Measuring optical fiber length by use of a short-pulse optical fiber ring laser in a self-injection seeding scheme

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A method for measuring the length of an optical fiber by use of an optical fiber ring laser pulse source is proposed and demonstrated. The key element of the optical fiber ring laser is a gain-switched Fabry–Perot laser diode operated in a self-injection seeding scheme. This method is especially suitable for measuring a medium or long fiber, and a resolution of 0.1 m is experimentally achieved. The measurement is implemented by accurately determining the pulse frequency that can maximize the output power of the fiber ring laser. The measurement results depend only on the refractive index of the fiber corresponding to this single wavelength, instead of the group index of the fiber, which represents a great advantage over both optical time-domain reflectometry and optical low-coherence reflectometry methods. © 2006 Optical Society of America

OCIS codes: 060.2300, 060.2310, 140.3510, 140.3560.

1. Introduction

Various methods have been developed for optical fiber length measurement. The two widely used approaches are optical low-coherence reflectometry (OLCR)[1,2] and optical time-domain reflectometry (OTDR).[3–5] OLCR is a high-precision measurement technique and is usually used to determine short optical fiber lengths because a reference optical fiber that is close to the length of the optical fiber to be measured is required during the measurement. Since OLCR employs a low-coherence light source, its measurement accuracy depends on the group index of the fiber. In contrast, OTDR is best suited for a medium or long optical fiber length measurement with submeter resolution. The measurement accuracy of OTDR depends not only on the exact timing but also on the group index and cabling factor of the fiber (for instance, a loose-buffered fiber is longer than a tightly buffered one).

Optical fiber lasers employing one or two gain-switched Fabry–Perot (F-P) semiconductor laser diodes have been explored.[6–11] When the output wavelength of self-,[6,7] external-,[8,9] and mutual-injection[10,11] seeding optical fiber ring lasers is tuned, the optical pulse repetition frequency and/or the variable optical delay line have to be adjusted to ensure that the emitted optical pulse can return to the laser diode during a new pulse emission time and to maximize the power and the side-mode suppression ratio (SMSR) of the output pulses. The optimum frequency of the output pulses depends on the fiber laser cavity length. Thus the total length of the optical fiber ring laser cavity, and hence the length of the optical fiber to be measured, can be calculated by use of the optimum pulse frequency obtained.

We demonstrate a method for measuring the optical fiber length by use of a self-seeded, gain-switched F-P laser diode in an optical fiber ring laser. An optical fiber with a length of ~2 km has been measured with a resolution of 0.1 m.

2. Experiments

Figure 1 illustrates the experimental setup for our method. The optical fiber to be measured is within the fiber ring laser cavity. A F-P laser diode with a maximum output power of 1 mW is dc biased at its threshold current of 11 mA and gain switched by a high-frequency electrical signal from a rf signal generator (HP E4422B). The rf signal is subsequently amplified by an electrical amplifier (Mini-Circuits ZHL-42W) with a gain of 30 dB and is then divided into two parts by a 10:90 power splitter. Then 10% of

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Received 13 January 2006; revised 6 April 2006; accepted 27 April 2006; posted 28 April 2006 (Doc. ID 67127).

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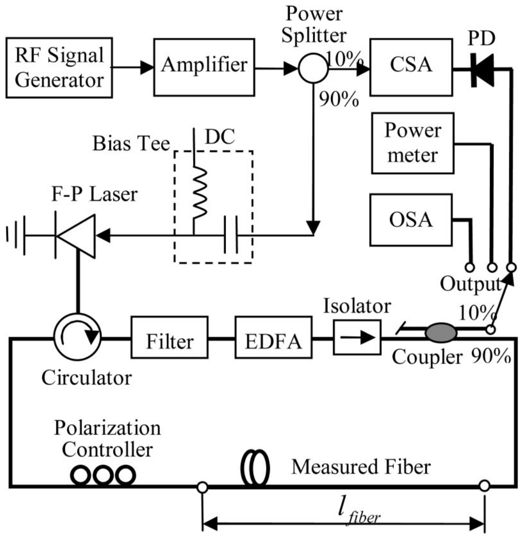

Fig. 1. Experimental setup for measuring the optical fiber length. OSA, optical spectrum analyzer; CSA, communication signal analyzer; PD, photodetector; EDFA, erbium doped fiber amplifier. Note that, in practice, the optical spectrum analyzer, the communication signal analyzer, the photodetector, and the power splitter can be omitted to simplify the measurement system.

the signal is used to trigger the communication signal analyzer (CSA 803C), and the rest is used to gain switch the F-P laser diode via a bias-T circuit. The multimode spectrum of optical pulses directly from the gain-switched F-P laser is shown in Fig. 2, which has a central wavelength of 1545.25 nm and a mode spacing of 1.1 nm. The gain-switched optical pulses transmit through an optical filter with a central wavelength of 1550 nm, an erbium doped fiber amplifier (EDFA), an isolator, a fiber coupler, an optical fiber to be measured, and a polarization controller and are injected back into the laser diode via a circulator. As long as the injected pulse arrives during the next pulse emission, a stable self-injection seeded optical short pulse can be established in the fiber ring laser cavity. The output port of the fiber ring laser can be connected to an optical powermeter (ML910B) with a sensitivity of 0.001 nW to measure the output optical power to the communication signal analyzer via a 25 GHz IR photodetector (Model 1414) to observe the optical pulse waveform, and to an optical

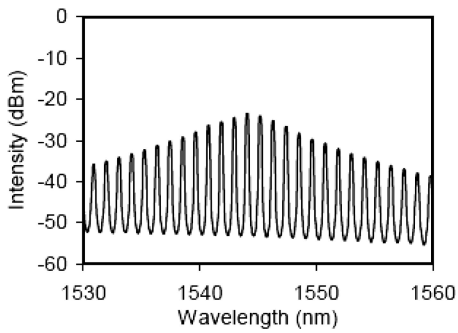

Fig. 2. Multimode optical pulse spectrum from the gain-switched F-P laser diode.

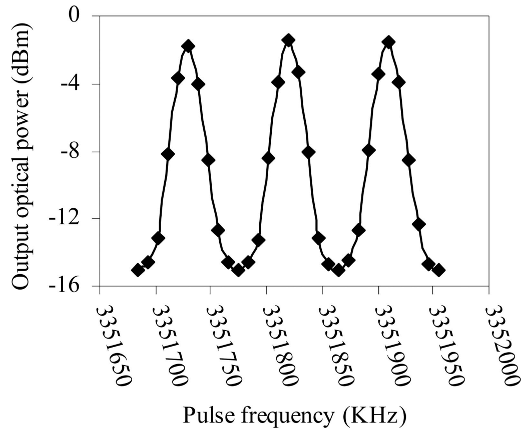

Fig. 3. Relationship between the output optical power of the fiber ring laser and the pulse frequency applied.

spectrum analyzer (HP 70952B) with a resolution of 0.08 nm to observe the optical pulse spectrum. In the fiber ring laser system the optical filter is used to transform the multimode output from the laser diode into single-wavelength light, the isolator is employed to ensure the pulse propagation direction and eliminate the light reflected by the other devices, the polarization controller is utilized to optimize the SMSR in the output optical spectrum, and the EDFA is used to amplify the optical pulses and to improve measurement precision.

The optical path length corresponding to the optical fiber to be measured is written as $L_{\text{fiber}} = l_{\text{fiber}} n_{\text{co}}$, where l_{fiber} is the length of the optical fiber to be measured and n_{co} is the refractive index of the fiber core. The optical path length corresponding to segments in the optical fiber ring cavity other than the optical fiber to be measured is L_{other}, which can be obtained by use of a precision reflectometer (Agilent 8540B). In our experiment L_{other} is measured to be 12.567 m and n_{co} is 1.534, corresponding to a wavelength of 1550 nm. Then the total optical path length corresponding to the whole optical fiber ring cavity is

$$L = L_{\text{fiber}} + L_{\text{other}} = l_{\text{fiber}} n_{\text{co}} + L_{\text{other}}. \quad (1)$$

It can be seen from Fig. 3 that the output power of the fiber ring laser changes periodically with the optical pulse repetition frequency f. Thus the maximum output optical power is obtained when the pulse frequency applied can ensure that the optical pulse returns to the laser diode during another pulse emission time. The measurement process can be divided into two steps. In the first step the pulse frequency is adjusted until a local maximum output optical power is observed for the first time by using an optical powermeter. The corresponding frequency of the ring laser cavity is f_0. Thus we have

$$f_0 L = Nc, \quad (2)$$

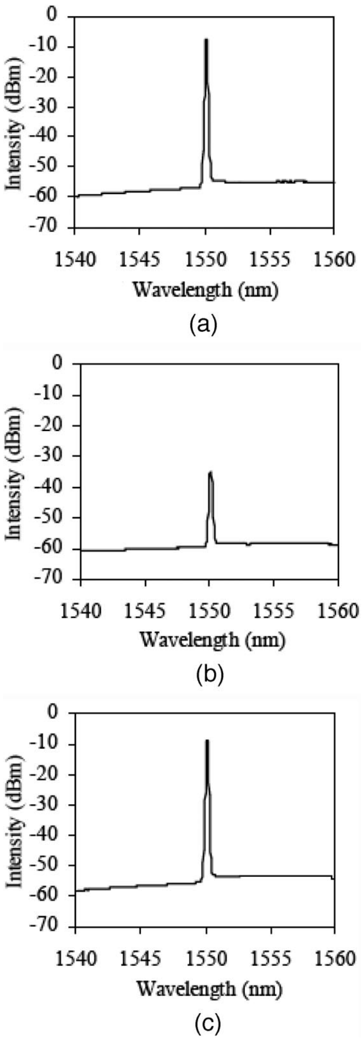

Fig. 4. Output optical pulse spectrum of the fiber ring laser while the pulse frequency (a) $f \rightarrow f_0 = 3351729485$ Hz satisfies Eq. 2, (b) $f \rightarrow (f_0 + f_m)/2 = 3351774712$ Hz fails to satisify Eqs. 2 and 3, and (c) $f \rightarrow f_m = 3351819939$ Hz satisfies Eq. 3.

where N is a positive integer and $c = 3 \times 10^8$ m/s is the velocity of light in vacuum. The optical spectra with maximum SMSR and waveform of the output pulses corresponding to this case are shown in Figs. 4(a) and 5(a), respectively, where $f_0 = 3351729485$ Hz. In the second step the pulse frequency is adjusted to the value f_m at which the output optical power reaches another local maximum for the $(m + 1)$th time. Here the relation

$$f_m L = (N + m)c \tag{3}$$

holds. The output pulse spectrum and waveform of the output pulses corresponding to this case are shown in Figs. 4(c) and 5(c), respectively, where $f_m = 3351819939$ Hz $(m = 1)$. For the case of $f = (f_0 + f_m)/2 = 3351774712$ Hz, both Eqs. (2) and (3) cannot be satisfied; the SMSR and the power of the output pulse are greatly reduced, as shown in Figs. 4(b) and 5(b), respectively. A number of measurements with different m values have been carried out to improve the measurement precision, and the results are listed in Table 1.

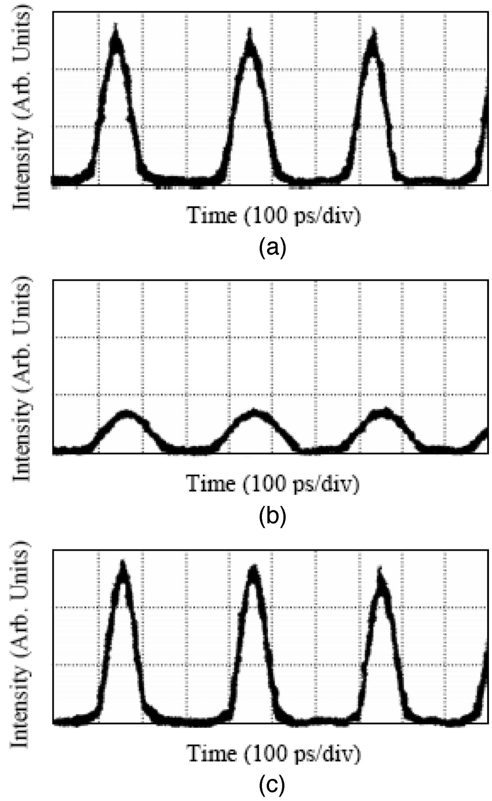

Fig. 5. Output pulse waveform of the fiber ring laser while the pulse frequency (a) $f \rightarrow f_0 = 3351729485$ Hz satisfies Eq. 2, (b) $f \rightarrow (f_0 + f_m)/2 = 3351774712$ Hz fails to satisfy Eqs. 2 and 3, and (c) $f \rightarrow f_m = 3351819939$ Hz satisfies Eq. 3.

3. Results and Discussions

From Eqs. (1)–(3), the length of the optical fiber to be measured can be expressed by

$$l_{\text{fiber}} = \frac{mc}{n_{\text{co}}(f_m - f_0)} - \frac{L_{\text{other}}}{n_{\text{co}}}. \tag{4}$$

Thus l_{fiber} can be calculated from the measurement result of m, f_0, and f_m, and the values obtained are

Table 1. Measurement Results for Various Values of m

Experiment Times	m	f_0 (Hz)	f_m (Hz)	l_{fiber} (m)
1	1	3351729485	3351819939	2153.811
2	5	3351910392	3352362647	2153.883
3	10	3352453102	3353357627	2153.847
4	15	3353448079	3354804854	2153.867
5	20	3354895307	3356704352	2153.853
6	25	3356794804	3359056099	2153.863
7	30	3359146549	3361860114	2153.855
8	35	3361950599	3365116414	2153.862
9	40	3365206867	3368824952	2153.856

listed in Table 1. The average value of the optical fiber length measured is $\bar{l}_{\text{fiber}} = 2153.855$ m, and the measurement resolution is 0.1 m, which is similar to that of OTDR.

From the above description, the key for the measurement is to determine the pulse repetition frequency that can maximize the output pulse power of the fiber ring laser, which is dependent on the sensitivity of the optical powermeter and the frequency tolerance corresponding to the maximum output optical power of the fiber ring laser. The frequency tolerance corresponding to the maximum output optical power depends strongly on the pulse frequency and the laser diode. That is, the larger the pulse frequencies f_0 and f_m, the smaller the measurement error. In addition, the measurement error of $(f_m - f_0)$ decreases as parameter m increases, as shown in Table 1. Thus the pulse frequencies f_0 and f_m and parameter m should be selected to be as large as possible to minimize the measurement error. The maximum pulse frequency applied is also dependent on the F-P laser diode employed.

As is shown in Eqs. (1) and (4), the length of the optical fiber measured is dependent on the refractive index of the optical fiber corresponding to the single wavelength, instead of the group index, which is an advantage over both OTDR and OLCR techniques. The optical spectrum analyzer and the communication signal analyzer shown in Fig. 1 are used only to demonstrate the measuring principle. In practice they can be removed, because the pulse frequency that maximizes the output optical power of the fiber ring laser can be accurately determined by use of only the optical powermeter. Furthermore, the proposed method also exhibits the advantages of simple configuration, easy operation, and high measurement resolution.

4. Conclusions

The optical fiber ring laser pulse source can be effectively used to measure the optical fiber length, and the measurement resolution achieved is 0.1 m. Such a method is especially suitable for measuring a medium or large length of optical fiber.

This work was supported by research grant G-YX51 from the Hong Kong Polytechnic University in a Postdoctoral Research Fellowship scheme and grant 60507013 from the National Science Foundation of China.

References

1. W. V. Sorin and D. F. Gray, "Simultaneous thickness and group index measurement using optical low-coherence reflectometry," IEEE Photon. Technol. Lett. **4,** 105–107 (1992).
2. Y. P. Wang, J. P. Chen, X. W. Li, X. H. Zhang, J. X. Hong, and A. L. Ye, "Simultaneous measurement of various optical parameters in a multilayer optical waveguide by a Michelson precision reflectometer," Opt. Lett. **30,** 979–981 (2005).
3. M. K. Barnoski, M. D. Rourke, S. M. Jensen, and R. T. Melville, "Optical time domain reflectometer," Appl. Opt. **16,** 2375–2379 (1977).
4. M. Nazarathy, S. A. Newton, R. P. Giffard, D. S. Moberly, F. Sischka, W. R. Trutna, and S. Foster, "Real-time long-range complementary correlation optical-time domain reflectometer," J. Lightwave Technol. **7,** 24–38 (1989).
5. M. Zoboli and P. Bassi, "High spatial-resolution order attenuation measurements by a correlation technique," Appl. Opt. **22,** 3680–3681 (1983).
6. L. P. Barry, R. F. Odowd, J. Debau, and R. Boittin, "Tunable transform-limited pulse generation using self-injection locking of an FP Laser," IEEE Photon. Technol. Lett. **5,** 1132–1134 (1993).
7. D. Huhse, M. Schell, J. Kaessner, D. Bimberg, I. S. Tarasov, A. V. Gorbachov, and D. Z. Garbuzov, "Generation of electrically wavelength tunable ($\Delta\lambda = 40$ nm) singlemode laser-pulses from a 1.3 μmFabry–Perot laser by self-seeding in a fiberoptic configuration," Electron. Lett. **30,** 157–158 (1994).
8. D. N. Wang, X. H. Fang, and W. Jin, "Generation of continuous wavelength-tunable optical short pulses with two Fabry–Perot laser diodes in an external injection-seeding scheme," J. Opt. Soc. Am. B **22,** 917–921 (2005).
9. Y. Matsui, S. Kutsuzawa, S. Arahira, and Y. Ogawa, "Generation of wavelength tunable gain-switched pulses from FP MQW lasers with external injection seeding," IEEE Photon. Technol. Lett. **9,** 1087–1089 (1997).
10. X. H. Fang and D. N. Wang, "Mutual pulse injection seeding by the use of two Fabry–Perot laser diodes to produce wavelength-tunable optical short pulses," IEEE Photon. Technol. Lett. **15,** 855–857 (2003).
11. X. H. Fang and D. N. Wang, "Wavelength-tunable optical short-pulse generation by mutual pulse injection seeding of two gain-switched Fabry–Perot laser diodes," Appl. Opt. **42,** 5522–5525 (2003).