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不同结构微光纤双结谐振器光谱特性理论和实验

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摘　要：基于环形谐振器和方向耦合器理论，提出了串联结构微光纤双结谐振器和并联结构微光纤双结谐振器的理论模型，推导了两谐振器中输出光场与输入光场之间的数学解析式，分析了两谐振器中光场的传输和耦合方向，及不同直径比的情况下其输出光谱的变化规律．数值模拟表明对于串联结构微光纤双结谐振器，位于其透射光谱包络下的透射峰数目等于其两环的直径比；对于并联结构微光纤双结谐振器，透射光谱中透射峰的数目随直径比的增加而增加，且每个直径比等间距的透射峰后会出现一个更窄的透射峰．实验制作了具有近似相等直径的串联结构微光纤双结谐振器和具有直径比近似为 2 的并联结构微光纤双结谐振器．两种结构的透射光谱均与理论模拟相一致，验证了理论分析的正确性．具有合适直径比的串联结构微光纤双结谐振器和并联结构微光纤双结谐振器在光学滤波器、微型激光器、传感器等方面有重要的应用．

关键词：光纤光学；微光纤双结谐振器；光学光纤耦合；光纤光学部件；光学光纤通信；光波导

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Theoretical and Experimental Study on Spectral Characteristics of Microfiber Double-knot Resonator with Different Structures

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Abstract: Based on the theories of the ring resonators and the directional coupler, the theoretical models of the microfiber double-knot resonator with a serial structure and the microfiber double-knot resonator with a parallel structure were proposed, the mathematic expressions between the output light field and the input one in the two resonators were deduced. The directions of the propagation and coupling in the two resonators were studied, the change rules of the transmission spectra under different diameter ratios of their two rings were analyzed. Numerical simulation indicates that the number of the transmission peaks of the microfiber double-knot resonator with a serial structure under the envelope of its transmission spectrum is equal to the diameter ratio of its two rings, the number of the transmission peaks of the microfiber double-knot resonator with a parallel structure increases with the increasing of the diameter ratio of its two rings and there is a narrower transmission peak per equal spacing peaks of the diameter

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ratio. The microfiber double-knot resonator with a serial structure for approximately equivalent diameters and the microfiber double-knot resonator with a parallel structure for a diameter ratio of approximate 2 were fabricated. The experimental transmission spectra show good agreements with the theoretical ones for each structure, indicating that the theoretical analysis is considerably correct. The microfiber double-knot resonator with a serial structure and that with a parallel structure for proper diameter ratios have significant applications in optical filters, miniature lasers, sensors, and so on.

Key words: Fiber optics; Microfiber double-knot resonator; Optical fiber coupling; Fiber optic components; Optical fiber communication; Optical waveguides

OCIS Codes: 130.3120; 230.5750; 220.4000; 060.2310; 060.2330

0 Introduction

Microfibers/nanofibers have attracted considerable interest recently as promising building blocks for a wide variety of photonic applications. This is due to their unique optical guidance properties, which include large evanescent field[1], high nonlinearity[2], tight optical confinement[3], controllable waveguide dispersion[4] and low-loss interconnection to other optical fibers and fiberized components. Based on these properties, various microfiber resonators, in the shape of loops[5], knots[6], and coils[7-8], have been demonstrated in a variety of components including filters[9], lasing systems[10-12], nonlinear optical systems[13], and sensing devices[14-15]. Among these microfiber resonators, the Microfiber Knot Resonator (MKR) has been regarded as one of the most attractive resonators[16-18], due to its many advantages, including easy fabrication, high stability, compatibility with the available communication system, compactness, low loss, high Q value and high finesse. Since, Jiang et al.[6] firstly proposed the MKR, the resonator has been extensively applied to add-drop filters[9], miniature lasers[10], slow-light system[19], and so on. Recently, Xiao et al. proposed a new method to directly fabricate a MKR from a double-ended tapered fiber[16], which benefits the high finesse. We also proposed another approach to fabricate MKR with different structures[20], which might prompt the resonator to have a more extensive application.

However, the investigation about the properties of MKRs with different structures has been seldom reported by now. In this paper, microfiber double-knot resonator with a serial structure and that with a parallel structure are investigated both theoretically and experimentally. By numerical simulating, we found that the performance of the overall structure is strongly dependent on the ratio of the diameters of the two knot rings in the microfiber double-knot resonator with different structures. Corresponding spectral characteristics have been demonstrated experimentally.

1 Theoretical model

The schematic diagram of the microfiber double-knot resonator with a serial structure is shown in Fig. 1. It is comprised of two knot rings labeled as 1 and 2, which are realized by a microfiber. The arrows indicate the light propagation and coupling directions within the two rings. Combining the theory of ring resonators[21-24] with that of directional couplers[25-27], the operational principle of the microfiber double-knot resonator with different structures could be deduced. For simplicity, the propagation and bending losses in the resonator can be assumed to be ignored owing to the excellent diameter uniformity and surface smoothness, as well as the small diameter of the microfiber[28]. The relationships between the output light fields (E_4, E_8) and the input ones (E_1, E_5) can be expressed as

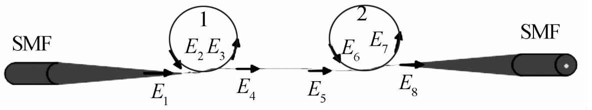


Fig. 1 Schematic diagram of the microfiber double-knot resonator with a serial structrue

$$\begin{bmatrix} E_4 \\ E_8 \end{bmatrix} = \begin{bmatrix} T_1 & 0 \\ 0 & T_2 \end{bmatrix} \begin{bmatrix} E_1 \\ E_5 \end{bmatrix} \tag{1}$$

$$T_1 = \frac{E_4}{E_1} = \frac{\mathrm{j}\sqrt{k_1(1-r_1)} + (1-r_1)\exp(\mathrm{j}\beta L_1)}{1-\mathrm{j}\sqrt{k_1(1-r_1)}\exp(\mathrm{j}\beta L_1)} \tag{2}$$

$$T_2 = \frac{E_8}{E_5} = \frac{\mathrm{j}\sqrt{k_2(1-r_2)} + (1-r_2)\exp(j\beta L_2)}{1-j\sqrt{k_2(1-r_2)}\exp(\mathrm{j}\beta L_2)} \tag{3}$$

$$E_5 = E_4 \exp(\mathrm{j}\beta L_{1,2}) \tag{4}$$

where T_1 and T_2 are the amplitude transmission coefficients, k_1, k_2 are the coupling coefficients, r_1, r_2 are the coupling loss coefficients and L_1, L_2 are the circumferences of the first MKR and the second one, respectively. $L_{1,2}$ is the distance between them, and β is the propagation constant given in Ref. [29]. Combining Eqs. (2) ~ (4), we obtain the overall amplitude transmission coefficient

$$T = T_1 T_2 \exp(\mathrm{j}\beta L_{1,2}) \tag{5}$$

It can be seen that the whole transmission spectrum is the overlapped consequence of the two transmission spectra produced by the two knot resonators.

Analogously, the schematic diagram of the microfiber double-knot resonator with a parallel structure is shown in Fig. 2. It consists of two knot rings labeled as 1 and 2, which are also realized by a microfiber. The smaller ring, MKR_1, is embedded into the larger one, MKR_2. Consider the light propagation and coupling within the two rings. Firstly, the input light field E_1 coupled from the SMF splits at the coupling region of the MKR_2 into E_3 and E_4, then E_3 propagates along ring_2 and converts to E_5 via a half circumference of ring_2. Subsequently, E_5 splits at the coupling region of MKR_1 into E_7 and E_8. Then E_7 propagates along ring_1 and converts to E_6 after a circumference of ring_1, E_6 splits into E_7 and E_8 again at the coupling region of MKR_1; then E_8 propagates along ring_2 and converts to E_2 after a half circumference of ring_2. Finally, E_2 splits into E_3 and E_4 at the coupling region of the MKR_2 again. The relationships between the output light fields (E_3, E_4, E_7, E_8) and the input ones (E_1, E_2, E_5, E_6) can be expressed as

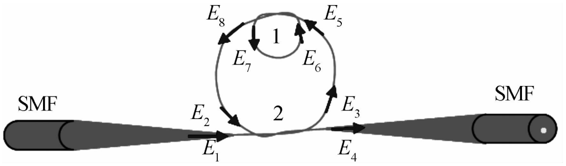


Fig. 2 Schematic diagram of the microfiber double-knot resonator with a two-ring parallel connection structure

$$\begin{bmatrix} E_3 \\ E_4 \\ E_7 \\ E_8 \end{bmatrix} = \begin{bmatrix} \sqrt{1-r_2} & 0 & 0 & 0 \\ 0 & \sqrt{1-r_2} & 0 & 0 \\ 0 & 0 & \sqrt{1-r_1} & 0 \\ 0 & 0 & \sqrt{1-r_1} & 0 \\ 0 & 0 & 0 & \sqrt{1-r_1} \end{bmatrix} \cdot \tag{6}$$

$$\begin{bmatrix} \sqrt{1-k_2} & \mathrm{j}\sqrt{k_2} & 0 & 0 \\ \mathrm{j}\sqrt{k_2} & \sqrt{1-k_2} & 0 & 0 \\ 0 & 0 & \sqrt{1-k_1} & \mathrm{j}\sqrt{k_1} \\ 0 & 0 & \mathrm{j}\sqrt{k_1} & \sqrt{1-k_1} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_5 \\ E_6 \end{bmatrix}$$

$$E_5 = E_3 \exp\left(\mathrm{j}\,\frac{1}{2}\beta L_2\right) \tag{7}$$

$$E_6 = E_7 \exp\left(\mathrm{j}\beta L_1\right) \tag{8}$$

$$E_2 = E_8 \exp\left(\mathrm{j}\,\frac{1}{2}\beta L_2\right) \tag{9}$$

From these equations, the amplitude transmission coefficients of ring_1 and ring_2 can be respectively expressed as

$$T_1 = \frac{E_8}{E_5} = \frac{\mathrm{j}\sqrt{k_1(1-r_1)} + (1-r_1)\exp\left(\mathrm{j}\beta L_1\right)}{1-\mathrm{j}\sqrt{k_1(1-r_1)}\exp\left(\mathrm{j}\beta L_1\right)} \tag{10}$$

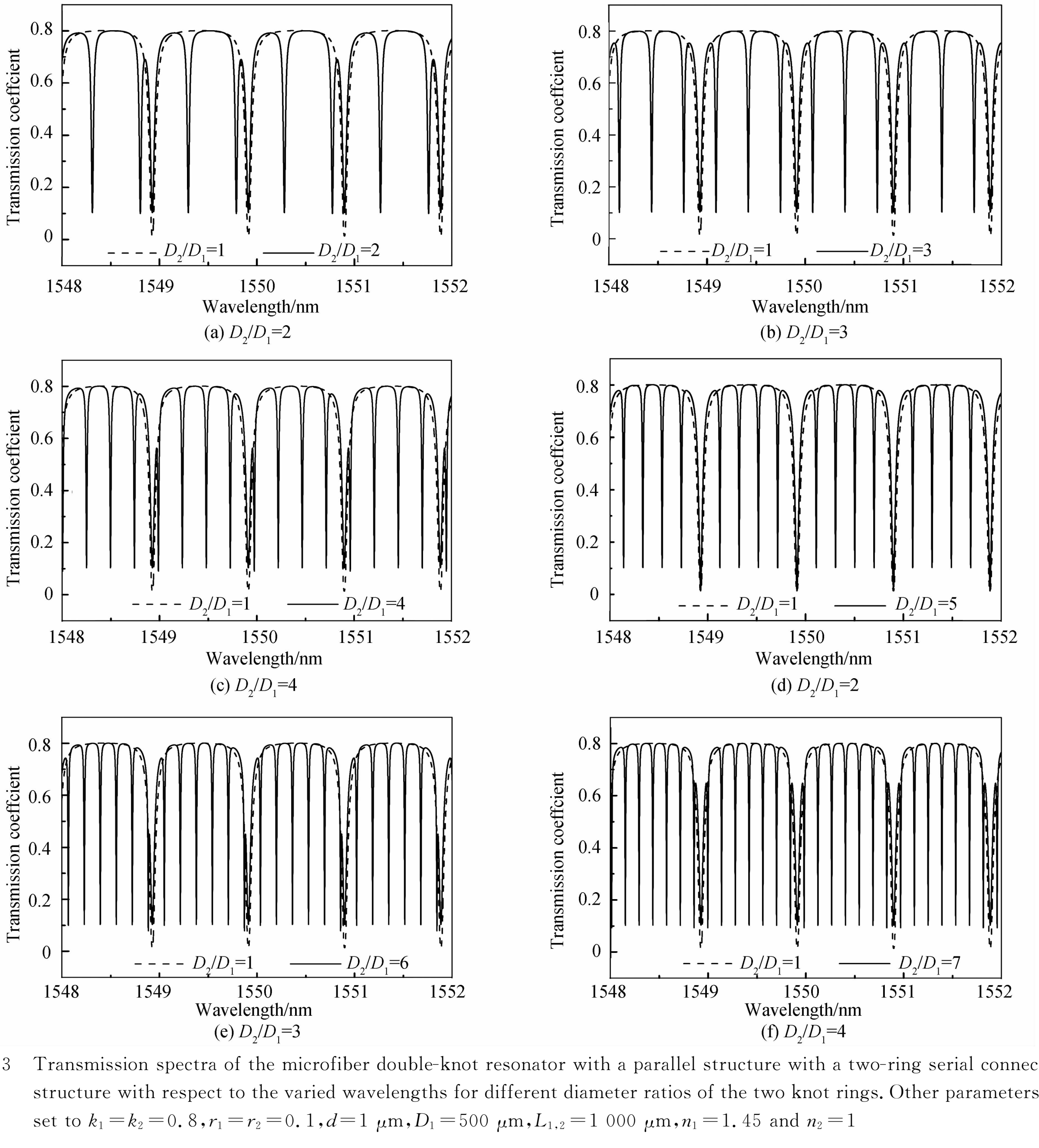
$$T_2 = \frac{E_4}{E_1} = \frac{\mathrm{j}\sqrt{k_2(1-r_2)} + (1-r_2)T_1\exp\left(\mathrm{j}\beta L_2\right)}{1-\mathrm{j}\sqrt{k_2(1-r_2)}\,T_1\exp\left(\mathrm{j}\beta L_2\right)} \tag{11}$$

Note that T_2, in fact, is the overall amplitude transmission coefficient T, i. e., $T = T_2$. From the expression of Eq. (11), one can see that T_2 is a function of T_1, so the whole transmission spectrum isn′t the simple overlapped consequence of the two transmission spectra produced by the two knot resonators.

2 Numerical simulations and discussions

Assuming the input light field $E_1 = 1$ and using Eq. (5), one can calculate the transmission spectrum of the microfiber double-knot resonator with a serial structure with respect to the wavelengths for different diameter ratios of the two knot rings. D_1 and D_2 are the diameters of MKR_1 and MKR_2 in Fig. 1, respectively. Numerical results are shown in Fig. 3, where, as an example, we set some other parameters to $k_1 = k_2 = 0.8$, $r_1 = r_2 = 0.1$, $d = 1\ \mu\mathrm{m}$, $D_1 = 500\ \mu\mathrm{m}$, $L_{1,2} = 1\,000\ \mu\mathrm{m}$, $n_1 = 1.45$ and $n_2 = 1$. From Fig. 3, one can see that when $D_2/D_1 = 1$, that is, the diameters of the two knot rings are equal, the two transmission spectra produced by the two knot rings overlap together completely. When $D_2/D_1 = 2, 3, 4, \cdots$, the transmission spectra of the two knot rings overlap together partly, which produces a series of narrow transmission peaks. With the increase of D_2/D_1, the transmission peaks become narrower and narrower. But the envelope of the whole transmission spectrum is overlapped completely with the transmission spectrum at $D_2/D_1 = 1$. The reason for this phenomenon is that the whole transmission spectrum of this structure is the overlapped result of the two transmission spectra produced by the single-ring MKR with a diameter of D_1 and the one with a diameter of D_2. According to the definition of the Free Spectral Range (FSR) of the resonator $\Delta\lambda_{\mathrm{FSR}} = \lambda^2/(n_{\mathrm{neff}} \cdot L)$, the FSR is in inverse proportion to the circumference of the resonator. Therefore, when $D_2/D_1 = 2, 3, 4, \cdots$, the FSR of the single-ring MKR with a diameter of D_2 is 1/2, 1/3, 1/4, ⋯, times that of the single-ring MKR with a diameter of D_1. When this two transmission spectra overlap together, the transmission spectrum of the single-ring MKR with a diameter of D_1 is corresponding to the envelope of the overlapped spectrum, while the transmission spectrum of the single-ring MKR with a diameter of D_2 is corresponding to the spectrum located in the envelope. Thus, with the increasing of D_2/D_1, under the case of the unchanged diameter D_1, the FSR of the spectrum located in the envelope will become smaller and smaller, while the envelope of the overlapped spectrum will keep constant. We believe that this structure is practical for a lot of applications, such as optical communication, optical sensing and optical filtering.

Analogously, assuming the input light field $E_1 = 1$ and using Eq. (11), one can calculate the transmission spectrum of the microfiber double-knot resonator with a parallel structure with respect to the wavelengths for different diameter ratios of the two knot rings. D_1 and D_2 are the diameters of MKR_1 and MKR_2 in Fig. 2, respectively. Numerical results are shown in Fig. 4, where, as an example, we set the parameters to $k_1=k_2=0.8$, $r_1=r_2=0.1$, $d=1$ μm, $D_1=500$ μm, $n_1=1.45$ and $n_2=1$. One can see that when $D_2/D_1=1,2,3,\cdots$, there will appear a narrow transmission dip per D_2/D_1 wide transmission peaks. In fact, these narrow transmission dips are quasi-Electromagnetically Induced Transparency (EIT) windows[30-32]. With the increase of D_2/D_1, they become narrower and narrower. The physical mechanism for this phenomenon can be explained as following. Considering only the first coupling (comparing with the first coupling, the transferred power occurred at the second, the third, ⋯ couplings becomes considerably small in the knot region of the MKR_1.), the microfiber double-knot resonator with a parallel structure is equivalent to a single-ring MKR with a circumference of $L_2=(D_2/D_1)\cdot L_1$ and a single-ring MKR with a circumference of $(L_1+L_2)=(D_2/D_1+1)\cdot L_1$. The whole transmission spectrum of the microfiber double-knot resonator with a parallel structure is the overlapped result of the transmission spectra of the two single-ring MKRs. When $D_2/D_1=1,2,3,\cdots$, the circumferences of the two single-ring MKRs increase, however, the FSRs of the two transmission spectra produced by them decrease correspondingly. Therefore, the FSR of the whole transmission spectrum reduces, which makes the transmission windows of the EIT-like become narrower and narrower. According to these characteristics, one can use these structures to fabricate miniature lasers, sensors, filters[33] and so on.



(a) $D_2/D_1=2$

(b) $D_2/D_1=3$

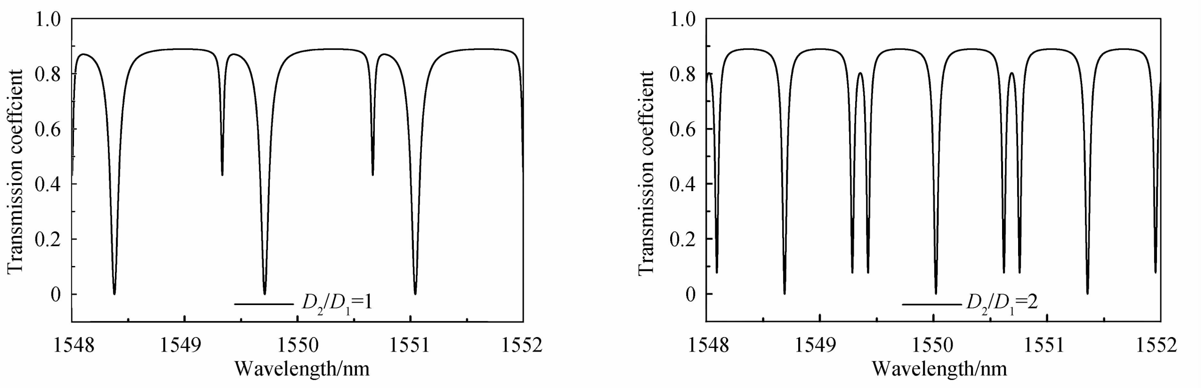
(c) $D_2/D_1=4$

(d) $D_2/D_1=2$

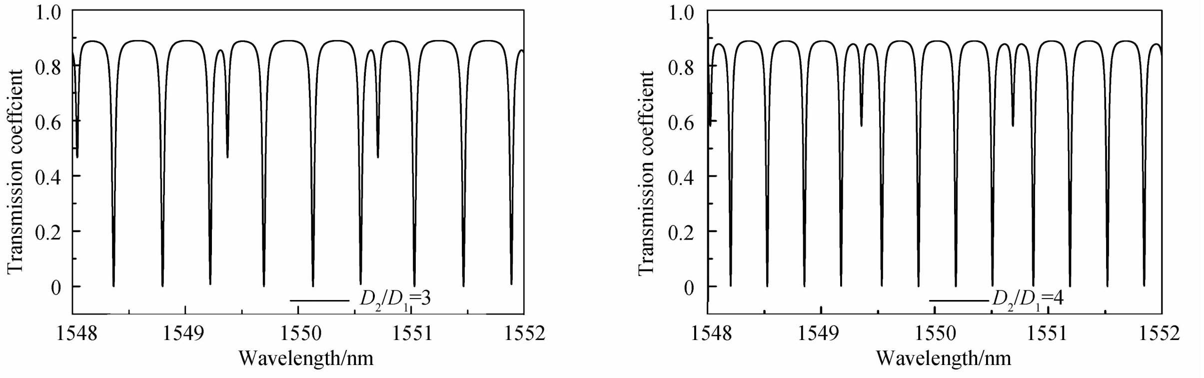
(e) $D_2/D_1=3$

(f) $D_2/D_1=4$

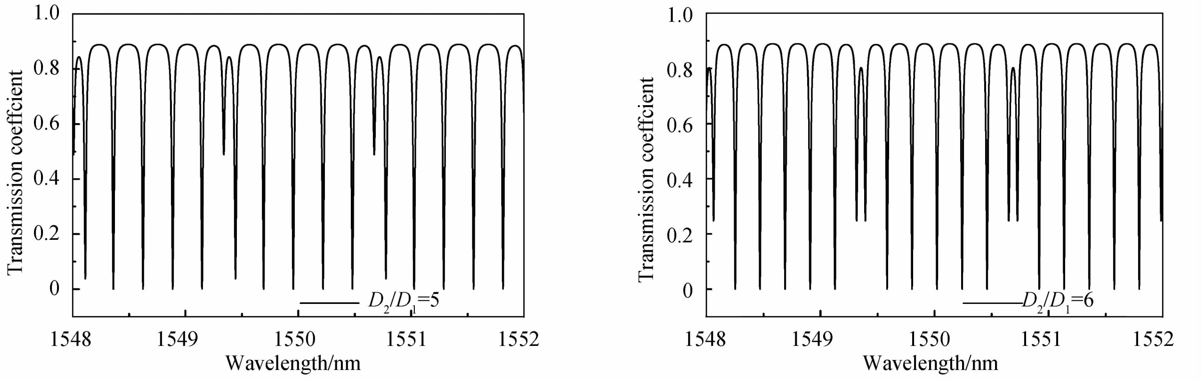
Fig. 3 Transmission spectra of the microfiber double-knot resonator with a parallel structure with a two-ring serial connection structure with respect to the varied wavelengths for different diameter ratios of the two knot rings. Other parameters are set to $k_1=k_2=0.8$, $r_1=r_2=0.1$, $d=1$ μm, $D_1=500$ μm, $L_{1,2}=1\ 000$ μm, $n_1=1.45$ and $n_2=1$



(a) D_2/D_1=1 (b) D_2/D_1=2



(c) D_2/D_1=3 (d) D_2/D_1=4



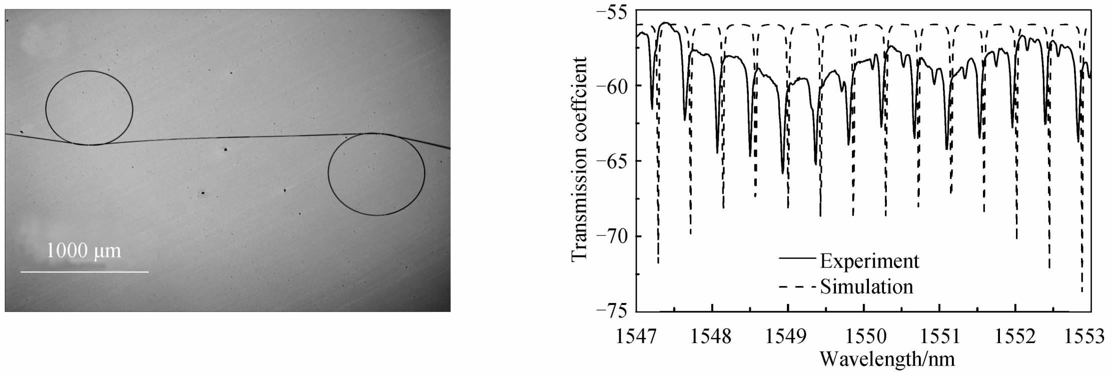
(e) D_2/D_1=5 (f) D_2/D_1=6

Fig. 4 Transmission spectra of the microfiber double-knot resonator with a parallel structure with a two-ring parallel connection structure with respect to the varied wavelengths for different diameter ratios of the two knot rings. Other parameters are set to $k_1=k_2=0.8$, $r_1=r_2=0.1$, $d=1$ μm, $D_1=500$ μm, $n_1=1.45$ and $n_2=1$

3 Experiment and result

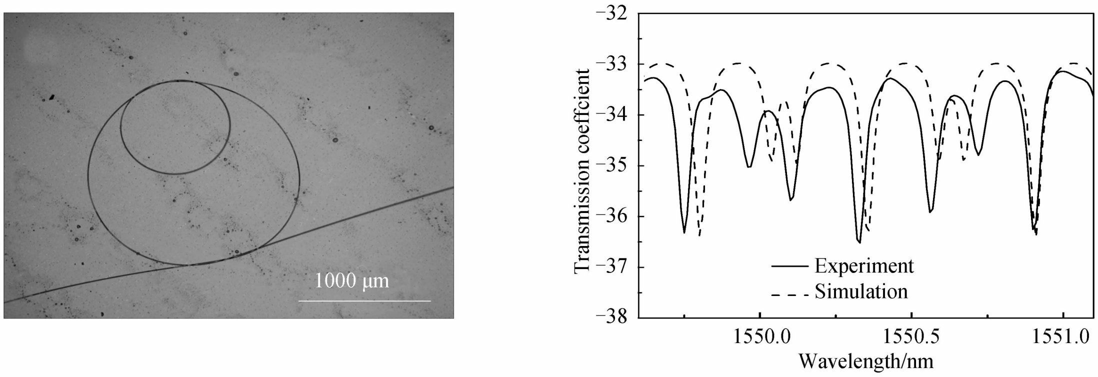
Using the method described in Ref. [20], we have fabricated the microfiber double-knot resonator with a serial structure for approximately equivalent diameters and that with a parallel structure for a diameter ratio of approximate 2. Fig. 5(a) shows an optical microscope image of the microfiber double-knot resonator with a serial structure. The diameter of the silica microfiber is about 2 μm, and the diameters of the small ring and the big ring are about 680 μm and 723 μm, respectively. The corresponding transmission spectra of this structure in theory and in experiment are shown in Fig. 5(b). Measured FSR $\Delta\lambda_{\mathrm{FSR}}$ and Full Width at Half-Maximum (FWHM) $\Delta\lambda_{\mathrm{FWHM}}$ are about 0.43 nm and 0.05 nm, respectively, with an extinction ratio of about 5 dB at the wavelength of around 1 550 nm. Obtained Q factor ($Q=\lambda/\Delta\lambda_{\mathrm{FWHM}}$) and finesse ($F=\Delta\lambda_{\mathrm{FSR}}/\Delta\lambda_{\mathrm{FWHM}}$) of the resonator are about 31 000 and 8.6, respectively. Fig. 5(c) shows an optical microscope image of the microfiber double-knot resonator with a parallel structure. The diameter of the silica microfiber is about 2 μm, and the diameters of the small ring and the big ring are about 788 μm and 1 605 μm, respectively. The corresponding transmission spectra of this structure in theory and in experiment are shown in Fig. 5(d). Measured FSR and FWHM are about 0.14 nm and 0.04 nm, respectively, with an extinction ratio of about

2 dB at the wavelength of around 1 550 nm. Obtained Q factor and finesse of the resonators are 38 750 and 3.5, respectively. It can be seen from Fig. 5(b) and Fig. 5(d) that the transmission spectra of these structures in theory and in experiment are approximately consistent, indicating that the theoretical analysis about these structures is considerably correct.



(a) A serial structure

(b) D_2/D_1=2



(c) A parallel structure

(d) Transmission spectra of (c)

Fig. 5 Optical microscope images of the fabricated microfiber double-knot resonator with a serial structure and that with a parallel structure, corresponding transmission spectra of these resonators

4 Conclusion

Based on the theory of ring resonators and that of directional couplers, microfiber double-knot resonator with a serial structure and that with a parallel structure are discussed, and the mathematic relationship between the output light fields and the input ones in these structures are deduced. Numerical simulations indicate that the spectral characteristics of these structures are significantly dependent on the diameter ratios of the two knot rings. In addition, a further analysis about the relationship between the transmission spectra and the diameter ratios of the microfiber multi-knot resonator with different structures is also investigated numerically. With the increase of the diameter ratio of the resonator, the FSR of the transmission spectrum becomes narrower and narrower, but there isn′t an obvious change rule. Experimentally, the microfiber double-knot resonator with a serial structure for approximately equivalent diameters and that with a parallel structure for a diameter ratio of approximate 2 have been successfully fabricated. The transmission spectra of these structures in experiment and in theory are approximately consistent, which indicates that the theoretical analysis is considerably correct. The microfiber double-knot resonator with different structures for a proper diameter ratio will have significantly potential applications in filters, miniature lasers, sensors and so on.

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