Radio frequency interrogated actively mode-locked fiber ring laser for sensing application

Jie Huang,[1] Xinwei Lan,[1] Tao Wei,[1] Qun Han,[1,2] Zhan Gao,[1] Zhi Zhou,[3] and Hai Xiao[1,*]

[1] *Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA*
[2] *College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin, 300072, China*
[3] *School of Civil Engineering, Dalian University of Technology, Dalian, 116024, China*
**Corresponding author: xiaoha@mst.edu*

Received November 15, 2011; revised December 18, 2011; accepted December 19, 2011;
posted December 19, 2011 (Doc. ID 158267); published February 6, 2012

This paper proposes an actively mode-locked fiber ring laser for sensing applications. Mode-locking of the laser is achieved by driving an electro-optic amplitude modulator at an RF corresponding to the fundamental beat frequency between the longitudinal modes. The change of the cavity length produces a frequency comb around the beat frequencies. The frequency separation of the comb is found to be linearly proportional to the cavity length change. The sensing mechanism of the device is shown. Temperature measurement is demonstrated using the proposed actively mode-locked fiber ring laser. © 2012 Optical Society of America

OCIS codes: 140.3510, 140.7090, 060.2370, 280.3420.

Demodulation of optical sensors in the radio frequency (RF) domain has attracted much attention in recent years due to the high measurement precision of frequency, low cost, and matured instrumentation in the RF regime [1]. In many optical lasing devices, the beat frequency between two optical modes falls in the RF regime. As a result, measurement of optical parameters can be achieved by monitoring the beat-frequency changes. Kringlebotn *et al.* reported a strain sensor based on measuring the beat frequency between two orthogonal polarization modes of a distributed feedback laser cavity in the RF domain [2]. Similar approaches have also been explored using a fiber Fabry–Perot laser formed by two fiber Bragg gratings. By monitoring the beat frequency of the two orthogonal polarization modes, the device has been demonstrated for measurement of various parameters such as acoustic, electric current, strain, and temperature [3–5]. Recently, a multi-longitudinal-mode fiber laser has been reported for temperature, strain, and vibration sensing based on measurement of the beat frequency between two longitudinal modes [6,7].

So far, most existing RF-interrogated optical laser sensors are mode-unlocked. An unlocked laser emits continuous waves with unsynchronized longitudinal modes, resulting in unstable beat frequencies, large phase noises, frequency pulling, and amplitude variations [8,9]. These instabilities induce errors in sensing. On the other hand, optical lasers can be mode-locked to establish a fixed phase relationship across a broad spectrum. A mode-locked laser emits pulses with low timing jitters and thus has stable beat frequencies in the spectrum domain [10]. Recently, an actively mode-locked laser has been explored to generate ultrastable microwave signals [11]. A 10 GHz microwave signal with a fraction frequency instability less than 8×10^{-16} observed in 1 s was reported. In this Letter, we propose an actively mode-locked fiber ring laser interrogated in the RF regime for sensing application.

Figure 1 shows the system configuration of the actively mode-locked fiber ring laser. A pump laser with a wavelength of 980 nm was launched into the single mode fiber (SMF-28) loop through a wavelength division multiplexer. In the fiber loop, a $LiNbO_3$ electro-optic modulator (Lucent x2623N) driven by a signal generator (HP 33120A) was used to modulate the amplitude of the light intensity for active mode-locking.

A section of erbium-doped fiber (EDF, Lucent HP980) with a length of 5.4 m was spliced into the loop. A fiber inline polarization controller (General Photonics) and an isolator were inserted into the loop to prevent mode hopping. A 98:2 fiber coupler was used to tap out the laser light for monitoring. The laser light from the 2% output port of the fiber coupler was further split by a 3 dB coupler for different measurements. The laser spectrum was acquired using an optical spectrum analyzer (Yokogawa AQ6373). A high-speed photodetector (HP87421A, DC-32GHz) was used to convert the light into an RF analog signal. Time domain measurement of the RF signal was performed by an oscilloscope (Tektronix DPO 7254), and RF frequency analysis of the signal was performed by a radio frequency spectrum analyzer (RFSA). The resolution bandwidth of the RFSA was 100 Hz, and the number of sampling points was 601. The oscilloscope was triggered by the signal generator. When performing temperature measurement, the EDF coil was placed in

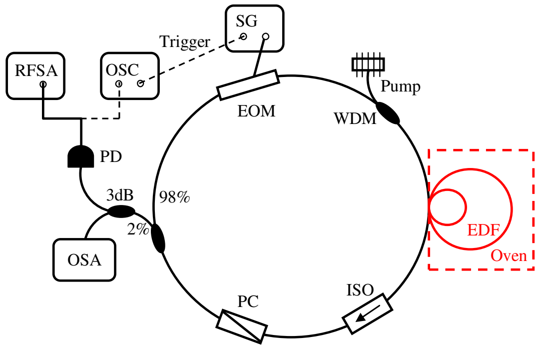

Fig. 1. (Color online) System configuration of the actively mode-locked fiber ring laser. WDM, wavelength division multiplexer; EOM, electro-optic modulator; SG, signal generator; EDF, erbium-doped fiber; ISO, isolator; PC, polarization controller; OSA, optical spectrum analyzer; PD, photodetector; RFSA, radio frequency spectrum analyzer; OSC, oscilloscope.

0146-9592/12/040494-03$15.00/0

an electric oven (Yamato DX3000) of various temperature settings.

It is known that the wavelength (λ_m) of the mth-order longitudinal mode (m is an integer) of a fiber ring laser can be written as [6]

$$\lambda_m = \frac{nL}{m}, \tag{1}$$

where n is the group index of the fiber mode propagating in the fiber and L is the length of the fiber loop. Thus the beat frequency (f_{pq}) of any two longitudinal modes (e.g., pth and qth orders) can be expressed as

$$f_{pq} = \frac{c}{\lambda_p} - \frac{c}{\lambda_q} = \frac{(p-q)c}{nL}, \tag{2}$$

where c is speed of light in vacuum and λ_p and λ_q are the lasing wavelengths of the pth- and qth-order longitudinal modes, respectively. The beat frequency of any two adjacent longitudinal modes is defined as the cavity mode spacing ($f_0 = c/nL$) of the fiber loop. If the EOM is driven at a modulation frequency (f_{mod}) that is the same as the cavity mode spacing, i.e., $f_{\text{mod}} = f_0$, all the excited longitudinal modes have a fixed phase relation and thus the laser is mode-locked.

A mode-locked laser has multiple longitudinal wavelength lines in a broadband optical spectrum confined by the spectrum width of the gain medium. When the laser is mode-locked, a periodic pulse train can be observed in time domain with a repetition rate equal to the cavity mode spacing. As shown in Fig. 2(a), the frequency spectrum of these periodic pulses is a series of lines in the RF regime. These lines have frequencies corresponding to the integer numbers of the cavity mode spacing as a result of beating among the multiple longitudinal modes. If the modulation frequency is slightly different from the cavity mode spacing, a frequency comb is formed around each beat frequency, as depicted in Fig. 2(b). The frequency separation (Δf_s) of two adjacent frequencies inside the frequency comb represents the difference between f_0 and f_{mod}. That is, $\Delta f_s = f_0 - f_{\text{mod}}$.

Let us assume that the fiber ring laser with the optical length of $(nL)_0$ has originally mode-locked to the modulation frequency of f_{mod} and $\Delta f_s = 0$. As a result of environmental disturbance (e.g., ambient temperature change), the optical length of the fiber ring changes slightly to $(nL)_1$, which produces a frequency comb around the beat frequencies with a frequency separation given by

$$\Delta f_s = \left|\frac{c}{(nL)_0} - \frac{c}{(nL)_1}\right| \approx \left|\frac{-c}{[(nL)_0]^2}\delta(nL)\right| = \left|\frac{f_{\text{mod}}}{(nL)_0}\delta(nL)\right|, \tag{3}$$

where $\delta(nL) = (nL)_0 - (nL)_1$ is the small optical length variation of the fiber ring loop.

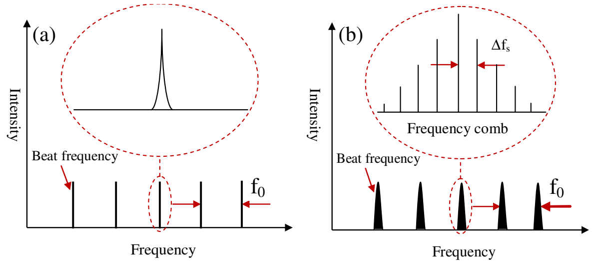

Fig. 2. (Color online) (a) Beat frequencies of a perfectly mode-locked fiber ring laser, (b) the beat frequencies of a mode-locked fiber ring laser with a slight difference between the modulation frequency and the cavity mode spacing.

Equation (3) indicates that frequency separation (Δf_s) of the frequency comb is directly proportional to the cavity optical length change $\delta(nL)$ of the fiber loop when the change $\delta(nL)$ is small. Using this operation mechanism, the actively mode-locked fiber ring laser can be used as a sensor to measure various parameters that cause the cavity length change.

The environmental temperature variation can change the optical length of the fiber loop through both thermal expansion and thermo-optic effects. The small change in optical length of the fiber loop can be calculated by

$$\delta(nL) = \frac{dn}{dT}L_s\Delta T + \frac{dL}{dT}n\Delta T = \left(\frac{dn}{dT} + \alpha n\right)L_s\Delta T, \tag{4}$$

where α is the coefficient of thermal expansion (CTE) of the fiber, dn/dT is the thermo-optic coefficient of the fiber, ΔT is the temperature change, and L_s is the physical length of the fiber section subjected to temperature change.

The CTE of a typical silica fiber is relatively small compared to the thermo-optic coefficient. Plugging Eq. (4) into Eq. (3), one finds the frequency separation Δf_s as a function of temperature given by

$$\Delta f_s = \frac{f_{\text{mod}}L_s\Delta T}{(nL)_0}\left(\frac{dn}{dT} + \alpha n\right). \tag{5}$$

It can be seen from Eq. (5) that the frequency separation Δf_s of the frequency comb is linearly proportional to the ambient temperature change when the change $\delta(nL)$ is small, and the sensitivity is directly determined by the thermo-optic coefficient and the CTE. To further enhance the sensitivity of this device, a material with a high thermo-optic coefficient and/or CTE can be used. Theoretically the intensity or signal-to-noise ratio (SNR) of a lower beat-frequency signal is greater than for a higher beat-frequency signal because each beat-frequency signal is the sum of many beat-frequency signals with the same frequency separation between two longitudinal modes. For this sensing mechanism, the interrogated frequency comb could fall around the lower beat-frequency region to enhance the measurement accuracy and reduce the cost of the interrogated facility.

In this experiment, the pump power is 85 mW and the modulation frequency is driven by 30.728 MHz with a power of 26 dBm, which matches well with the cavity mode spacing with a fiber loop of 6.8 m. Figure 3(a) shows the mode-locked fiber ring laser output in the optical domain with a 3 dB linewidth of 4.8 nm and the pulse train in the time domain with a repetition rate of 30.728 MHz, indicating a mode-locked laser is formed

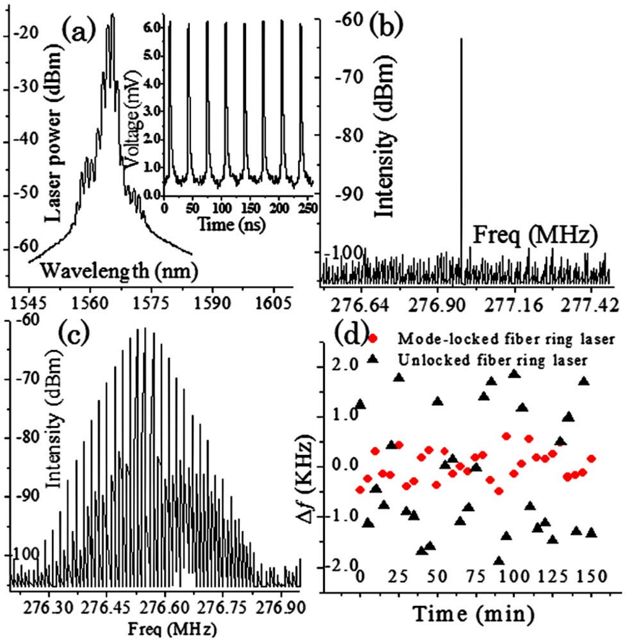

Fig. 3. (Color online) (a) Laser output in the optical domain and pulse train in the time domain of an actively mode-locked fiber ring laser, (b) a beat frequency of an actively mode-locked fiber ring laser, (c) generation of a frequency comb around a beat frequency at 36 °C, (d) stability test of beat frequencies in a frequency comb and an unlocked fiber ring laser.

(room temperature is 24 °C). The FWHM of these pulses was measured with the oscilloscope to be 3.1 ns. Figure 3(b) shows a beat frequency of the mode-locked fiber ring laser at 276.9 MHz. The linewidth of this beat frequency is around 14 KHz. The SNR is over 30 dB. Figure 3(c) shows the generation of a frequency comb around a beat frequency at 36 °C. Just as predicted, the frequency comb appeared around a beat frequency, and the frequency separation (Δf_s) is proportional to the cavity length change (from 24 °C to 36 °C). Figure 3(d) plots the stability test of beat frequencies in a frequency comb around 276.9 MHz and an unlocked fiber ring laser in 265 MHz, respectively. The frequency is measured every 5 min for 2.5 h at 24 °C. The fluctuation of the frequency shift in the frequency comb is ±600 Hz. This result is much better than the unlocked continuous fiber ring laser (around ±2 kHz), indicating a higher measurement accuracy and detection limit for the mode-locked fiber ring laser sensor.

Figure 4 plots the Δf_s of the mode-locked fiber ring laser as a function of temperature in the range from 24 °C to 78 °C with a step of 3 °C. Frequency combs with 10× separation ($10 \times \Delta f_s$) were interrogated in a frequency comb to further enhance the measurement accuracy and sensitivity. It is obvious that the frequency separation Δf_s increases as the temperature increases. A linear curve fitting (red line) is used, and the slope is 1.7 kHz/°C at 276.9 MHz, which agrees well with the theoretic prediction of 1.712 kHz/°C according to Eq. (5) (EDF length of 5.4 m, loop length of 6.8 m, and thermo-optic coefficient of $\sim 7 \times 10^{-6}$/°C). The linear temperature response indicates that the actively mode-locked fiber ring laser can be used as a temperature sensor after it is properly calibrated.

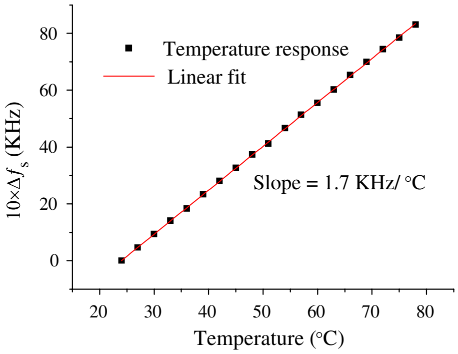

Fig. 4. (Color online) Temperature response of the actively mode-locked fiber ring laser.

To summarize, this paper reports an actively mode-locked fiber ring laser for sensing applications. By driving an electro-optic amplitude modulator at a radio frequency corresponding to the fundamental beat frequency, the fiber ring laser is actively mode-locked. The change of the cavity length produces a frequency comb around the beat frequencies. The frequency separation of the comb is found to be linearly proportional to the cavity length change. The fluctuation of the beat frequency is reduced from ±2 kHz to ±0.6 kHz by using the active mode-locking laser. The analytical calculation and the experimental data matched well. The mode-locked ring laser was demonstrated for temperature measurement. Other mode-locking methods (e.g., passive mode-locking) can also be explored to further improve the measurement accuracy. The stabilized frequency comb around the beat frequency and the linear response to the ambient temperature indicate that the actively mode-locked fiber ring laser may lead to many potential sensing applications.

This work is supported by the Department of Energy (DOE-NETL) (DE-FE0001127).

References

1. G. Gagliardi, M. Salza, P. Ferraro, and P. De Natale, Opt. Express **13**, 2377 (2005).
2. J. T. Kringlebotn, W. H. Loh, and R. I. Laming, Opt. Lett. **21**, 1869 (1996).
3. B. O. Guan, H. Y. Tam, S. T. Lau, and H. L. W. Chan, IEEE Photon. Technol. Lett. **17**, 169 (2005).
4. B. O. Guan and S. N. Wang, IEEE Photon. Technol. Lett. **22**, 230 (2010).
5. O. Hadeler, E. Ronnekleiv, M. Ibsen, and R. I. Laming, Appl. Opt. **38**, 1953 (1999).
6. Z. Yin, L. Gao, S. Liu, L. Zhang, F. Wu, L. Chen, and X. Chen, J. Lightwave Technol. **28**, 3403 (2010).
7. S. Liu, Z. Yin, L. Zhang, L. Gao, X. Chen, and J. Cheng, Opt. Lett. **35**, 835 (2010).
8. Y. Jeong, J. Sahu, D. Payne, and J. Nilsson, Opt. Express **12**, 6088 (2004).
9. G. A. Ball and W. W. Morey, Opt. Lett. **17**, 420 (1992).
10. J. Chen, J. W. Sickler, E. P. Ippen, and F. X. Kärtner, Opt. Lett. **32**, 1566 (2007).
11. T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Oates, and S. A. Diddams, Nat. Photon. **5**, 425 (2011).