Theoretical Analysis of Resonant Mode Splitting in A Single Microfiber Knot-Ring Resonator

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***Abstract*—In this paper, we established a theoretical model and made an analysis of single knot-ring resonator by polarization transmission matrix. The theoretical analysis shows that two orthogonal polarization modes of knot-ring, which are originally resonant at the same wavelength, will be split into two resonant modes at two different wavelengths. The mode splitting owes to the twisted coupler of the knot-ring, which makes these two orthogonal polarization modes couple each other. This results can provide a novel method to implement coupled-resonator-induced transparency in a single knot-ring.**

Keywords—microfiber;resonator;knot-ring;coupled-resonator-induced transparency;

I. INTRODUCTION

Optical microfibers have been intriguing due to its strong confinement of light in the micro or nano scale[2-5], leading to enhancement of the interaction with material and the sensitivity to its environment. Of all devices based on microfiber, the ring-like resonator is most intriguing, Recently, a simple and low-cost method are reported to fabricate optical resonator, i.e. knot-ring resonator by a single microfiber[2]. Many devices based on the knot-ring resonator are also reported, such as sensors[6,7], a lasers[8]，an all optical tunable filter[9]. For all these devices, the resonant mode of the knot-ring is vital. However, it is not reported before that the resonant mode splitting can be induced by the twist coupler of a knot-ring. In this paper, the theoretical model of a knot-ring is established by transmission matrix method, and the resonant mode splitting due to coupling of two polarization modes is analyzed.

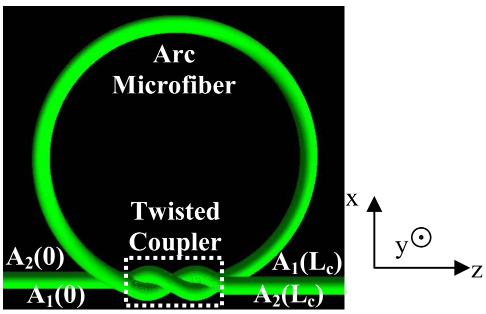

Fig. 1. Shematic of theoretical model of a knot-ring resonator constructed by a single micro-fiber

II. THEORETICAL MODEL OF A KNOT-RING RESONATOR

In this section, the theoretical model of a knot-ring resonator is established. As shown in Fig.1, this knot-ring resonator is usually composed of two parts, one isa twisted coupler and other an arc segment of micro-fiber.

According to the coupling mode theory of K. Morishita[10] the output E-field components [$a_{ix'}$, $a_{iy'}$] in rotated coordinates can be represented by the input [a_{ix}, a_{iy}] in laboratorial coordinates for the twisted coupler.

$$\begin{bmatrix} a_{1x'}(L_c) \\ a_{1y'}(L_c) \\ a_{2x'}(L_c) \\ a_{2y'}(L_c) \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ -t_{12} & t_{22} & -t_{14} & t_{24} \\ t_{13} & t_{14} & t_{11} & t_{12} \\ -t_{14} & t_{24} & -t_{12} & t_{22} \end{bmatrix} \cdot \begin{bmatrix} a_{1x}(0) \\ a_{1y}(0) \\ a_{2x}(0) \\ a_{2y}(0) \end{bmatrix} \exp(-i\beta L_c), \quad (1)$$

On the other hand, the transmission Jones matrix through the arc microfiber in knot-ring can be given by,

$$\mathbf{A_2}(0) = \alpha \exp(-i\beta L_r) \cdot \mathbf{A}_1(L_c), \quad (2)$$

where α is total loss coefficient after a circular propagation, and L_r is length of the arc microfiber. As shown in Fig.1, $\mathbf{A}_1(L_c)$= [$a_{1x}(L_c)$, $a_{1y}(L_c)$] and $\mathbf{A}_2(0)$=[$a_{1x}(0)$, $a_{1y}(0)$] are respectively the input and the output E-field amplitudes of the twisted coupler of the knot-ring. The propagation constant of the arc microfiber $\beta=2\pi n_{eff}/\lambda$.

By rewriting the Eq.(1) in sub-matrix form and substituting Eq.(2) in it, the transmission equation of knot-ring resonator can be obtained in matrix form,

$$\mathbf{A_2(L_c)} = \mathbf{T} \cdot \mathbf{A_1(0)}, \quad (3)$$

where **T** is the transmission matrix of the knot-ring,

$$T_{xx} = T_{yy}, \quad T_{xy} = -T_{yx}. \quad (4)$$

During the above deduction, the rotational transform of E-field components was done from rotated coordinates to laboratorial coordinates.

III. RESULTS AND DISCUSSIONS

In the below, a practical case is considered that the total twisting angle θ is not exactly equal to 2π, and can be written as θ=2π+δθ. In this case, a knot-ring has a radius of a=60μm, $L_R=2\pi a$, effective refractive index n_{eff}=1.4, and circular loss coefficient α=0.98, and the coupling coefficient of the twisted coupler is of κ=0.9799. The transmissions t_{xy} and t_{xx} are deduced by using transmission matrix **T** in Eq.(3) and Eq.(4) when the input E_x-field $\mathbf{A}_1(0)=[1,0]$ is launched without E_y-field. The transmission spectrum of t_{xx} and t_{yx} for the knot-ring can be obtained, which are shown in Fig.2 and Fig.3 respectively.

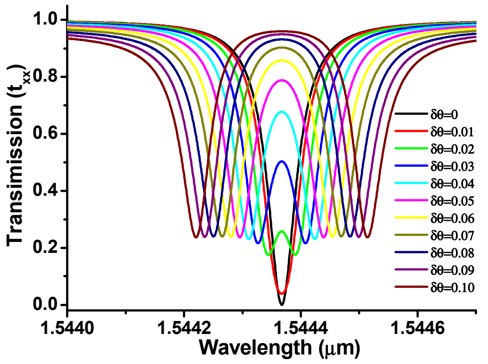

Fig. 2. Transmission spectrums t_{xx} of the knot-ring under different values of δθ , where t_{xx} denotes the normalized transmission to include only x polarization mode.

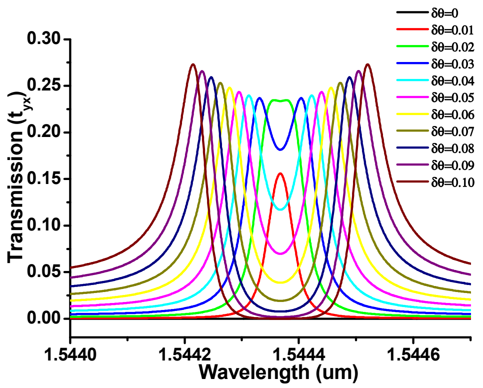

Fig. 3. Transmission spectrums t_{yx} of the knot-ring under different values of δθ , where t_{yx} denotes the normalized transmission to y polarization mode.

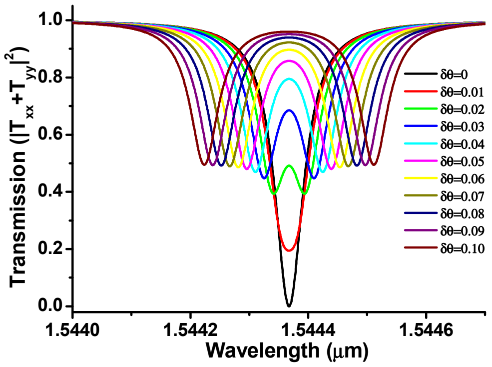

Fig. 4. Total transmission spectrums $|T_{xx} + T_{yx}|^2$ of the knot-ring under different values of δθ , where $|T_{xx} + T_{yx}|^2$ denotes the total normalized transmission contributed both by x and y polarization field.

Both Fig.2 and Fig.3 show that the deviation δθ of twist angle from 2π leads to the coupling between x and y polarization resonant mode in the knot-ring, and thus resonant mode splitting which is analogous to the mode splitting induced by two coupled resonators[11], i.e. coupled-resonator-induced transparency. Fig. 3 also shows that transmission of the E_y-field without initial energy reaches the maximum at the resonant wavelength. This separation of the two split modes can be tuned by δθ. All these twisting angles are in radian unit. It is important to notice that an evident resonant mode splitting can be observed only when δθ is large enough. In this case, δθ should not be less than 0.02rad as shown in Fig.2. This large δθ can be achieved in practical experiment by rotating the knot-ring around the microfiber that constitutes it.

The total transmission spectrum $|T_{xx} + T_{yx}|^2$ through the knot-ring, i.e. the spectrum measured by optical spectrum analyzer, are shown in Fig.5. It shows that the absorption at resonant wavelength with mode splitting, i.e. δθ≠0, becomes shallower than that with polarization mode coupling, i.e. δθ=0. It implies that the twist angle θ of the knot ring is also an essential factor that contributes to deterioration of the resonance.

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