration time of about 5 ms. The output signal of the VVA is then amplified by another RF amplifier with the same specifications as the other two amplifiers and is fed into the MZM through an RF directional coupler with a coupling ratio of 22 dB. The output of the coupler is used for measuring the generated pulses. At a low repetition rate, the signal-to-noise ratio (SNR) at the input of the feedback system that controls the VVA decreases since more noise is accumulated between the pulses while the average signal power decreases. Therefore, we have built an RF power detector with a 65 dB dynamic range and a minimum sensitivity of about –50 dBm. The integration time of the electronic feedback was also increased to 5 ms. In the mode-locked OEO, the MZM promotes the generation of pulses since it functions as a fast saturable absorber with a time response that is significantly shorter than the pulse duration. The combination of the MZM and the VVA with its electronic feedback promotes the generation of short pulses. Such short pulses are transmitted efficiently through the modulator due to their high peak voltage. At the same time, such pulses have a very low average power. As a result, the attenuation of the VVA is minimal and the total amplification becomes maximal.

Measurement of the pulse-to-pulse timing jitter was performed by using a sampling oscilloscope (Agilent DCA-J 86100C). Measurement of each pulse was triggered by the former pulse in the pulse train. The trigger pulse was obtained by adding a 10 dB optical coupler to the output of the MZM. The pulse was then delayed by an optical fiber of length L_d and detected by a second photodetector (PD_2) that was connected to the trigger port of the sampling oscilloscope. To measure the pulse-to-pulse jitter while minimizing the internal jitter of the oscilloscope [15], it is important to properly choose the fiber length L_d. Since most of the cavity delay is determined by the fiber length L_c, the length of the fiber that is used to delay the trigger pulse, L_d, should be chosen to be comparable but slightly shorter than L_c. Hence, for an OEO with a cavity length L_c of 150, 2200, 5370, and 10,400 m, the fiber length L_d was equal to about 142, 2192, 5362, and 10,392 m, respectively.

3. EXPERIMENTAL RESULTS

We have measured the generated pulses for four different cavity lengths of about $L_c = 150$, 2200, 5370, and 10,400 m. A stable single pulse train with a repetition time of about $\tau = 0.75$, 10.8, 26.3, and 51 μs; a full width at half-maximum (FWHM) of 580, 570, 580, and 590 ps; and optical pulse energy of about 0.62, 0.53, 0.84, and 0.72 pJ, respectively, was obtained. The repetition rate approximately equals the delay induced by the fiber and hence only a single pulse has propagated in the cavity. The pulse profiles and the corresponding spectrum envelopes at the input of the MZM are shown in Figs. 2(a) and 2(b), respectively. The figures indicate that the pulse duration, pulse profile, and pulse amplitude almost do not depend on the cavity length. The measured RMS pulse-to-pulse jitter was about 3 ps for all four cavity lengths, L_c. This result was close to the minimum timing jitter that can be measured by our sampling oscilloscope, which is about 2.85 ps [15]. Under the limitations of our sampling oscilloscope, the measured pulse-to-pulse jitter almost did not depend on the cavity length. This result can be explained by using the simple theoretical model given below. The result of the model also indicates that the measured results are close to the theoretical limit.

The pulse spectra at lower frequencies and around higher frequencies of about 350 MHz are shown in Fig. 3 for an OEO with a cavity length of $L_c = 10{,}400$ m. The RBW was set to 10 Hz. The frequency difference between the comb lines equals 19.6 kHz, as expected from the modes of a cavity with a length of $L_c = 10{,}400$ m. The noise floor at low frequencies

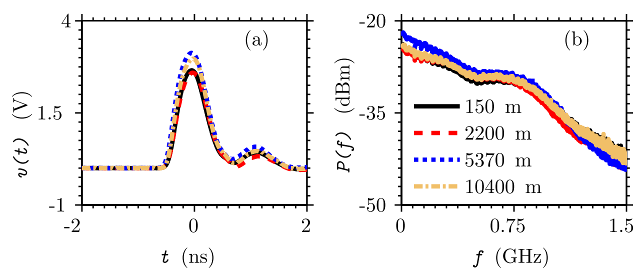

Fig. 2. (a) Time domain waveforms and (b) the corresponding spectra of pulses at the input of the MZM that were generated by a passively mode-locked OEO with a cavity length of $L_c = 150$, 2200, 5370, and 10,400 m (black solid, red dashed, blue dotted, orange dashed–dotted curves, respectively) measured by a sampling oscilloscope and an RF spectrum analyzer with a resolution bandwidth (RBW) of 100 kHz.

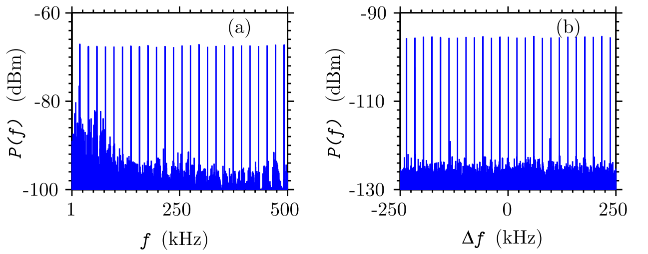

Fig. 3. Spectrum of the generated pulse train for a cavity length of $L_c = 10{,}400$ m that was measured by an RF spectrum analyzer (a) at low frequencies and (b) around a frequency of 350 MHz. The RBW was set to 10 Hz. The noise floor at frequencies <100 kHz is strongly affected by the internal noise of the spectrum analyzer.

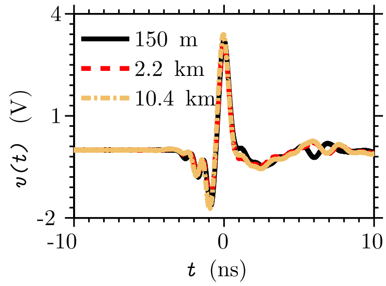

Fig. 4. Time domain waveforms of a single-cycle pulse with a carrier frequency of about 380 MHz generated by an OEO with a cavity length of $L_c = 150$, 2200, and 10,400 m (black solid, red dashed, orange dashed–dotted curves, respectively). For obtaining the single-cycle pulses, the RF amplifier G_3 in Fig. 1 was replaced by the amplifier used in the experiment described in Ref. [12].

(<100 kHz) is strongly affected by the internal noise of the RF spectrum analyzer.

4. DISCUSSION

In a previous work, we demonstrated that a single-cycle pulse train can be generated by using a passively mode-locked OEO [12]. In this work, we show that such a device can be used to overcome the formation of multiple pulses in passively mode-locked fiber lasers when the cavity length is increased. The pulse shape and the pulse-to-pulse timing jitter did not change significantly when the cavity length was increased from 150 to 10,400 m. A very stable operation was obtained even for the longest cavity that we studied. Unlike in ultralong passively mode-locked fiber lasers, only a single pulse propagated in the cavity and the maximum pulse power did not decrease as the cavity length was increased as shown in Fig. 2. This result is obtained since the fast saturable absorber in the mode-locked OEO is formed by the nonlinear transmission curve of the MZM. Therefore, the fast nonlinear transmission that is required to promote passive mode-locking does not depend on the fiber length. Since the bandwidth of the RF pulses is only about 500 MHz, the increase in dispersion and polarization mode delay due to increase in the fiber length does not affect the pulses significantly. Indeed, by adding optical couplers to a mode-locked OEO of length $L_c = 10{,}400$ m and measuring the optical pulse at the input and the output of the fiber we have verified that the pulse did not change while propagating in the fiber. Since the detector is not sensitive to the polarization of the detected light, changes in the polarization of the light that propagates in the fiber due to environmental changes do not affect the device operation. Since fiber loss (about 0.2 dB/km) is very small in comparison with the RF amplifiers' gain, the fiber loss can be compensated by the RF amplifiers without affecting the device operation significantly. Hence, a very stable operation of the mode-locked OEO was obtained even for a very long cavity of about 10,400 m.

The mode-locked OEO that is described in Ref. [12] has generated a single-cycle pulse with a carrier frequency of about 650 MHz. The amplifier used in that experiment had a 5 dB amplification spectrum between 440 and 880 MHz. The amplifiers that were used in the current experiment had a 3 dB amplification spectrum that started at only 30 kHz. Therefore, the carrier frequency of the pulses shown in Fig. 2(b) is close to zero. To verify that the carrier frequency of the generated pulses is determined by the amplifier spectrum, we changed the amplifier that was connected to the MZM (G_3) to the amplifier described in Ref. [12]. Figure 4 shows the pulse waveforms that were obtained after changing the amplifier for cavity lengths: $L_c = 150$, 2200, and 10,400 m. The figure shows that single-cycle pulses with a carrier frequency of about 380 MHz and a duration of about 4 ns were obtained. The pulse profile in this system did not depend significantly on the cavity length as was also obtained for the pulses shown in Fig. 2. The pulse duration is longer than that obtained for the pulses shown in Fig. 2(a) since the bandwidth of the amplifier G_3 is narrower. The pulse-to-pulse jitter that was measured for the three cavity lengths was about 5 ps. The carrier frequency that was measured is smaller than that obtained in Ref. [12] since we exchanged only the last amplifier and not the other amplifiers in the system.

In a previous work [12], it was shown that the pulse-to-pulse jitter of a mode-locked OEO is mainly determined by an additive white Gaussian noise, which is added by the RF amplifiers. Assuming that the pulse waveform without noise equals $f(t)$, the standard deviation of pulse-to-pulse jitter equals [12]:

$$\sigma_\tau = \frac{2}{E_0}\sqrt{\frac{G\rho_N Z}{2}\int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} t^2 f^2(t)\mathrm{d}t}, \qquad (1)$$

where $f(t)$ is the pulse waveform, τ is the round-trip duration, $E_0 = \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} f^2(t)\mathrm{d}t$ is the pulse energy, $t = t' - T_p$ is the central pulse time, with $T_p = \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} t' f^2(t)\mathrm{d}t'$, $\rho_N = NF \cdot k_B \cdot T_{\mathrm{amp}} + 2q_e I_{\mathrm{PD}} Z$ is the noise spectral density, caused by thermal noise in the RF amplifiers and by the shot noise of the photodetector, k_B is Boltzmann constant, T_{amp} is the RF amplifiers' working temperature, NF is the effective noise figure of the RF chain, q_e is the electron charge, I_{PD} is the photocurrent, G is the total RF gain at steady-state condition, and $Z = 50$ is the input impedance of the RF chain. Equation (1) indicates that the jitter does not directly depend on the cavity length since the pulse energy, E_0, and the pulse waveform, $f(t)$, that were measured almost did not depend on the cavity length. A weak dependence of the jitter on the length is obtained due to very small changes in the gain and in the pulse shape as a function of the length. However, unlike in optical fiber lasers [16], the pulse shape and the jitter do not change significantly when the cavity length increases since fiber dispersion has a very weak effect on the propagating pulses.

Substituting the measured pulsed waveform $f(t)$ in Eq. (1), we can estimate the theoretical limit for the pulse-to-pulse RMS timing jitter. Assuming an ideal RF chain with an effective noise figure $NF = 1$ that operates at a nominal temperature of 300 K, a photocurrent $I_{PD} = 4$ mA, and an effective system gain $G = 38$ dB, the effective power spectral density (one-sided) equals $\rho_N = 7 \times 10^{-20}$ W/Hz and the pulse-to-pulse RMS timing jitter equals 1.05, 1.05, 1.05, 0.89, and 0.87 ps for cavity length $L_c = 150$, 2200, 5370, and 10,400 m, respectively. The small changes in the timing jitter are caused by the weak changes in the pulse waveform as a function of the cavity length. In longer cavities, the energy of the pulses tends to increase slightly and hence the jitter calculated by using Eq. (1) decreases. The measured jitter was about 3 ps. This result is higher than the theoretical limit since the RF amplifiers are not ideal and since the minimum jitter that can be measured by our oscilloscope is about 2.85 ps. Since the effect of fiber dispersion is very weak in the mode-locked OEO, the jitter does not increase when the cavity length increases, as occurs in lasers [16] due to Gordon–Haus effect. The theoretical model also indicates that the jitter obtained for the single-cycle pulses, shown in Fig. 4, should be larger than that obtained for the pulses shown in Fig. 2(a) since the duration of these pulses is broader. The jitter calculated for the pulses shown in Fig. 4 is about 3 ps. The jitter measured for these pulses was 5 ps.

We believe that the minimum repetition rate of the device can be further decreased by increasing the fiber length. To increase the cavity length, the feedback circuit to the VVA should be improved since the SNR at the power detector decreases. Techniques such as lock-in amplification can be utilized to limit the noise added by the integration of the signal in the current system. However, we believe that for ultralong cavities the jitter will depend on the cavity length and will be the main limitation on ultralong OEOs. In ultralong fibers, noise induced by scattering [17] and environmental perturbations will be added by the fiber. Indeed, in the longest cavity of 10,400 m that we used in our experiments, some noise could be observed in the pulses that were measured by using the sampling oscilloscope, although this noise did not affect the measured pulse-to-pulse jitter.

5. CONCLUSION

We have demonstrated the generation of an ultralow-repetition-rate pulse train with a repetition period of 51 μs by passive mode-locking of an OEO. The low-repetition-rate operation was obtained by adding a 10,400 m fiber to the OEO cavity. Only a single pulse propagated in the cavity. Thus, passive mode-locking in OEOs enables to overcome the limitations of mode-locked fiber lasers that tend to generate multiple low-power pulses when the cavity length is increased. The pulse shape, width, and jitter were not changed significantly when the cavity length was increased from 150 to 10,400 m. The measured RMS pulse-to-pulse jitter was as low as 6×10^{-8} of the pulse repetition time. Such low jitter cannot be obtained today in electronic systems. Low-repetition-rate pulses with ultralow jitter, such as that generated by the device described in this paper, can be used to improve the performance and to develop novel radars that will be able to measure the position and the velocity of long-distance targets accurately. We believe that by improving the electronic feedback in the OEO, the repetition rate of the pulses can be decreased significantly while maintaining a stable propagation of a single pulse in the cavity.

ACKNOWLEDGMENTS

This work was supported by the Israel Science Foundation (ISF) of the Israeli Academy of Sciences (grant no. 1092/10). The authors are highly grateful to Denis Dikarov, Yuri Komarovsky, Haim Malka, and Vladimir Smulakovsky for their assistance and fruitful remarks.

REFERENCES

1. W. W. Shrader and V. G. Hansen, "MTI radar," in *Radar Handbook*, M. I. Skolnik, ed. (McGraw-Hill, 2008), pp. 2.12–2.100.
2. A. B. Grudinin, D. J. Richardson, and D. N. Payne, "Energy quantisation in figure eight fibre laser," IEEE Electron. Lett. **28**, 67–68 (1992).
3. D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, "Mechanism of multisoliton formation and soliton energy quantization in passively mode-locked fiber lasers," Phys. Rev. A **72**, 043816 (2005).
4. R. Weill, A. Bekker, V. Smulakovsky, B. Fischer, and O. Gat, "Spectral sidebands and multipulse formation in passively mode-locked lasers," Phys. Rev. A **83**, 043831 (2011).
5. M. Horowitz, Y. Barad, and Y. Silberberg, "Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser," Opt. Lett. **22**, 799–801 (1997).
6. S. Kobtsev, S. Kukarin, and Y. Fedotov, "Ultra-low repetition rate mode-locked fiber laser with high-energy pulses," Opt. Express **16**, 21936–21941 (2008).
7. S. V. Smirnov, S. M. Kobtsev, S. V. Kukarin, and S. K. Turitsyn, "Mode-locked fibre lasers with high-energy pulses," in *Laser Systems for Applications*, K. Jakubczak, ed. (InTech, 2011), pp. 39–58.
8. Y. Senoo, N. Nishizawa, Y. Sakakibara, K. Sumimura, E. Itoga, H. Kataura, and K. Itoh, "Ultralow-repetition-rate, high-energy, polarization-maintaining, Er-doped, ultrashort-pulse fiber laser using single-wall-carbon-nanotube saturable absorber," Opt. Express **18**, 20673–20680 (2010).
9. J. S. Lee and C. Nguyen, "Novel low-cost ultra-wideband, ultra-short-pulse transmitter with MESFET impulse-shaping circuitry for reduced distortion and improved pulse repetition rate," IEEE Microw. Wirel. Compon. Lett. **11**, 208–210 (2001).
10. F. Zito, D. Pepe, and D. Zito, "UWB CMOS monocycle pulse generator," IEEE Trans. Circuits Syst. I Reg. Papers **57**, 2654–2664 (2010).
11. L. Smaini, C. Tinella, D. Helal, C. Stoecklin, L. Chabert, C. Devaucelle, R. Cattenoz, N. Rinaldi, and D. Belot, "Single-chip CMOS pulse generator for UWB systems," IEEE J. Solid-State Circuits **41**, 1551–1561 (2006).
12. E. C. Levy and M. Horowitz, "Single-cycle radio-frequency pulse generation by an optoelectronic oscillator," Opt. Express **19**, 17599–17608 (2011).
13. M. Ramaswamy, M. Ulman, J. Paye, and J. G. Fujimoto, "Cavity-dumped femtosecond Kerr-lens mode-locked Ti:$A1_2O_3$ laser," Opt. Lett. **18**, 1822–1824 (1993).
14. G. N. Gibson, R. Klank, F. Gibson, and B. E. Bouma, "Electro-optically cavity-dumped ultrashort-pulse Ti:sapphire oscillator," Opt. Lett. **21**, 1055–1057 (1996).
15. Agilent Technologies Inc., "Infiniium DCA-J Agilent 86100C technical specification," http://cp.literature.agilent.com/litweb/pdf/5989-0278EN.pdf.
16. H. A. Haus and A. Mecozzi, "Noise of mode-locked lasers," IEEE J. Quantum Electron. **29**, 983–996 (1993).
17. O. Okusaga, J. P. Cahill, A. Docherty, C. R. Menyuk, and W. Zhou, "Spontaneous inelastic Rayleigh scattering in optical fibers," Opt. Lett. **38**, 549–551 (2013).