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Ultra-small microring resonator based on sub-micrometer fiber*

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The transfer function of the microring resonator is deduced, and the effects of the normalized loss, coupling coefficient and surrounding media on the resonance performance are investigated thoroughly. Utilizing the improved fused tapering technique and ingenious self-coiling coupling method, a high-quality microring resonator (radius of about 500 μm) with larger extinction ratio (>10 dB) and sharper resonance is designed and fabricated by a segment of continuous sub-micrometer fiber. The microring resonator constructed in this way demonstrates extremely small connection loss with communication fiber in contrast to the planar waveguide technology.

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Microring resonators have attracted considerable attention in recent years for their potential applications as novel optical components, such as all-optical wavelength converters[1], photodetector[2], lasers[3] and sensors[4]. Since microring resonators are usually made by planar waveguide technology[5], device chips need to be fiber pigtailed before they can be used in practical applications. Although the fiber-to-chip coupling loss as low as 0.5 dB has been reported using waveguide mode converters, the fiber alignment and attachment still add the cost of the device. In order to solve problems above, Sherwood et al[6] has used a side-polished optical fiber as an excitation source to couple light into and out of the polymer resonator, and Cristina et al[7] has fabricated a silicon microring resonator on optical fiber facet. But the mismatch between input/output fiber and polymer/Si resonator reduces the coupling efficiency only to ~20%, which deteriorates the performance of the device seriously.

In this letter, utilizing the improved fused taper technique and ingenious self-coiling coupling method, a high-quality all-fiber microring resonator is designed and fabricated by sub-micrometer fiber. Because the micoring resonator is made by a segment of continuous optical fiber, the device is expected to improve the coupling efficiency and to avoid many problems associated with the fiber-to-chip connection.

Fig.1 illustrates the configuration of a ring resonator. According to the theories of directional coupler and resonator, the electric fields inside the resonator and input/output waveguides can be expressed in matrix form:

$$\begin{bmatrix} E_2 \\ E_2' \end{bmatrix} = \mathrm{e}^{\mathrm{j}\beta l} \begin{bmatrix} \mathrm{j}\sin(cl) & \cos(cl) \\ \cos(cl) & \mathrm{j}\sin(cl) \end{bmatrix} \begin{bmatrix} E_1 \\ E_1' \end{bmatrix}, \tag{1}$$

where c and l are the coupling coefficient and the coupling length of directional coupler, respectively.

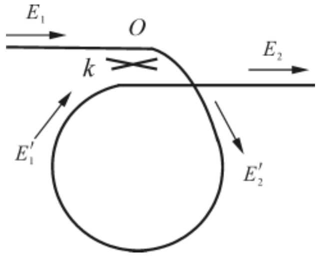

Fig.1 Configuration of a ring resonator

Define the normalized transfer coefficient and the normalized coupling coefficient as $t=\mathrm{e}^{\mathrm{j}\beta l}\cos(cl)$ and $k=\mathrm{e}^{\mathrm{j}\beta l}\sin(cl)$, respectively, and supplement Eq.(1) by the following condition:

$$E_1' = \tau E_2' \cdot \exp(\mathrm{j}\phi) \ . \tag{2}$$

The amplitude transfer function of the ring resonator can be obtained as:

$$|T| = \left|\frac{E_2}{E_1}\right|^2 = \frac{k^2 + 2k\tau\sin\phi + \tau^2}{1 + 2k\tau\sin\phi + k^2\tau^2} \ , \tag{3}$$

where $\phi = \frac{2\pi}{\lambda} n \cdot 2\pi R$ is the phase shift for one roundtrip along the resonator, where R and n are the resonator radius and

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refractive index, respectively. And τ is the normalized loss of the resonator, which is expressed as:

$$\tau=\exp(-\alpha\cdot 2\pi R)\ , \qquad (4)$$

where α is the loss coefficient of the ring waveguide.

In Fig.2, the lossless ($\tau=1$) all-pass resonator is usually used as a phase adjustor, such as Mach-Zehnder interferometer[8]. If the loss is introduced, the resonator will demonstrate periodic resonance at some particular wavelengths. Especially, when the normalized loss matches with the normalized coupling coefficient ($\tau=k$), the resonant output can reach zero and perfect resonance characteristics are exhibited (see the black solid line in Fig.2). On the other hand, as the loss increasing, the transmission power at non-resonant wavelengths decreases synchronously, which results in the device unsuitable for many applications. Therefore, the loss in the resonator should match with the coupling coefficient and should be made as low as possible.

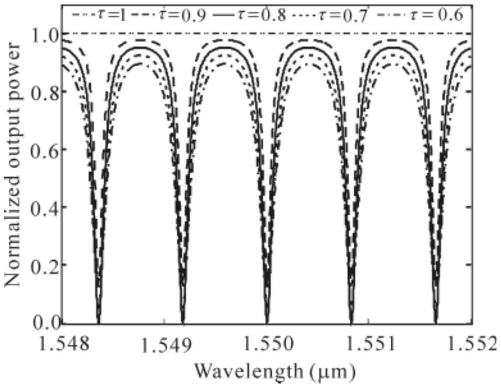

Fig.2 Influence of the normalized loss on transmission spectra of the ring resonator with coupling coefficient of k=0.8

Before fabricating an all-fiber ring resonator, bending characteristics of the optical fiber are investigated. According to Ref.[9], the bendloss coefficient of the optical fiber is calculated by the asymptotic formula:

$$\alpha=\frac{1}{2}\left(\frac{\pi}{r_{\mathrm{co}}R}\right)^{1/2}\frac{U^2}{V^2W^{3/2}K_1^2(W)}\exp\left(-\frac{4RW^3\varDelta}{3r_{\mathrm{co}}V^2}\right), \qquad (5)$$

where r_{co} is the fiber core radius, $\varDelta=\frac{n_{\mathrm{co}}^2-n_{\mathrm{cl}}^2}{2n_{\mathrm{co}}^2}$ is the relative refractive index, K_1 is the modified Bessel function of the second kind, and the normalized parameters U, W, V are defined as $U=(k_0^2n_{\mathrm{co}}^2-\beta^2)^{1/2}\cdot r_{\mathrm{co}}$, $W=(\beta^2-k_0^2n_{\mathrm{cl}}^2)^{1/2}\cdot r_{\mathrm{co}}$, $V=k_0(n_{\mathrm{co}}^2-n_{\mathrm{cl}}^2)^{1/2}\cdot r_{\mathrm{co}}$, respectively.

Results in Fig.3 show that for the conventional single-mode fiber, the minimum ring radius should be or more than 3 cm ($R\geqslant 10^{3.5}\cdot r_{\mathrm{co}}$) to avoid inducing too much loss. However, the free spectral range (*FSR*) of the resonator is approximately in inverse proportion to the ring radius as shown in Fig.4. To meet the requirement of high-speed optical communication, the ring resonator with larger *FSR* ($\geqslant$ 0.4 nm) and smaller size (microring) should be constructed.

According to Eq.(5), in order to reduce the resonator size without deteriorating loss, the fiber with smaller radius should be employed. In our experiment, a sub-micrometer fiber is fabricated by the improved fused tapering technique. In addition,

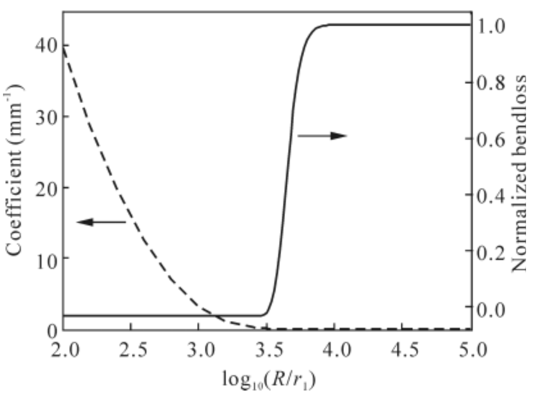

Fig.3 Bendloss characteristics of the conventional single-mode optical fiber

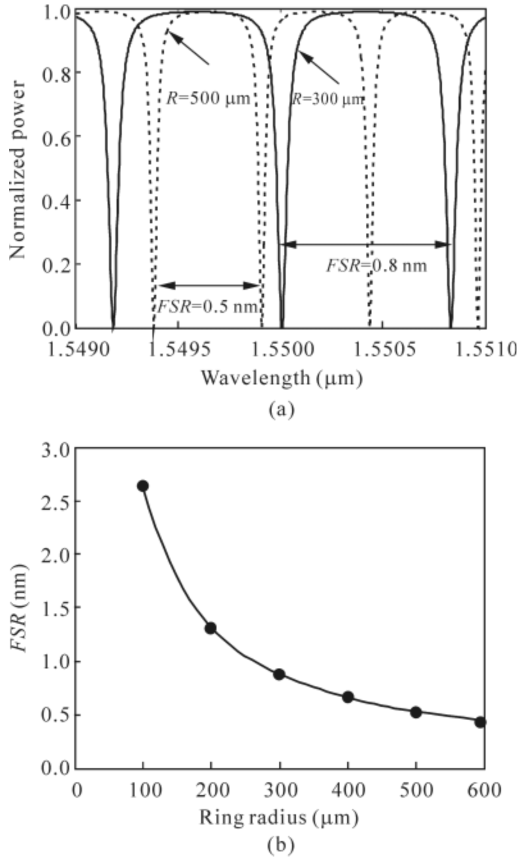

Fig.4(a) Definition of free spectral range; (b) Relationship between *FSR* and ring radius

the slowness adiabatic condition is maintained during the tapering process, otherwise the scattering loss between the guide mode and the local cladding modes will be excited and the uniformity in the biconical waist will be worsen.

Then, utilizing the ingenious self-coiling coupling method, a 500 μm-radius microring resonator is constructed by the sub-micrometer fiber. Fig.5 gives the microscope image of the microring resonator. In order to obtain good resonance performance, the normalized coupling coefficient is regulated by investigating the influence of the surrounding medium on the normalized coupling coefficient and the normalized loss. As can be seen from Fig.6, matching can be achieved by imbedding the fabricated microring resonator into the medium with refractive index of ~1.33. The transmission spectral response of the imbedded all-fiber microring resonator is measured by the broadband EDFA light source and ANDO AQ6317C optical spectrum analyzer with a resolution of 0.02 nm. Experimental result in Fig.7 is in good agreement with the numerical calculation and demonstrates much higher extinction ratio (>10 dB) and sharper resonant characteristic compared with the reported results in Ref.[6] (Fig.4) and Ref.[10] (Fig.9). Although there are unfavorable ripples, they can be eliminated by encapsulating the device in the future.

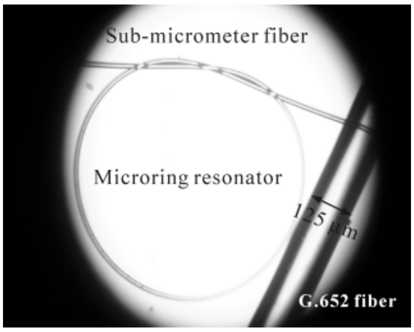

Fig.5 Microscope image of the fabricated microring resonator

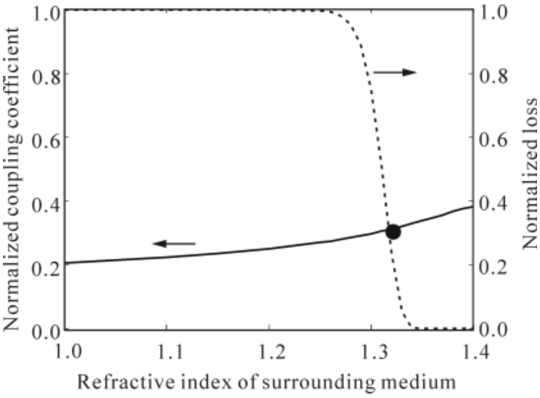

Fig.6 Influence of surrounding medium on the normalized coupling coefficient and normalized loss

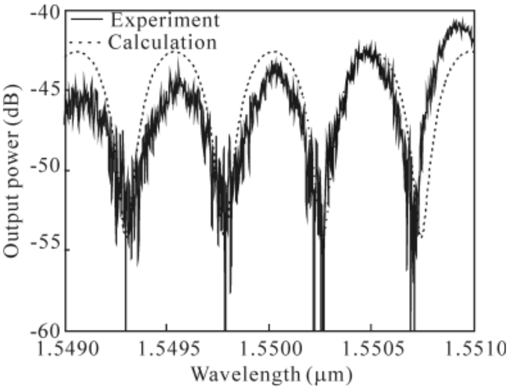

Fig.7 Transmission spectra of the fabricated microring resonator

We design and fabricate a 500 μm-radius all-fiber microring resonator by the improved fused tapering technique and ingenious self-coiling method. Experiment results demonstrate much higher extinction ratio and sharper resonance performance. This compact, low-loss all-fiber microring resonator is expected to find great potential for future optical communications and sensing systems.

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