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Realization of spectral tunable filter based on thermal effect in microfiber structure

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ABSTRACT

This paper demonstrates a new approach for tuning the extinction ratio of a complex microfiber structure output using thermal effect. The microfiber filter device comprises of a microfiber Mach–Zehnder interferometer followed a knot structure, where temperature is controlled by a DC current applied to a copper wire placed inside the knot. This enables electrical tuning, where applying electrical current increases the temperature and affects the optical path. The change of temperature facilitates the fine tuning of the resonance output spectrum. From the experiment, it was observed that the extinction ratio of the output comb spectrum can be controlled within 2 dB to 10 dB by varying the current rating from 0 A to 1.22 A.

1. Introduction

Microfiber structures are designed to provide stable light coupling and to support single-mode operation. Various microfiber structures include Mach–Zehnder interferometer [1,2], microfiber ring [3,4], knot [5,6], coil [7,8], and some multi knot structures [9]. These structures have been constructed and used as modulators and convertors [10], provide time delay [11] and generate tunable lasers [12]. They can also be utilized as sensors to measure physical entities like humidity [13], refractive index [14] and temperature [15]. Most microfiber-based sensors monitor changes in the resonance spectrum which was caused by the evaluated physical entity or variable variations. If the process is reversed, one can tune the characteristics of the resonance spectrum by controlling the physical variables that affect its extinction and suppression ratio, bandwidth and resonance wavelength. This tuning ability is quite useful in when developing filter, laser, and modulators with specific features or characteristics.

A simple way to control the temperature of an optical microfiber structure is by passing electrical current through a conductor in its vicinity. The heat generated by the conductor is transferred the microfiber structure, thereby changing its path length and influences its resonance spectrum. There is a previous work in which a microfiber knot which surrounded a copper wire has been used for current sensing [14]. Also a similar structure has been reported as a temperature based microfiber current sensor that employs knot resonator, MZI and graphen based microfiber coil [16–20].

This paper, investigated using of DC to tune and improve the extinction ratio of the output spectrum of a microfiber filter consisting of Mach–Zehnder and Knot structure. It is found that the extinction ratio of the output spectrum could be varied by passing a different amount of current through a copper wire inserted in the knot structure. The current shifts the resonance wavelength of one of the structure elements that causes a change in extinction ratio of the superposition output spectrum of the structure.

2. Theory

The proposed structure is depicted in Fig. 1a. It consists of one microfiber Mach–Zehnder interferometer (MZI) and one knot. Microscopic images of the MZI and the knot are shown separately in Fig. 1b and Fig. 1c in order. In the filter, the input light propagates through the MZI and then passes through the microfiber knot. The output spectrum of the filter is a superposition of the two elements.

Any change in one of these elements affects the output characteristic of the filter. The surrounding environments may effect on the resonance spectrum while changes the resonance wavelength. In this work, the changes are applied to the knot. The free spectral range of the knot and its phase are defined as below [21–23]:

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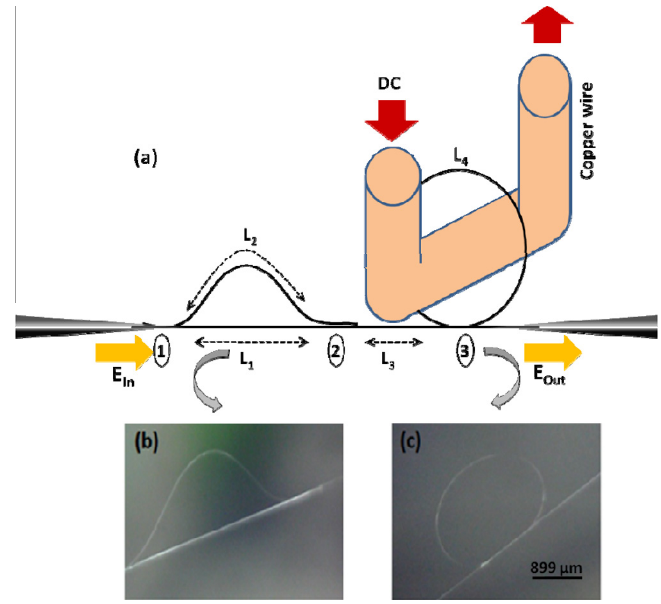

Fig. 1. The schematic diagram of the proposed structure (a), microscopic image of the MZI (b) and the knot (c).

$$FSR = \frac{\lambda^2}{n_{eff}L} \tag{1}$$

$$\varphi_4 = \frac{2\pi n L_4}{\lambda} \tag{2}$$

where λ is the operating wavelength, n_{eff} and L indicate the effective index of the microfiber and the length of the resonator, respectively. Thermal effect stemming from current affects on n_{eff} and L which leads to resonance shift. This is described in the following expression

$$\frac{\Delta\lambda}{\lambda} = \left(\frac{\Delta n}{n} + \frac{\Delta L}{L}\right)_{Temp} \tag{3.1}$$

$$\text{in which} \quad \frac{\Delta n}{n} = \alpha\Delta T, \frac{\Delta L}{L} = \beta\Delta T \tag{3.2}$$

Here, $\propto$ and β are the thermal expansion coefficient and thermal optic coefficient of the microfibers, respectively. The temperature change is proportional to the resonance wavelength based on the following equation [21,22].

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\rho I^2}{A} \tag{4}$$

where the constants ρ and A are the conductor resistivity and the cross section area of the conductor rod, respectively. Base on the coupled mode theory [23], the output spectrum from the complex structure is given by:

$$\begin{aligned} E_{Out} = & -ik_3\{e^{(-i\varphi_3-\alpha L_3)}[-ik_2e^{(-i\varphi_1-\alpha L_1)}(-ik_1)E_{in} + t_2e^{(-i\varphi_2-\alpha L_2)}t_1E_{in}]\} \\ & + t_3\left\{\frac{t_3e^{(-i\varphi_4-\alpha L_4)}}{ik_3e^{(-i\varphi_4-\alpha L_4)}+1}e^{(-i\varphi_3-\alpha L_3)}[-ik_2e^{(-i\varphi_1-\alpha L_1)}(-ik_1)E_{in}\right. \\ & \left. + t_2e^{(-i\varphi_2-\alpha L_2)}t_1E_{in}]\right\} \end{aligned} \tag{5}$$

$$t^2_{1,2,..} + k^2_{1,2,..} = 1 - \gamma \tag{6}$$

$$\varphi_{1,2,..} = \frac{2\pi n L_{1,2,..}}{\lambda} \tag{7}$$

where t is transmission coefficient, k is coupling coefficient, γ is coupling loss and α is round trip loss. Because of the changes at knot resonance character which arises from a change in φ_4, the combined output spectrum which follows Eq. (5) will be changed as well.

3. Experiment

To prepare the microfiber, a single mode fiber (SMF28) was first tapered using flame brushing method until its diameter decreased to about 6 µm. To construct the filter with a cascaded MZI and knot structure (as in Fig. 1), the microfiber was first cut into two sections with equal length. The first microfiber section was first twisted around two nonstick separated bars to form a knot. Then the two bars were pressed together and pulled out of the knot. The other microfiber section was curved to form an MZI structure. After making the MZI structure, the microfiber ends of the two structures were attached together by van der Waals and electrostatic forces so that the combined structure have one input and one output. The fabrication process was performed in free air at the fixed room temperature. Packaging is one important step to obtain more robustness. Some different methods of packaging process such as setting the structure on MgF_2 or embed the structure in low refractive index polymers have been demonstrated in some previous work [24–26]. The wire at this experiment can be replaced on top of the knot instead of inside it during the packaging the system. Here, the system was not packaged to avoid the effect of substrate on microfiber due to the current heat induce. Therefore the environment was controlled during the measurement through vibration control and keeping a constant temperature. Finally, a copper rod was inserted into the knot structure. In the experiment, amplified spontaneous emission (ASE) light from an erbium doped fiber amplifier (EDFA) was injected at the input end. The output end was connected to an optical spectrum analyzer (OSA) to monitor the output spectrum. The Current was injected into the copper wire using a DC source. The wire has been set quiet close to the knot but not touching it.

In this experiment, the effect of temperature on the spectrum shift and its implementation in tuning the extinction ratio of the output are compared to those of an individual knot. The individual knot has a radius of 899.5 µm that corresponds to the following resonance characteristics: free spectral range (FSR) = 300 pm, quality factor ≅9000, full-wave half maximum (FWHD) = 175 pm and finesse = 1. 8 and extinction ratio = 6 dB. Fig. 2a demonstrates the output spectrum of the laser before and after tapering. This figure shows the output experiences about 4 dBm loss due to the tapering process. Forming the knot and the MZI causes an extra 3 dB loss as shown in Fig. 2b. The total loss is about 7 dB.

Changing the current flowing through the copper rod from 0 A to 1.22 A, the output comb spectrum from the knot structure experienced a red wavelength shift of about 0 to 150 pm as shown in Fig. 2b. The wavelength shift versus current is illustrated in Fig. 3a. The room temperature has been fixed on 28 °C. The temperature difference produced by the copper wire, with 250 µm diameter, resistivity of 1.68×10^{-8} Ωm and 10 cm length, is calculated for different current values as shown in Fig. 3b using the following relation

$$\Delta T = \frac{\rho l I^2}{AmC_w} \tag{8}$$

where ρ is the resistivity, l the length, I the current, A the cross section, m the mass and C_w is the copper heat capacity.

The output spectrum from the cascaded structure is shown in Fig. 4a. The cascaded structure includes the knot and a MZI with two branches with a length difference of 6000 µm that generates