Novel method for measurement of effective cavity length of DBR fiber

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A novel method to measure the effective cavity length of distributed Bragg reflector (DBR) fiber laser with fiber Bragg grating (FBG) Fabry-Pérot cavity as the resonator is proposed. The effective cavity length of DBR fiber laser is accurately measured by measuring the frequency spacing of two adjacent longitudinal modes in the cavity without the precise physical length of FBGs. The measuring accuracy as high as 10^{-5} mm can be obtained by setting the resolution bandwidth of the spectrum analyzer.

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Distributed Bragg reflector (DBR) fiber lasers capable of providing narrow-linewidth, low-noise, and compact in-fiber configuration[1−3] have attracted widespread attention for a good variety of applications, including spectroscopy, optical communications, sensors, and interferometry[4−8]. To ensure single-longitudinal-mode lasing, the cavity length should be short enough for DBR fiber lasers. However, high power laser output requires a relatively longer cavity. In this case, there should exist some optimal cavity length to ensure single-longitudinal-mode operation and maximum output power at the same time[7]. Hence, the research on the cavity length of the DBR fiber laser is of great theoretical and practical significance.

In a DBR fiber laser, a piece of active fiber with two fiber Bragg gratings (FBGs) is used to form the Fabry-Pérot cavity and accordingly the effective cavity length of DBR fiber laser includes the two FBGs and the length of active fiber between them. Since the FBG reflector is distributed along its length, the effective length of the FBG is usually not consistent with its physical length, resulting in the difficulty of an appropriate estimation of the cavity length. Several methods have been investigated to calculate the effective length of FBG-based Fabry-Pérot cavity[9−11]. One can use side-scattered light to measure the power distribution along FBGs[9], but we cannot obtain the precise value of the gratings' effective length with this type of measurements. Reference [10] presented an analytical formula to calculate the effective length of the FBG near its peak wavelength, taking into account the grating diffraction efficiency and its physical length. In Ref. [11], another analytical formula to calculate the effective length of FBG was presented, by which the phase factor of the FBG reflection coefficient was linearly simulated using the effective mirror surface model, and the expression of effective length of the FBG was obtained. However, the effective length of FBG changed a lot as different analytical formulas were applied.

In this letter, we report a novel method for the measurement of the effective cavity length of the FBG-based Fabry-Pérot cavity. The effective cavity length of DBR fiber laser can be accurately obtained by measuring the frequency spacing which can be obtained from the beating signal of two adjacent longitudinal modes in the cavity. The measurement accuracy as high as 10^{-5} mm can be obtained by setting the resolution bandwidth of the spectrum analyzer.

DBR fiber laser is a common linear-cavity fiber laser and it is constructed with an active fiber with a pair of wavelength-matched FBGs (FBG1, FBG2) as resonators, as shown in Fig. 1, where L_1 and L_2 are the physical lengths of FBG1 and FBG2, respectively, and L_0 is the length of the active fiber in between.

The free spectral range of the DBR fiber laser $\Delta\lambda$ can be expressed as[10]

$$\Delta\lambda = \frac{\lambda^2}{2n_{\mathrm{g}}(L_0 + L_{\mathrm{eff1}} + L_{\mathrm{eff2}})}, \qquad (1)$$

where λ is the free-space wavelength; n_{g} is the group refractive index for LP01 fiber mode; L_0 is the length of the active fiber. L_{eff1} and L_{eff2} are the effective lengths for the corresponding FBGs. For conventional optical fibers, $n_{\mathrm{g}} \approx n_{\mathrm{eff}}$, where n_{eff} is the effective refractive index of optical fibers, thus n_{g} can be replaced with n_{eff}.

An analytical formula to calculate the effective length of the FBG at the wavelength λ_0 has been proposed

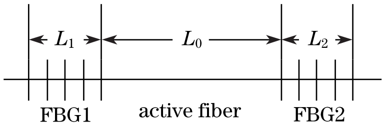

Fig. 1. FBG Fabry-Pérot fiber cavity in DBR fiber laser.

as[10]

$$L_{\mathrm{eff}} = L\frac{\sqrt{R}}{2\mathrm{atanh}(\sqrt{R})}, \qquad (2)$$

where L_{eff} and L are the effective length and physical length of FBG, respectively, and R is the grating diffraction efficiency. The dependence of R on grating amplitude n_0 can be expressed as

$$R = \tanh^2(\pi n_0 L/\lambda_0), \qquad (3)$$

where λ_0 is the Bragg wavelength. According to Eqs. (2) and (3), we acquire the dependence of effective length of the FBG on its diffraction efficiency and physical length. The accuracy of the effective length can be found as

$$\mathrm{d}L_{\mathrm{eff}} = \mathrm{d}L\frac{\sqrt{R}}{2\mathrm{atanh}(\sqrt{R})} + \frac{\pi n_0 L^2\left[\mathrm{atanh}(\sqrt{R}) + \frac{\sqrt{R}}{2(1-R)}\right]}{4\lambda_0\mathrm{atanh}^2(\sqrt{R})\cosh(\pi n_0 L/\lambda_0)}\left(\frac{\mathrm{d}L}{L} + \frac{\mathrm{d}n_0}{n_0}\right), \qquad (4)$$

where $\mathrm{d}L$ and $\mathrm{d}n_0$ are the accuracy of the physical length and grating amplitude of the FBGs, respectively. Since the accurate values of the physical length and the grating amplitude of FBG are unavailable, $\mathrm{d}L$ and $\mathrm{d}n_0$ cannot be correctly estimated.

Another analytical formula for calculating effective length of FBG is given by[11]

$$L_{\mathrm{eff}} = \frac{1}{2k}\mathrm{atan}(kL), \qquad (5)$$

where $k{=}\pi n_0/\lambda_0$ is the coupling coefficient.

According to Eq. (1), we can get the frequency spacing $\Delta\upsilon$ of two adjacent longitudinal modes of the FBG Fabry-Pérot cavity as

$$\Delta\upsilon = \frac{c}{2n_{\mathrm{eff}}(L_0 + L_{\mathrm{eff1}} + L_{\mathrm{eff2}})}, \qquad (6)$$

where n_{eff} and c are the effective refractive index and the light velocity in vacuum, respectively, L_{eff1} and L_{eff2} are the effective lengths of the FBG1 and FBG2, respectively, and L_0 is the length of the active fiber.

From Eq. (5), the effective length of DBR fiber laser can be obtained if we know the values of n and $\Delta\upsilon$. In fact, the value of $\Delta\upsilon$ can be obtained from the beating signal of two adjacent longitudinal modes in the cavity. The effective refractive index of optical fiber includes two dispersion components: material dispersion and waveguide dispersion. The former (bulk silica glass) is described by equation of Sellmeier[12],

$$n_{\mathrm{eff}}(\lambda) = \sqrt{1+\frac{0.6961663\lambda^2}{\lambda^2-0.0684043^2}+\frac{0.4079426\lambda^2}{\lambda^2-0.11677414^2}+\frac{0.8974794\lambda^2}{\lambda^2-9.896161^2}}, \qquad (7)$$

where λ is the wavelength of the light propagating in fiber, and the latter depends on the fiber geometry and material composition.

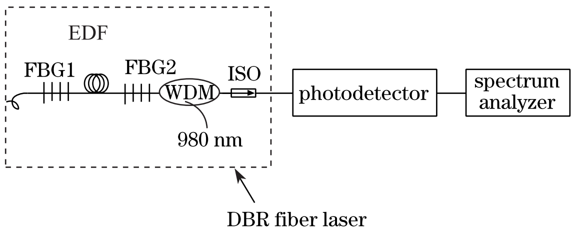

Fig. 2. Experimental setup for the measurement of effective cavity length of the DBR fiber laser.

As shown in Fig. 2, the DBR fiber laser consists two FBGs as reflector and Er^{3+}-doped fiber (EDF) as active fiber. Two FBGs (FBG1, FBG2) with Bragg wavelength of 1546.7 nm are spliced with 9-mm EDF. The lengths of FBG1 and FBG2 are 5.9 and 9 mm, respectively. The grating amplitudes of FBG1 and FBG2 are both 5×10^{-4}. According to Eq. (3), the grating diffraction efficiency R of FBG1 and FBG2 are both 99%. The 980-nm pump light is guided into the cavity through a wavelength division multiplexer (WDM). An optical isolator (ISO) is placed at the laser output to eliminate any backward reflection.

According to Eqs. (2), (3), and (5), the effective lengths of FBG1 and FBG2, and the total cavity length of DBR fiber laser can be obtained, as shown in Table 1. From Table 1, it can be found that the effective lengths of FBG1 and FBG2, and the total cavity length change a lot when different analytical formulas are applied.

Table 1. Theoretical Calculation Results of the Effective Lengths of FBG1 and FBG2, and the Total Cavity Length Based on the Methods Above (Unit: mm)

	Effective Length of FBG1	Effective Length of FBG2	Total Cavity Length
Results Based on Ref. [10]	0.49232	0.49233	9.9846
Results Based on Ref. [11]	0.69193	0.71970	10.41163

When the power of the pump light is 13.8 mW, dual-wavelength single-longitudinal-mode lasing is achieved. The peak wavelengths of the dual-wavelength laser are 1546.608 and 1546.688 nm, respectively, as shown in Fig. 3.

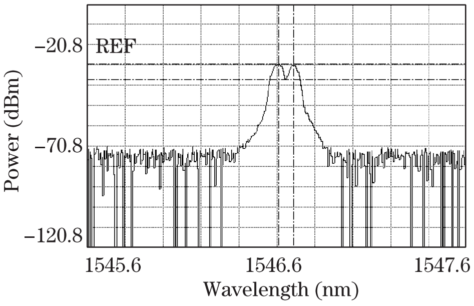

Fig. 3. Output spectra of dual-wavelength single-longitudinal-mode laser.

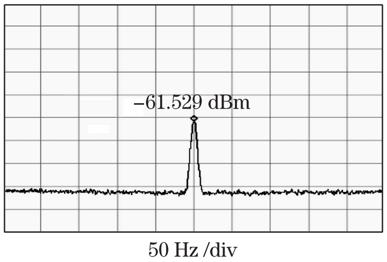

Fig. 4. Electrical spectrum of the generated beating signal.

To detect the beating signal generated from the dual-wavelength single-longitudinal-mode laser, a 10-GHz photodetector was employed in our experiment. A spectrum analyzer (Agilent E4445 PSA Series, Agilent, VSA) with a frequency range from 3 Hz to 13.2 GHz is utilized to monitor the dual-wavelength laser spectrum shown in Fig. 4.

As shown in Fig. 4, a single beating signal with frequency of 10.51 GHz, corresponding to a wavelength spacing of 0.08 nm is observed in the spectrum analyzer, indicating the laser is in single-longitudinal-mode operation. Therefore, the frequency spacing Δv of the two longitudinal modes is 10.51 GHz.

The numerical aperture and fiber diameter of the optical fiber we used are 0.22 and 125 μm, respectively. So the effective refractive index, n_{eff}, of the optical fiber is 1.429563 with operating wavelength of 1546.6 nm.

Therefore, according to Eq. (6), the effective length of the cavity can be obtained as

$$\begin{aligned} L_{\mathrm{c}} &= \frac{c}{2n_{\mathrm{eff}}\Delta v} = \frac{3\times 10^8}{2\times 1.429563\times 10.51\times 10^9} \\ &= 9.9835\ (\mathrm{mm}). \end{aligned} \quad (8)$$

The difference between the measurement result and the theoretical calculated result based on the formula presented in Ref. [10] is 0.0011 mm.

From Eq. (6), the measurement is found as

$$\mathrm{d}L_{\mathrm{c}} = \frac{-c}{2n_{\mathrm{eff}}\cdot\Delta v}\left[\frac{\mathrm{d}n_{\mathrm{eff}}}{n_{\mathrm{eff}}} + \frac{\mathrm{d}(\Delta v)}{\Delta v}\right]. \quad (9)$$

From Eq. (8), we know that the measurement accuracy of the effective cavity length is related to n_{eff}, Δv, $\mathrm{d}n_{\mathrm{eff}}$, and $\mathrm{d}(\Delta v)$, where $\mathrm{d}n_{\mathrm{eff}}$ is the accuracy of n_{eff} and $\mathrm{d}(\Delta v)$ is the resolution bandwidth of the spectrum analyzer. In our experiment, $\mathrm{d}n_{\mathrm{eff}}$ is 10^{-6} when different wavelengths are applied, and $\mathrm{d}(\Delta v)$ is automatically set as 470 kHz when Δv is 10.51 GHz and hence the measurement accuracy is 4.43×10^{-4} mm. Since $\mathrm{d}(\Delta v)$ is tunable in the range of 1 Hz–5 MHz, the measurement accuracy of this method is tunable also.

Figure 5 shows the measurement accuracy with respect to the resolution bandwidth of the spectrum analyzer for the measurement of the effective length of linear-cavity fiber laser. It can be found that at relatively small resolution bandwidth, the measurement accuracy is high. The measurement accuracy as high as 10^{-5} mm can be obtained by setting the resolution bandwidth appropriately.

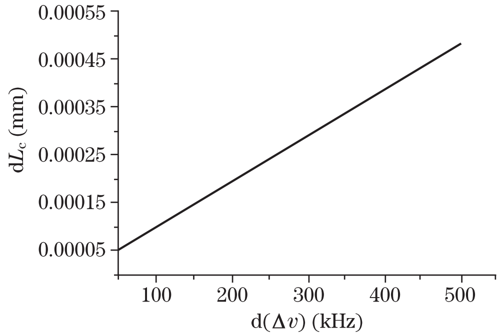

Fig. 5. Measurement accuracy with respect to $\mathrm{d}(\Delta v)$.

In conclusion, we have proposed a novel method for the measurement of the DBR fiber laser formed by fiber grating Fabry-Pérot cavity. The effective length of the fiber grating Fabry-Pérot cavity is accurately measured through the frequency spacing in the cavity without the precise information on fiber gratings. The measurement accuracy as high as 10^{-5} mm can be obtained by setting the resolution bandwidth of the spectrum analyzer appropriately.

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References

1. Ch. Spiegelberg, J. Geng, Y. Hu, Yu. Kaneda, S. Jiang, and N. Peyghambarian, J. Lightwave Technl. **22,** 57 (2004).
2. S. Pradhan, G. E. Town, and K. J. Grant, IEEE Photon. Technol. Lett. **18,** 1741 (2006).
3. P. Polynkin, A. Polynkin, M. Mansuripur, J. Moloney, and N. Peyghambarian, Opt. Lett. **30,** 7087 (2005).
4. Y. Zhang and B. Guan, IEEE Photon. Technol. Lett. **21,** 280 (2009).
5. B. O. Guan, H. Y. Tam, S. T. Lau, and H. L. W. Chan, IEEE Photon. Technol. Lett. **16,** 169 (2005).
6. G. Bonfrate, F. Vaninetti, and F. Negrisolo, IEEE Photon. Technol. Lett. **10,** 1109 (1998).
7. H. Xiao, F. Li, Y. Wang, L. Liu, and Y. Liu, Chinese J. Lasers (in Chinese) **7,** 87 (2009).
8. K. Xie, Y. Rao, and Z. Ran, Acta Opt. Sin. (in Chinese) **28,** 569 (2008).
9. J. Canning, M. Janos, and M. G. Sceats, Opt. Lett. **21,** 609 (1996).
10. Y. O. Barmenkov, D. Zalvidea, S. Torres-Peiró, J. L. Cruz, and M. V. Andrés, Opt. Express **14,** 6394 (2006).
11. W. Ren, Y. Wang, S. Feng, Z. Tan, Y. Liu, and S. Jian, Acta Phys. Sin. (in Chinese) **57,** 7758 (2008).
12. M. Wu, H. Liu, and D. Huang, Acta Opt. Sin. (in Chinese) **28,** 539 (2008).