Microlens optical fiber Fabry-Pérot tunable filter

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Abstract. An optical fiber Fabry-Pérot tunable filter is constructed by fixing two microlensed mirror-coated fibers to the opposite ends of a piezoelectric transducer. A tunable filter with a free spectral range of 70 nm, a finesse of 175, an insertion loss of 1.05 dB, and a tuning frequency exceeding 1 kHz has been experimentally demonstrated. The filter is easy to construct at a low cost, and it is anticipated that it will be used in fiber-optic sensing systems, spectrometers, and tunable optical fiber lasers.
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Subject terms: fiber-optic sensors; optical tunable filter; Fabry-Pérot interferometer; microlens.

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1 Introduction

Optical fiber Fabry-Pérot interferometer–based filters play a critical role in many fields, such as fiber-optic networks,[1] fiber-optic sensing systems,[2] spectrometers,[3] and fiber lasers.[4] Various configurations of the fiber Fabry-Pérot filter (FFPF) have been proposed. The direct way to construct an FFPF is by forming the Fabry-Pérot cavity in an air gap between two closely spaced fibers with reflection mirrors deposited on their plane end faces.[5,6] By varying the cavity length, the free spectral range (FSR) of an FFPF can be changed and the resonant wavelength can be tuned. However, this kind of air-gap FFPF with plane mirrors suffers from the diffraction loss of the resonant cavity, which decreases the finesse, and also suffers from the mismatch between fiber and resonator mode, which increases the insertion loss.[7] For example, the finesse of the plane-mirror air-gap FFPF in Ref. 6 is 17, and the insertion loss is 2.7 dB. To obtain high finesse and low insertion loss, it was suggested that a short piece of fiber could be inserted inside the Fabry-Pérot cavity.[8] However, it is very difficult and costly to prepare a piece of fiber as short as about 10 μm for use inside the resonator, thus making such an FFPF very expensive.

In previous work,[9,10] we have reported the fabrication of a microlens fiber Fabry-Pérot interferometer with a finesse of ~65; these were used as fixed filters[9] and sensors.[10] In this paper, we increase the reflectivity of the mirrors, improve the quality of the microlenses, and obtain a much higher finesse of 175. Driven by a piezoelectric transducer (PZT), a tunable filter is demonstrated based on this improved microlens fiber Fabry-Pérot interferometer. The microlens fiber Fabry-Pérot tunable filter (FFP-TF) possesses high finesse and low insertion loss and, above all, is easy to construct at a low cost.

2 Fabrication of Microlens FFP-TFs

The configuration of the microlens FFP-TF is illustrated in Fig. 1(a), and a micrograph of the microlens Fabry-Pérot cavity displayed on a fusion splicer is shown in Fig. 1(b). The microlens FFP-TF is based on a plane-mirror FFPF similar to the one described in Ref. 6, except that there is a semispherical convex lens on each plane mirror. The two fibers are fixed to the opposite ends of a PZT using epoxy. By applying a voltage to the PZT, the filter can be tuned. A plane reflection mirror with a convex lens on it has the same focusing ability as a concave reflection mirror, so the microlens Fabry-Pérot resonator has a similar property to a resonator constructed of two concave reflection mirrors.[11] With the two microlenses, the mode size in the resonator is decreased and the diffraction loss is reduced, making it possible to obtain a filter with high finesse and low insertion loss. The two mirrors are automatically aligned by inserting the two fibers into a hollow-core tube.

A microlens is manufactured by forming and curing a droplet of transparent epoxy on the mirrored end of a fiber.

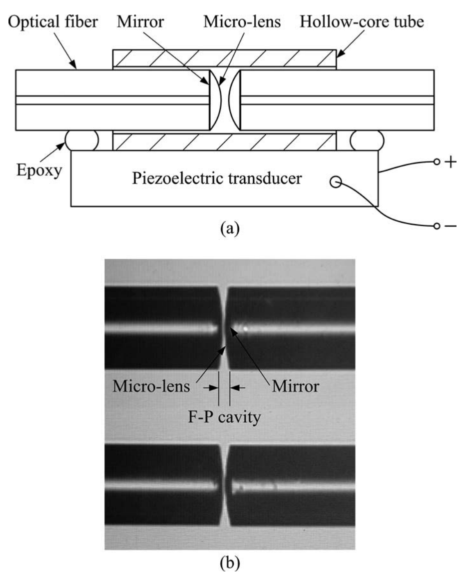

Fig. 1 Illustration of a microlens FFP-TF: (a) the configuration; (b) a micrograph of the microlens Fabry-Pérot (F-P) cavity displayed on a fusion splicer.

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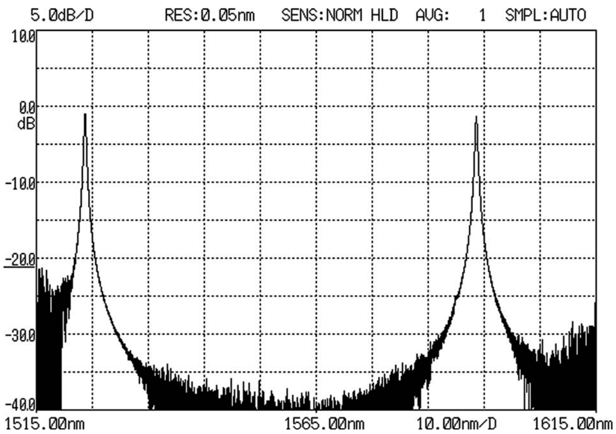

Fig. 2 Normalized transmission spectrum of a microlens FFP-TF.

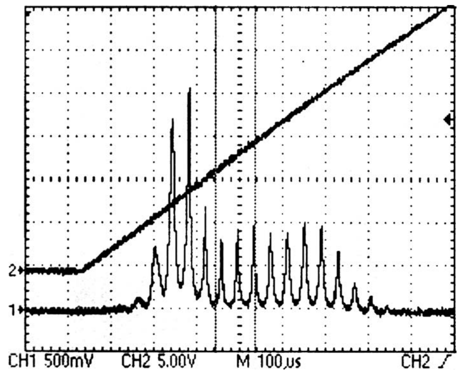

Fig. 3 Transmission light of the etalon on CH1 and driving sawtooth wave on CH2.

The manufacturing procedure is carried out on a fusion splicer, in the same way as in Refs. 9 and 10. First, fibers are cleaved, polished, and mirror-coated using conventional methods. The reflectivity of the mirror is about 98.5%. The microlens is manufactured on the mirrored fiber end using the method described in Refs. 9 and 10. The length of the Fabry-Pérot cavity is the sum of the height of two microlenses and the spacing between them. The height of microlenses limits the minimum Fabry-Pérot cavity length that can be fabricated, and thus limits the free spectral range (FSR) or the wavelength tuning range of the microlens FFP-TF. In Refs. 9 and 10, the microlens was made of NOA 61, a UV-curable adhesive produced by Norland Products, and the height of the microlens was 8 μm. Letting the spacing between the two microlenses be 2 μm, the Fabry-Pérot cavity length is 18 μm, and the FSR is $\sim$45 nm. A microlens fiber Fabry-Pérot interferometer with an FSR of 45 nm or even smaller is adequate for a sensor, but for a tunable filter, it is better to have a larger FSR to cover the C-band wavelength range of an amplified spontaneous emission (ASE) source. In this paper, the microlens is made of a two-component adhesive EPO-TEK 353ND, and the height of the microlens is reduced further to 5.5 μm, which is measured by the method described in Ref. 10, and thus a wider FSR can be achieved. In addition, compared to the NOA 61, which cures in a few seconds, EPO-TEK 353ND takes a much longer time to cure under room temperature (24 h in our experiment). This property is beneficial for improving the quality of the microlens because gravity is utilized to form the convex lens.[9,10] EPO-TEK 353ND also has a much higher operating temperature (250°C) than NOA 61 (60°C before aging, 60°C after aging), and this is helpful for its life span and applications. After the microlenses have been prepared, two fibers with a microlens on each mirrored end are inserted into a hollow-core tube with an inner diameter of 127 μm, and the spacing between the two mirrors is adjusted to obtain the desired FSR. Then the two fibers are fixed to the opposite ends of a 20-mm-long PZT by epoxy, and a microlens FFP-TF is constructed.

The transmission spectrum of a microlens FFP-TF is shown in Fig. 2; it was measured using an optical spectrum analyzer (OSA) AQ6317C, while illuminated by an ASE source with the wavelength covering 1515 to 1615 nm. The microlens FFP-TF was found to have an FSR of 70 nm, a full width at half maximum (FWHM) of 0.4 nm at the first transmission peak, and thus a finesse of 175. The insertion loss was found to be 1.05 dB at the first transmission peak. The wavelength tunable range of the microlens FFP-TF is wider than the wavelength range of a C- or an L-band ASE source, and the line width is comparable to that of the FFP-TF used to interrogate fiber Bragg grating sensors in Ref. 2, which is 0.38 nm. This shows that the microlens FFP-TF can be also used as a wavelength scanner in fiber-optic sensing systems.[2,3]

A direct-current voltage was applied to the PZT and increased by a step of 2 V to tune the resonant wavelength. It is found that the microlens FFP-TF has a wavelength-voltage tuning sensitivity of 20 V/FSR. An ASE source with a wavelength covering 1525 to 1565 nm is used to illuminate the microlens FFP-TF, and a sawtooth wave is applied to the PZT. The output light of the microlens FFP-TF is injected into an etalon with an FSR of 3.25 nm and a finesse of 40, and the transmission light is detected by a photoelectric diode (PD). The detected signal and the sawtooth wave are both monitored by an oscilloscope TDS210, as shown in Fig. 3. The spectrum of the etalon is clearly obtained. Figure 3 also shows that the microlens FFP-TF has a tuning frequency of at least 1 kHz. In fact, a scanning frequency of several tens of kilohertz can be reached with this tunable filter because the size of the filter is tiny. The scanning frequency is limited only by the frequency of the PZT. Due to the hysteresis of PZT, the microlens FFP-TF exhibits nonlinear behavior and poor repeatability, resulting in a random shift of the scanning wavelength. To precisely determine the scanning wavelength, an etalon with fixed wavelengths[12] or an absorption gas cell[13] is usually used as a multiwavelength reference to calibrate the scanning wavelength.

As the materials used to fabricate the microlens FFP-TF are sensitive to temperature, we tested the wavelength dependence of a microlens FFP-TF on temperature. The microlens FFP-TF was put into a drying oven in which temperature can be adjusted, and its transmission spectrum was monitored on an OSA. The temperature was increased at a step of 5°C, and the resonant wavelength was recorded. The resonant wavelength decreased from 1557 to 1517 nm (about 0.57 FSR) when the temperature increased from

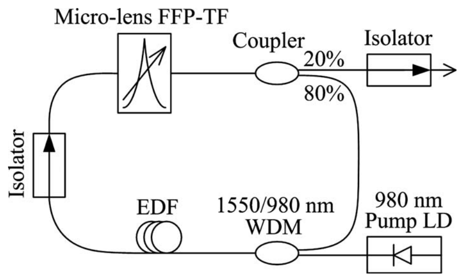

Fig. 4 Configuration of the tunable erbium-doped fiber (EDF) ring laser.

27.5 to 58 °C. One FSR range of the wavelength shift represents an optical cavity length change of ~0.75 μm, then it is calculated that the temperature sensitivity of the optical cavity length is about –0.014 μm/ °C. As the distance between the two bonding points is 20 mm, more than 1000 times larger than the optical cavity length, the mismatch of thermal expansion coefficient (TEC) between PZT and optical fiber has prominent influence on the temperature sensitivity of the optical cavity length. The optical fiber used in the microlens FFP-TF is Corning SMF28 fiber, the TEC of which is approximately $0.55\times 10^{-6}/$ °C. The TEC of the PZT is not available at present. The TEC mismatch between PZT and optical fiber can be passively compensated by using other material with proper TEC and length, as shown in Ref. 14. The TEC of EPO-TEK 353ND used in the experiment is about $54\times 10^{-6}/$ °C under 90 °C As the total height of the two microlenses is only 11 μm, their thermal expansion has little contribution to the change of cavity length. The wavelength shift caused by temperature variation can also be corrected by using multiwavelength reference technique, as shown in Ref. 12.

3 Microlens FFP-TF–Based Tunable Fiber Laser

The microlens FFP-TF can be used as a wavelength-selecting component in a tunable fiber laser. A wavelength-tunable erbium-doped fiber (EDF) ring laser based on the microlens FFP-TF is constructed, and its configuration is illustrated in Fig. 4. A 5-m-long Er20-4/125 EDF manufactured by Liekki, Inc., is used as the gain medium. The EDF has an absorption of 20 dB/m at 1530 nm and a mode field diameter of 6.5 μm at 1550 nm. The EDF is pumped by a 980-nm diode with a power of 85 mW. An isolator is inserted into the ring to ensure unidirectional operation. The laser light is output through an 80:20 coupler and monitored by an OSA AQ6317C. Another isolator is placed before the output to prevent back reflection from fiber links.

The lasing wavelength of the EDF ring laser is determined by the microlens FFP-TF. Figure 5(a) shows the optical spectra of the EDF ring laser while the driving voltage applied to the PZT is changed. A tuning wavelength range of over 44 nm with a single emission line, between 1524 and 1568 nm, was achieved by increasing the driving voltage from 0 to 12 V. The FWHM bandwidth of the emission lines was measured to be less than 0.01 nm; this is limited by the resolution of the OSA, 0.01 nm. The output power is greater than 3 mW from 1528 to 1568 nm, and the maximum power is about 6 mW at 1562.5 nm, as illustrated in Fig. 5(b). The ratio of the laser power to the background ASE light is greater than 30 dB during wavelength tuning, except at the edge of the wavelength tuning range. The variation in output power comes from the wavelength-dependent gain of the EDF, which can be reduced by optimizing the length of the EDF and the pumping power.

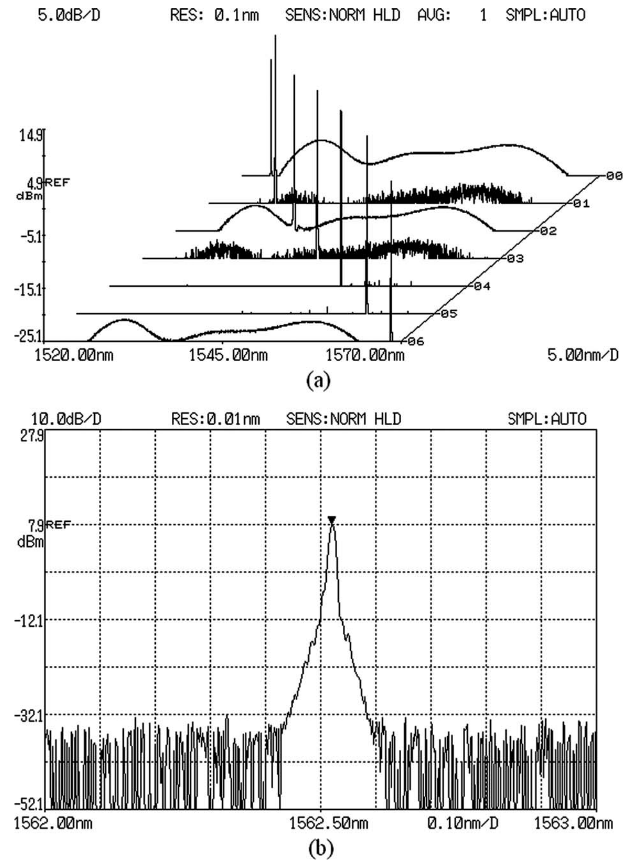

Fig. 5 Output spectra of the EDF ring laser: (a) the laser's spectra while increasing the driving voltage by a step of 2 V; (b) the laser's spectrum at 1562.5 nm.

4 Conclusion

We have demonstrated a microlens FFP-TF that has a tuning range of 70 nm, a finesse of 175, and an insertion loss of 1.05 dB. The microlens FFP-TF is tuned by driving a PZT with a wavelength-voltage tuning sensitivity of 20 V/FSR and a tuning frequency of greater than 1 kHz. The microlens FFP-TF has also been successfully used in a wavelength-tunable EDF ring laser. This kind of microlens FFP-TF is easy to construct at a low cost, and it is anticipated that it will be used in fiber-optic sensing systems, spectrometers, and fiber lasers.

Acknowledgments

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