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Spectral characteristics of the microfiber MZ interferometer with a knot resonator

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ABSTRACT

This paper investigates the transmission spectral characteristics of microfiber MZ interferometer with a knot resonator (MZIKR). The MZIKR exhibits a combined effect of resonance and interference in its transmission spectra. By adjusting the coupling coefficients to convert the relative strength of resonance and interference, the transmission spectra show various shapes, mainly reflected in the direction of fringes. The obtained upward fringe exhibits an extinction ratio of 17 dB and a FWHM of 0.3 nm. The tunable transmission spectrum demonstrated here may have great potential for narrow-band filtering, and the coexisting resonance and interference effect also allows the MZIKR to perform dual-parameters sensing.

1. Introduction

Microfiber has attracted a significant degree of attention due to its versatile advantages, which include low transmission loss, strong evanescent field, compact size and flexible structure. Currently, microfibers have been fabricated into a variety of different structures including microfiber Bragg gratings (mFBG) [1–3], knot and loop resonators (MKR, MLR) [4–12], MZ interferometers (MZI) [13–17], FP interferometers (FPI) [18,19], couplers [20,21], and taper [22]. Among the structures mentioned above, MKR and MZI are the most widely used devices because of their simple manufacture process and low cost. A MKR is fabricated by bending and knotting a single microfiber. The transmission spectra of MKRs are comb-like spectra, containing a series of downward resonance dips of which the extinction ratio (ER) and free spectral range (FSR) can reach to be 20 dB and 14.9 nm, respectively [4]. Based on the spectral characteristics, MKRs have been developed into a number of devices, including sensors [5–7], filters [4,8] and lasers [9,10]. The existing microfiber MZIs mainly have two structural forms, which include in-line MZI and dual-microfiber MZI. In-line MZIs are made up of multimode microfibers in which multi-mode would be allowed to transfer and generate optical path difference (OPD). Because of the stable structure and different response of multi-mode to the variation of ambient, in-line MZIs are commonly used in sensing [13,14]. While, the dual-microfiber MZIs are assembled by two microfiber arms to generate OPD. Because of the flexibly tunable arms, the dual-microfiber MZIs can be used as modulator and filter [15,16].

In this paper, we propose a microfiber MZI with a MKR (MZIKR) and investigate its transmission spectral characteristics. The transmission spectra show the combined effect of resonance and interference, corresponding to MKR and MZI, respectively. Furthermore, the shapes of spectra are highly dependent on the relative strength of resonance and interference. By altering the coupling coefficients to convert the relative strength of resonance and interference, the typical spectra with different shapes, mainly reflected in the direction of fringes, are obtained in both theoretical simulation and experiment study. This paper includes an illustration of the mechanism of transmission spectra, which would offer useful references for developing MZIKR-based dual-parameters sensor and narrow-band filter.

2. Spectra simulation

A MZIKR, whose schematic diagram is shown inFig. 1, is assembled by two microfibers. Light inputting from microfiber 1 is divided into two beams in coupler 1, one of which propagates to coupler 3 via microfiber 2 directly, and the other one propagates to coupler 3 via a MKR. The transmission coefficient of MKR t_r is given by [23]:

$$t_r = j\sqrt{k_2(1-r_0)} + \left(\frac{(1-k_2)(1-r_0)\exp(j\beta_1 L_r)}{1-j\sqrt{k_2(1-r_0)}\exp(j\beta_1 L_r)}\right) = A\exp(j\phi) \quad (1)$$

where k_2 is the coupling coefficient of coupler 2, r_0 is the transmission loss, β_1 is the propagation constant of microfiber 1 and L_r is the length of the ring, Aandϕ represent the relative transmission amplitude and phase, respectively. Two beams would interfere when they recombine in coupler 3, and the transmission coefficient of the MZIKR t is given

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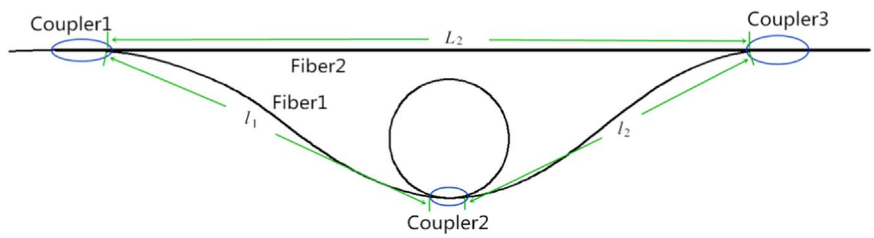

Fig. 1. The schematic diagram of the MZIKR.

by [24]:

$$t = \frac{E_{out}}{E_{in}} = j\sqrt{k_1}\,\alpha\exp(j\beta_2 L_2) + \sqrt{1-k_1}\,\delta\exp(j\beta_1 L_1)\cdot t_r \tag{2}$$

where k_1 is the coupling coefficient of coupler 1, L_2 is the length of microfiber 2, β_2 is the propagation constant of microfiber 2, L_1=l_1+l_2, α and δ are the coupling ratio in coupler 3. In the simulation below, we assume that two beams would be completely picked up in coupler 3, in other words, α=1, δ=j.

The parameters of the MZIKR are assumed as follows: the length of two microfiber arms L_1, L_2 are 5 mm and 4.8 mm, respectively, the diameters of microfiber 1 and 2 are 3 µm and 3.2 µm, respectively, and the diameter of the MKR is 600 µm. In order to investigate the influence of the coupling coefficients on the transmission spectra, k_2 is fixed as 0.8 initially and k_1 is varying. In the case of k_1=0.05, the transmission spectrum is obtained and shown in Fig. 2(a). The spectrum shows series of dense fringes and sparse envelop, which are caused by knot resonance and MZ interference, respectively. In this situation, all the fringes are downward, and the interference envelop is floating on the transmission spectrum. It is noted that similar spectra can be obtained under the condition of k_1 < 0.18. However, when k_1 > 0.18, the spectra get considerable change. For instance, the transmission spectrum of k_1=0.5 is simulated and shown in Fig. 2(b). The transmission spectrum is also simultaneously modulated by knot resonance and MZ interference. Compared with Fig. 2(a), the interference envelop simultaneously reaches the top and bottom of the transmission spectrum, and the fringes at the interference envelop dip are in the opposite direction.

In addition, the transmission spectrum with a beat-wave shape can be observed when both k_1 and k_2 are relative small. For instance, Fig. 2(c) shows two typical spectra with beat-wave shape when k_1=0.05, k_2=0.4 and k_1=0.05, k_2=0.6. The two spectra in Fig. 2(c) show the opposite direction of fringe at interference envelop dip, which means that they are special cases belonging to Fig. 2(a) and (b).

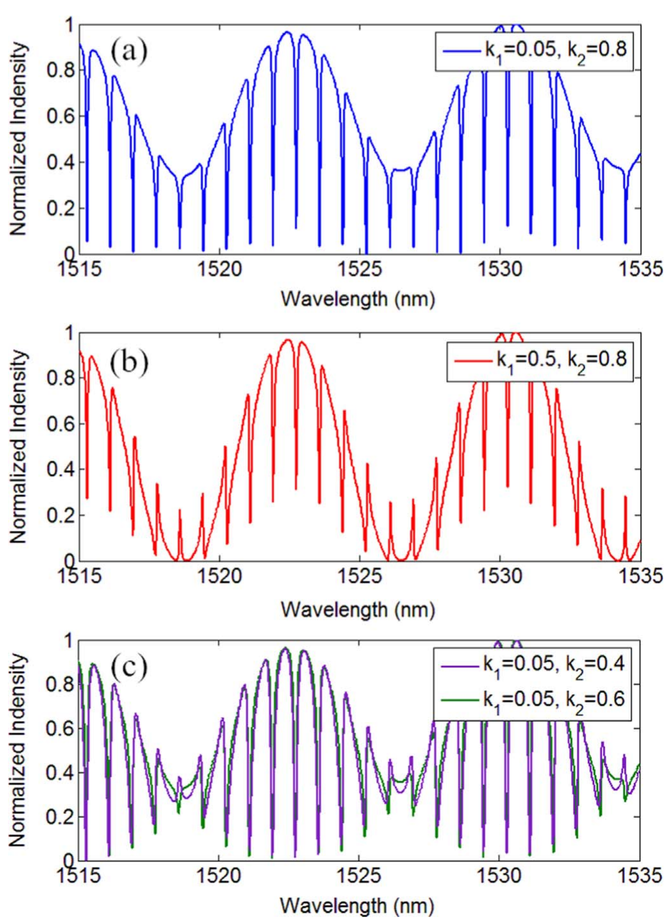

Fig. 2. The transmission spectrum under the condition of (a) k_1=0.05, k_2=0.8, (b) k_1=0.5, k_2=0.8, (c) k_1=0.05, k_2=0.4 and k_1=0.05, k_2=0.6.

3. Mechanism analyses of transmission spectra

By changing the coupling coefficients, MZIKR shows diverse transmission spectra. In this part, a detailed analysis of the impact of the coupling coefficients on spectra is carried out. We assume a single MKR with 600-µm ring diameter and 3-µm fiber diameter to keep the same parameters with the MKR of the above MZIKR. According to expression (1), the relative transmission intensity of MKR can be calculated. Meanwhile, the phaseϕ can be express as:

$$\phi = \tan^{-1}\left[\frac{\mathrm{Im}(t_r)}{\mathrm{Re}(t_r)}\right] \tag{3}$$

Based on expressions (3), the phase of this single MKR is simulated and shown in Fig. 3. It is obvious that the resonance dip is corresponding to the phase at -π/2, while the phase of non-resonance wavelength concentrates at about π/2. Meanwhile, a single MZI with the same parameters as the microfiber arms of the above MZIKR is also assumed to simulate its transmission spectrum. The simulated normalized spectrum is shown in Fig. 4 (black line).

In terms of phase, the single MKR can be regarded as a phase modulator, which would lead to the periodic variation of phase $\Delta\varphi_\lambda$. Compared the single MZI and the MZIKR, the only difference is

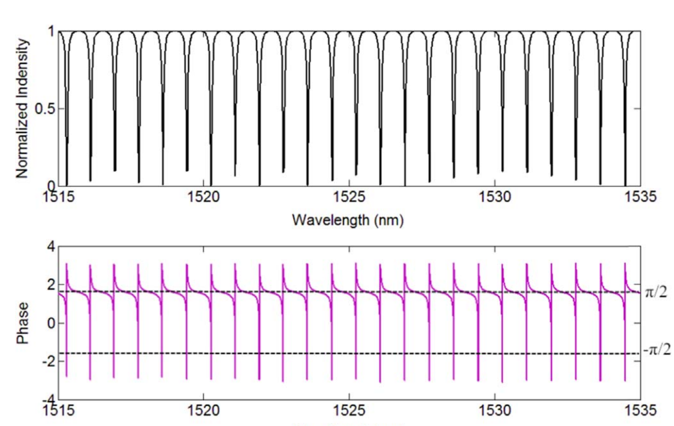

Fig. 3. The normalized transmission spectrum and the phase of a single MKR with 600-µm ring diameter and 3-µm fiber diameter.