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并联结构微光纤双结谐振器中的慢光效应

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摘 要:为了研究基于微光纤的谐振器中的慢光效应,设计并制作了并联结构的微光纤双结谐振器.基于环形谐振器和方向耦合器理论,提出并联结构微光纤双结谐振器的理论模型,分析了该谐振器中光场传输和耦合的方向,推导了该谐振器中输出光场与输入光场之间的数学解析式和群延时表达式.通过数值模拟,给出了有关该谐振器的透射光谱和群延时,分析了群延时与透射光谱中谐振波长的对应关系.数值结果表明在该谐振器中,大的群延时能够在具有大消光比的谐振波长处产生.实验制作了一个并联结构的微光纤双结谐振器,测得的透射光谱与理论模拟相一致,验证了该谐振器理论分析的正确性.利用示波器上脉冲延时的方法,搭建了慢光延时测量系统,测得该谐振器中大约 75 ps 的群延时,远大于现有文献中的值.该谐振器可用于微纳光学的数据延时线、光学开关和光学存储等.

关键词:光纤光学;慢光;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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Slow-light Effect in Microfiber Double-knot Resonator with a Parallel Structure

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Abstract: In order to study the slow-light effect in the microfiber based resonator, a microfiber double-knot resonator with a parallel structure was designed and fabricated. Based on the theories of the ring resonator and the direction coupler, the theoretical model of the microfiber double-knot resonator with a parallel structure was proposed, the direction of the light-field propagation and coupling in the resonator was analyzed, the mathematic expression between the output light and the input one in the resonator was deduced, and the expression of the group delay time was also obtained. By numerical simulating method, the spectra of the transmission and the group delay time were given, the corresponding relationship between group delays and resonant wavelengths of the transmission spectrum in the resonator was analyzed. The numerical result indicates that a large group delay can be obtained at the resonant wavelength with a large extinction ratio in the resonator. In experimental, a microfiber double-knot resonator with a parallel structure was fabricated, the transmission spectrum of the fabricated resonator was well consistent with the theoretical simulation, indicating that the theoretical analysis is correct. Employing the pulse-delay method in the Oscilloscope, a measuring system of the slow-light delay in the resonator was set up. A group delay of about 75 ps in the fabricated resonator is achieved, which is larger

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than the reported value. The resonator could be beneficial to applicating in data delay lines, optical switches and optical memories, etc.

Key words: Fiber optics; Slow light; Optical fiber coupling; Fiber optic components; Optical fiber communication; Optical waveguides

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0 Introduction

In recent years, there has been an increasing interest in the development of slow-light technique, owning to its potential applications[1-4], such as data synchronization, tunable optical delay lines, all-optical switches, nonlinear optics, and quantum computing[5-6]. Different kinds of methods have been proposed and demonstrated theoretically or experimentally, they include Electromagnetically Induced Transparency (EIT)[2,7], Coherent Population Oscillations (CPO)[8-9], Stimulated Brillouin Scattering (SBS)[10-11], Stimulated Raman Scattering (SRS)[12-13], Optical Parametric Amplification (OPA)[14], Coupled-Resonator-Induced Transparency (CRIT)[15-16], photonic crystal structures[17-18], and so on. However, these works have respective limitations, e. g., extreme condition (extremely cold or hot gases) for EIT, large pulse width (ms) for CPO, narrow bandwidth (tens of MHz) and small temporal delay (1 bit period) for SBS, large bandwidth but small temporal delay (smaller than SBS) for SRS, dependent on single mode sources at very long wavelength (out of the 1.55-μm window) and relatively small temporal delay for OPA, highly compact size but likewise small temporal delay for CRIT, and tunable only by heating (not all-optical tunable) for photonic crystal-based resonance structures.

Recently, microfibers drawn from Single Mode Fibers (SMFs) have attracted considerably attention due to their large evanescent fields, tight optical confinement, controllable waveguide dispersion, and low-loss interconnection to other optical fibers and fiberized components[19]. Various structures of microfiber resonators, including loop, knot and coil, have been investigated[20-22] and extensively applied to optical filters[23], optical sensors[24], microfiber lasers[25], and slow light systems[26] owing to their easy fabrication, high Q factor, tunable free spectral range, high stability, high integration, compatibility with available communication systems, and low loss. However, to date, the slow-light behavior in the microfiber double-knot resonator with a parallel structure has not been investigated completely. In this paper, the slow-light effect in microfiber double-knot resonator with a parallel structure is investigated both theoretically and experimentally. The numerical result indicates that the large group delay can be obtained at the resonant wavelength with a large extinction ratio in the resonator. In experimental, a microfiber double-knot resonator with a parallel structure is fabricated. A group delay of about 75 ps in the fabricated resonator is achieved, which is larger than the reported value in the published paper.

1 Operational principle

The schematic diagram of the microfiber double-knot resonator with a parallel structure is shown in Fig. 1. It consists of two knot rings labeled as 1 and 2, which are realized by a microfiber. The smaller ring, MKR_2, is embedded into the larger one, MKR_1. The arrows indicate the light propagation and coupling directions within the rings. Combining the theory of ring resonators[27-30] with that of directional couplers[31-33], one can deduce the theory of the microfiber double-knot resonator with a parallel structure. Owing to the excellent diameter uniformity and surface smoothness, as well as the small diameter of the microfiber[34], the propagation and bending losses in the resonator can be ignored. 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

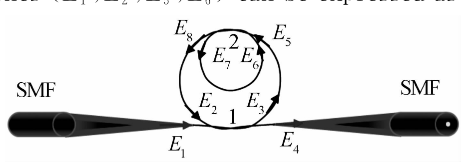

Fig. 1 Schematic diagram of the microfiber double-knot resonator with a parallel structure

$$\begin{bmatrix} E_3 \\ E_4 \\ E_7 \\ E_8 \end{bmatrix} = \begin{bmatrix} \sqrt{1-r_1} & 0 & 0 & 0 \\ 0 & \sqrt{1-r_1} & 0 & 0 \\ 0 & 0 & \sqrt{1-r_2} & 0 \\ 0 & 0 & 0 & \sqrt{1-r_2} \end{bmatrix} \cdot \begin{bmatrix} \sqrt{1-k_1} & \mathrm{j}\sqrt{k_1} & 0 & 0 \\ \mathrm{j}\sqrt{k_1} & \sqrt{1-k_1} & 0 & 0 \\ 0 & 0 & \sqrt{1-k_2} & \mathrm{j}\sqrt{k_2} \\ 0 & 0 & \mathrm{j}\sqrt{k_2} & \sqrt{1-k_2} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_5 \\ E_6 \end{bmatrix} \tag{1}$$

$$E_5 = E_3 \exp\left(\mathrm{j}\,\frac{1}{2}\beta L_1\right) \tag{2}$$

$$E_6 = E_7 \exp\left(\mathrm{j}\beta L_2\right) \tag{3}$$

$$E_5 = E_3 \exp\left(\mathrm{j}\,\frac{1}{2}\beta L_1\right) \tag{4}$$

where k_1 and k_2 are the coupling coefficients, r_1 and r_2

are the coupling loss coefficients, and L_1 and L_2 are the circumferences of $ring_1$ and $ring_2$, respectively. β is the propagation constant given by[35]

$$\beta=\frac{2\pi}{\lambda}+\frac{\gamma^2\lambda}{4\pi} \tag{5}$$

$$\gamma=\frac{2.246}{d}\exp\left(\frac{n_1^2+n_2^2}{8n_2^2}-\frac{n_1^2+n_2^2}{n_2^2(n_1^2-n_2^2)}\frac{\lambda^2}{(\pi d)^2}\right) \tag{6}$$

Here γ is the transversal component of the propagation constant, d is the diameter of the microfiber, λ is the free space wavelength, n_1 is the refractive index of the microfiber and n_2 is the refractive index of the ambient medium. The amplitude transmission coefficients of $ring_2$ and $ring_1$ can be obtained by

$$T_2=\frac{E_8}{E_5}=\frac{\mathrm{j}\sqrt{k_2(1-r_2)}+(1-r_2)\exp(\mathrm{j}\beta L_2)}{1-\mathrm{j}\sqrt{k_2(1-r_2)}\exp(\mathrm{j}\beta L_2)} \tag{7}$$

$$T_1=\frac{E_4}{E_1}=\frac{\mathrm{j}\sqrt{k_1(1-r_1)}+(1-r_1)T_2\exp(\mathrm{j}\beta L_1)}{1-\mathrm{j}\sqrt{k_1(1-r_1)}T_2\exp(\mathrm{j}\beta L_1)} \tag{8}$$

respectively. Note that T_1, in fact, is the overall amplitude transmission coefficient T, i. e., $T=T_1$. The phase of the transmission amplitude can be expressed as

$$\varphi_T=\mathrm{Im}(\ln(T)) \tag{9}$$

As the group delay is determined by the derivative of the phase of T with respect to the radiation angular frequency[36], it can be expressed as

$$\tau_g=\frac{\mathrm{d}\varphi_T}{\mathrm{d}\omega}=\frac{n_{\mathrm{eff}}}{c}\left(\frac{\mathrm{d}\varphi_T}{\mathrm{d}\beta}\right)=\frac{n_{\mathrm{eff}}}{c}\frac{\mathrm{d}\lambda}{\mathrm{d}\beta}\frac{\mathrm{d}\varphi_T}{\mathrm{d}\lambda}=\frac{n_{\mathrm{eff}}}{c}\frac{1}{-\frac{2\pi}{\lambda^2}+\frac{\gamma^2}{4\pi}-\frac{I\lambda^2\gamma^2}{\pi}}\frac{\mathrm{d}\varphi_T}{\mathrm{d}\lambda} \tag{10}$$

where c is the speed of light in vacuum, n_{eff} is the effective refractive index of the propagating mode and $I=(n_1{}^2+n_2{}^2)/[n_2{}^2(n_1{}^2-n_2{}^2)(\pi d)^2]$. Assuming an optical pulse propagates in this resonator, ϕ_T is modulated effectively, which leads to a sharp increase in $\mathrm{d}\phi_T/\mathrm{d}\omega$. As a result, the group delay increases greatly, meaning that there exists a huge decrease in the group velocity. This phenomenon is the so-called slow light. It should be pointed out that the positive/negative sign of the group time delay determined by the over-coupling/under-coupling state corresponds to the slow/fast light, respectively[37].

Based on the theoretical model mentioned above, we simulate the dependence of the transmission and the group delay of the microfiber double-knot resonator with a parallel structure on the wavelengths. Referring to the given parameters in Ref. [38], the parameters of the structure are chosen to be $k_1=k_2=0.8$, $r_1=r_2=0.1$, $d=2$ μm, $D_1=1\ 000$ μm, $D_2=500$ μm, $n_{\mathrm{eff}}=n_1=1.45$ and $n_2=1$. D_1 and D_2 are the diameters of the MKR_1 and the MKR_2 in Fig. 1, respectively. The simulation results of them are shown in Fig. 2. It can be seen that, a series of narrow transmission dips, which are the transparency windows of the EIT-like[15,39-40], are produced between two wide transmission peaks. The extinction ratio of the resonant wavelength between two wide transmission peaks is larger than that located around the transparency window of the EIT-like. Correspondingly, the group delay at the resonant wavelength with a larger extinction ratio is enhanced considerably, which might benefit the resonator to the applications in data delay lines, optical buffers, optical memories, etc.

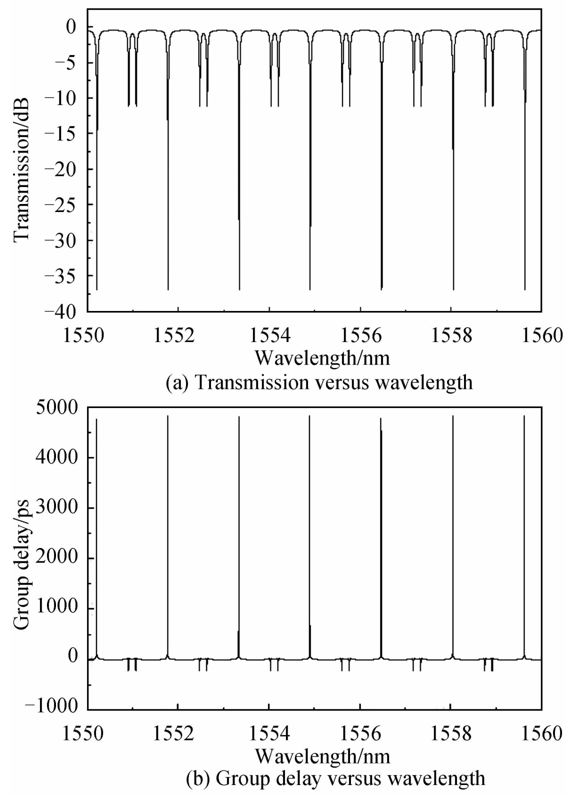

Fig. 2 Dependence of the transmission and the group delay in the microfiber double-knot resonator with a parallel structure on the wavelengths

2 Device fabrication and spectral characterization

The microfiber employed to fabricate the double-knot resonator with a parallel structure is drawn from a standard SMF using the electro-heated taper-drawing technique[41]. The temperature of the microfiber heater (MHI FIBHEAT200, USA) with a dimension of 40 mm×40 mm×50 mm can be controlled accurately from room temperature to 1 900 centi-degrees by managing its current from 0 to 75 A. The drawing speed of the heated fiber can be precisely regulated in the range between 30 μm/s and 50 mm/s. Fiber-drawing directions can be controlled by a computer, too. Using this technique, we can draw a microfiber with a length of tens of centimeters and a minimum diameter of several hundred nanometers. Each end of the microfiber is connected with a SMF through the tapered region. After fabricating a microfiber with a length of about 28 cm and a minimum diameter of about 2 μm, we firstly assembled a single-ring MKR with a diameter of several hundred micrometers using the method proposed by Xiao et al.[42], Then, using the same method, we fabricated a bigger single-ring MKR and made the small MKR embed into the big one. By drawing the SMF of one end of the microfiber slowly, the diameter of the big ring can be reduced gradually. The fabricated microfiber double-knot resonator with a parallel structure using this method can avoid the coupling problem produced by the interacted two microfibers via van der Waals and electrostatic forces between them[43], which makes this structure have a higher mechanical stability and a smaller propagation loss. Fig. 3(a) shows an optical microscope image of the fabricated microfiber double-knot resonator with a parallel structure. Fig. 3(b) gives the optical microscope

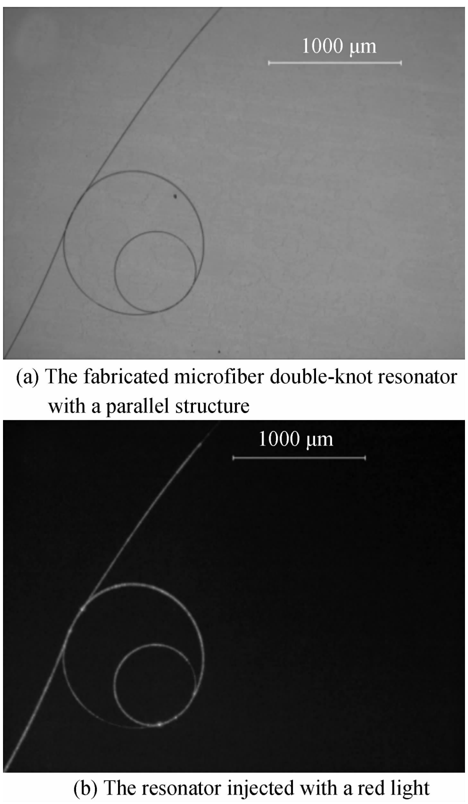

Fig. 3 Optical microscope images of the fabricated microfiber double-knot resonator with a parallel structure and the resonator injected with a red light

image of the resonator injected with a red light. The diameters of the small ring and the big ring are about 596 μm and 1 081 μm, respectively. Since the two ends of the fabricated device are standard SMFs, it can be directly connected to optical fiber systems. Its transmission property can be measured by an Optical Spectrum Analyzer (OSA). After tuning the extinction ratio of the transmission spectrum by carefully adjusting the coupling regions of the two knot rings, we put the resonator onto the surface of the MgF_2 crystal (with a reflective index of 1.37) so that the resonator is in a stable coupling state. The obtained spectral transmission curve is shown in Fig. 4. In addition, employing the parametric values of the fabricated resonator, we simulate the transmission spectrum indicated by the black dash line in Fig. 4. The obtained coupling coefficients k_1 and k_2 are about 0.8 and 0.4, respectively.

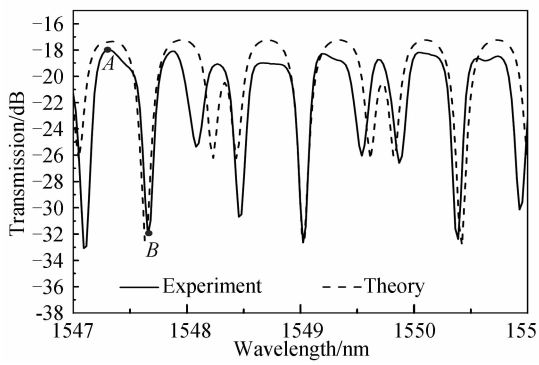

Fig. 4 Transmission spectrum of the fabricated microfiber double-knot resonator with a parallel structure

3 Experimental results and discussion

The schematic diagram of the group-delay measurement system is shown in Fig. 5. The light from the Tunable Wavelength Laser (TWL, tunable frequency precision: 0.1 GHz, tunable wavelength range: 1 528.77 nm-1 563.86 nm) experiences the polarization controller (PC) before passing through the Electro-Optic Modulator (EOM, insertion loss: 3.3 dB, Bandwidth: 11 GHz). The bias voltage of the EOM is provided by the Direct Voltage (DV). The radio-frequency signal from the Data Timing Generator (DTG 5 334, 3.35 Gb/s bit rates) is carried onto the continuous laser by means of the EOM, which is used to generate the Nonreturn-to-Zero (NRZ) signal. The light pulses after being amplified by the Erbium-Doped Fiber Amplifier (EDFA) pass through the Tunable Optical Filter (TOF, 3 dB bandwidth: 1.5 nm) so that the noise signals produced by the EDFA can be reduced. Furthermore, 95% of the light energy from the coupler is injected into the microfiber double-knot resonator with a parallel structure and then sent into the Oscilloscope (OSC, bandwidth: 25 GHz, sample rate: 80 GS/s) by means of the photodetector (PD, bandwidth: $>$ 5 GHz, rise and fall time: $<$ 70 ps, wavelength range: 900 nm-1 650 nm), labeled by PD_1. The other 5% of the light energy from the coupler, which is used to generate a synchronized triggered signal, is also sent into the OSC by means of the PD_2 after passing through the Variable Optical Attenuation (VOA).

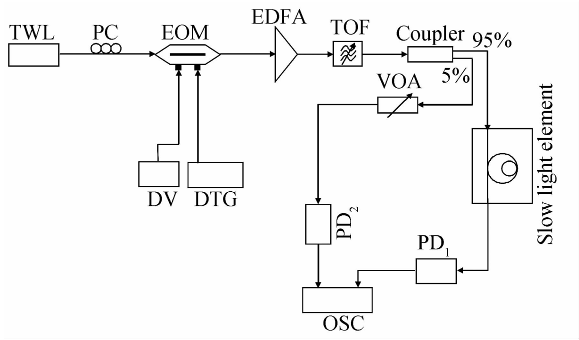

Fig. 5 Experimental setup used for the measurement of group delay in the microfiber double-knot resonator with a parallel structure

In experiment, a radio-frequency signal with a data rate of 3.35 Gb/s from the DTG (the maximum signal data rate is 3.35 Gb/s) is carried onto the continuous laser by means of the EOM, so that the continuous laser is converted to the pulse laser. In order to observe the pulse delay, firstly, we tune the wavelength of the TWL to 1 547.30 nm so that the resonator is located at the off-resonance state, which is corresponding to the black dot A in Fig. 4. The normalized output pulse recorded in the OSC is shown in Fig. 6. Then, we tune the wavelength of the TWL to 1 547.67 nm, in this case, the state of the resonator is converted to the on resonance, which is corresponding to the black dot B in Fig. 4. The normalized output pulse recorded in the OSC is also shown in Fig. 6. It is easy to see that there is a relative pulse delay when the light pulse is tuned from the off-resonance state to the on-resonance state, and the relative pulse delay is about 75 ps, which is larger than the value in Ref. [37].

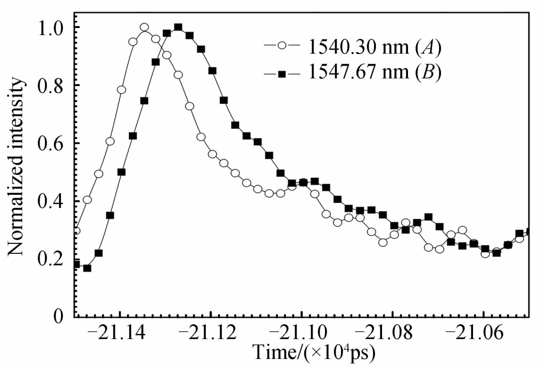

Fig. 6 Normalized output pulses of the microfiber double-knot resonator with a parallel structure recorded in the OSC

4 Conclusion

Based on the theoretical model of the microfiber double-knot resonator with a parallel structure, the transmission spectrum and the group delay of the resonator are investigated theoretically. The numerical result indicates that the large group delay can be obtained at the resonant wavelength with a large extinction ratio in the resonator. In order to demonstrate this phenomenon experimentally, the microfiber double-knot resonator with a parallel structure has been fabricated successfully. The transmission spectrum of the fabricated resonator is well consistent with the numerical simulation. A group delay of about 75 ps in the fabricated resonator is achieved, which could benefit the resonator to have potential applications in data delay lines, optical buffers, optical memories, etc.

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