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All-fibre micro-ring resonator based on tapered microfibre*

Dong Xiao-Wei(董小伟)†, Lu Shao-Hua(鲁韶华),
Feng Su-Chun(冯素春), Xu Ou(许 鸥), and Jian Shui-Sheng(简水生)

State Key Laboratory of All Optical Network & Advanced Telecommunication Network, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, *China*

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In this paper, bendloss characteristics of an optical fibre are investigated in detail, and the results show that the resonator with a smaller ring radius, wider free spectrum range (FSR), higher fineness (f) and quality-factor (Q) can be achieved by using microfibres. Based on the improved fused taper technique, a high-quality microfibre with 5 μm radius has been fabricated, and an all-fibre micro-ring resonator with a radius of only 500 μm is realized using self-coiling coupling method. The good-resonant characteristic makes the all-fibre device be expected to avoid bendloss and connection loss associated with planar waveguide integration.

Keywords: all-fibre device, micro-ring resonator, microfibre, fused taper
PACC: 4281W, 4281

1. Introduction

Ring resonators have attracted considerable attention for their potential applications, such as optical filters,[1] switches,[2] laser[3] and sensor.[4] Based on the improved planar waveguide technology, ring resonators with radius less than 10 μm have been achieved, which make device integration density increase significantly ($> 10^5/\mathrm{cm}^2$).[5] But for ring resonators made in this way, bending loss and chip-to-fibre coupling loss must be reduced before they can be employed in the practical communication system. In recent years, many workers have explored the side-polished[6] or tapered[7] optical fibres to couple light into and out of the resonator. These methods have the advantage that the excitation sources can be made from optical fibres and thus are convenient to use. But due to the differences in structures and materials, coupling efficiency between the input/output optical fibre and resonator is very low (only ∼20%), and as a result, device performance deteriorates badly.

In this paper, bendloss characteristics of optical fibres are investigated and an all-fibre micro-ring resonator is fabricated to avoid many problems associated with planar waveguide integration.

2. Theory background

Figure 1 illustrates two general configurations of ring resonator. Their properties are equivalent if the normalized coupling coefficient k in (a) and $1-k$ in (b) are interchanged.[8]

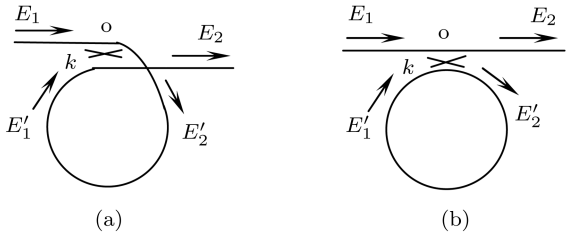


Fig.1. Two equivalent configurations of a ring resonator.

According to the theories of directional coupler and resonator, amplitude transfer function of the ring resonator in Fig.1(a) can be expressed as

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

where $k = \mathrm{e}^{\mathrm{j}\beta l}\sin(cl)$ is the normalized coupling coefficient(c, l, β are respectively coupling coefficient,

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†Corresponding author. E-mail: way7803@163.com

coupling length and propagation constant in the coupling region); $\tau = \exp(-\alpha \cdot 2\pi R)$ and $\phi = \beta \cdot 2\pi R$ are respectively the normalized loss and phase for one roundtrip along the resonator; R and α are respectively the ring radius and bendloss coefficient.

Figure 2 shows the spectral responses of ring resonator with different normalized losses. It can be seen that the output power remains unchanged for $\tau = 1$. This type of lossless all-pass resonator is usually used as phase adjustor to enhance the performance of other devices, such as Mach–Zehnder interferometer.[9] However, the resonator itself can demonstrate very good wavelength-dependent characteristics if proper ring loss is introduced. The transmitted output can even reduce to zero and achieve notch filtering response at some particular resonant wavelengths by matching the normalized loss τ with the normalized coupling coefficient k.

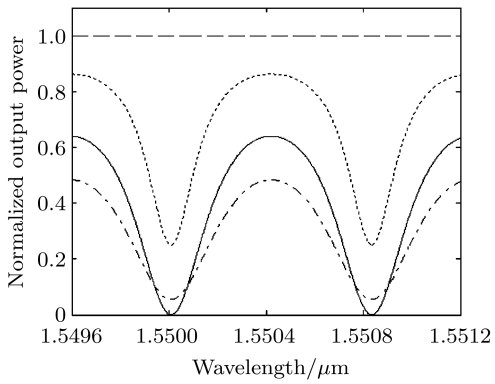


Fig.2. Influences of the normalized loss on the spectral responses of the resonator ($k = 0.5$) for different τ. $\tau = 1$ (dashed), $\tau = 0.8$ (dotted), $\tau = 0.5$ (solid), $\tau = 0.3$ (dot-dashed).

Free spectral range (FSR), fineness (f) and qualify-factor (Q) are three most important parameters for ring resonator, which are defined as[10]

$$\mathrm{FSR} = \lambda_{m+1} - \lambda_m \approx \frac{\lambda^2}{2\pi n_{\mathrm{eff}} R}, \tag{2}$$

$$f = \frac{\mathrm{FSR}}{\Delta\lambda_{\mathrm{FWHM}}} \approx \frac{1}{\alpha R}, \tag{3}$$

$$Q = \frac{\lambda_m}{\Delta\lambda_{\mathrm{FWHM}}} \approx \frac{2\pi n_{\mathrm{eff}}}{\alpha\lambda_m}, \tag{4}$$

here n_{eff} is the effective index, λ_m and $\Delta\lambda_{\mathrm{FWHM}}$ are the centre wavelength and the full bandwidth at half maximum for the mth resonant response, respectively.

From formulas (2)–(4), it can be seen that the resonator with a smaller radius and a lower bendloss should be employed in order to enhance FSR, f and Q-factor. But bendloss increases exponentially as ring radius decreases; and loss coefficient α can be calculated by the asymptotic formula[11]

$$\alpha = \frac{1}{2}\left(\frac{\pi}{r_1 R}\right)^{1/2} \frac{U^2}{V^2 W^{3/2} K_1^2(W)} \times \exp\left(-\frac{4}{3}\frac{R}{r_1}\frac{W^3 \Delta}{V^2}\right), \tag{5}$$

where r_1 is core radius; $\Delta = \dfrac{n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2}{2n_{\mathrm{co}}^2}$ is the relative refractive index; the normalized constants U, W, V are defined as: $U = \left(k_0^2 n_{\mathrm{co}}^2 - \beta^2\right)^{1/2} r_1$, $W = \left(\beta^2 - k_0^2 n_{\mathrm{cl}}^2\right)^{1/2} r_1$ and $V = k_0 \left(n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2\right)^{1/2} r_1$.

Figure 3 shows the bendloss characteristic of conventional single-mode optical fibre with a radius of 62.5 μm. It is shown that ring radius $R \geq 10^{3.6} r_1$ should be satisfied to avoid inducing too much loss. This means that the achievable minimum resonator will be larger than 3 cm if the conventional single-mode optical fibre is used; and as a result, FSR is too small (only 1 GHz) to meet the requirement of high-speed optical communication. In order to reduce resonator size without deteriorating device performance, we think that the fibre with a thinner radius (called microfibre) should be used.

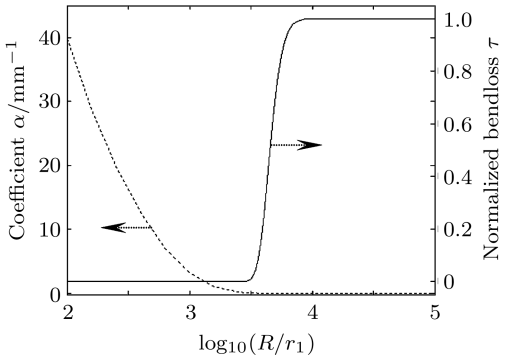


Fig.3. Bendloss characteristic of the conventional single-mode fibre.

3. Fabrication of all-fibre micro-ring resonator

By drawing conventional single-mode fibre and using its biconical waist as microfibre, the problem of connection loss can be solved naturally. During the tapering process, the core and cladding decrease in the same proportion. Defining taper ratio

as $D = \dfrac{r_{\mathrm{q}}}{r_{\mathrm{h}}}$ (r_{q} and r_{h} are the waist radii before and after fibre is drawn), influences of taper ratio on the effective index and power distribution of the guide mode are analysed. As can be seen from Fig.4, when the taper ratio is larger than 2.3 (radius of conventional single-mode fibre is reduced from 62.5 μm to 27.5 μm), the effective index will be less than the refractive index of fibre cladding, and the power in the cladding $\eta = \dfrac{P_{\mathrm{clad}}}{P_{\mathrm{clad}} + P_{\mathrm{core}}}$ will increase significantly, indicating that the light is no longer guided by the core-cladding interface but is guided by the cladding-external medium interface. Therefore, the weakly guiding approximation condition is broken and the exact vectorial model developed by Snyder and Love should be used to analyse the microfibre.[12,13] Figure 5 shows the bendloss characteristics of microfibres with different r_{h}. Results obtained demonstrate that the resonator with smaller size can be achieved with thinner microfibres.

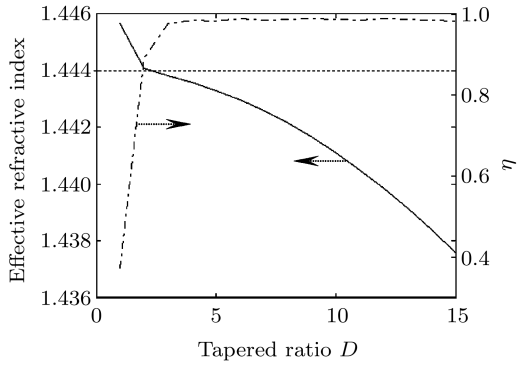


Fig.4. Influence of taper ratio on effective refractive index and power distribution of fibre's guide mode. Dotted line: refractive index of fibre cladding.

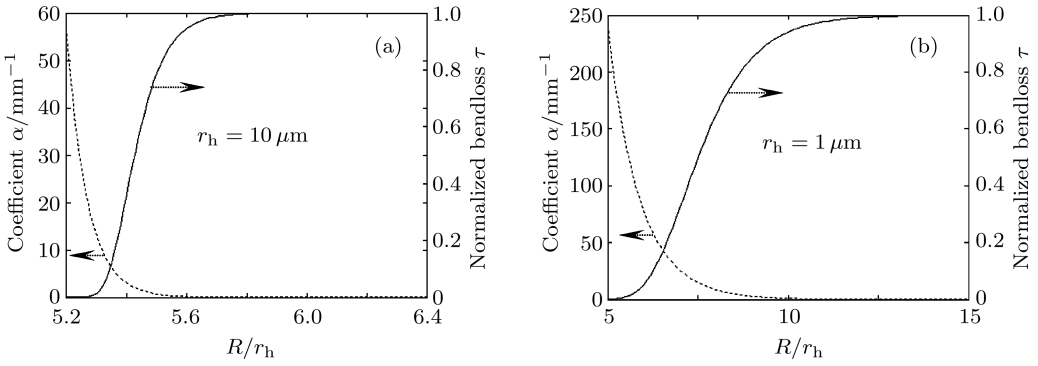


Fig.5. The achievable minimum resonator for microfibres with different radii: (a) $R = 56\,\mu$m; (b) $R = 10\,\mu$m.

4. Experimental results

As can be seen from the analyses above, fabrication of microfibre is the key to obtain high-quality all-fibre micro-ring resonator. In this paper, flame heating method is used to draw the microfibre. The flame should be clean and the burning gas flow should be controlled carefully so that the air convection does not break the fibre during the drawing process.[14] In the meantime, the slow and adiabatic condition should be maintained, otherwise scattering loss induced by coupling between the guide mode and the local cladding modes will arise. Furthermore, the tapered waist should be uniform and long enough to form the ring resonator. Figure 6 gives the microscopic image of the microfibre, as compared with the conventional single-mode fibre.

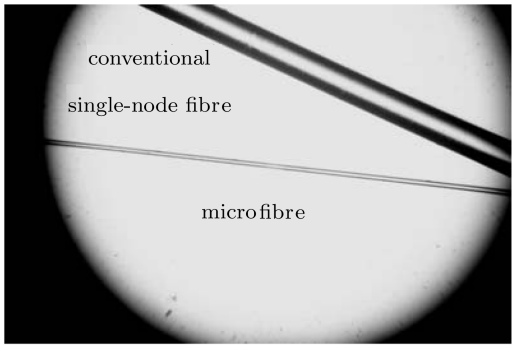


Fig.6. Comparison of microfibre with conventional single-mode fibre.

Figure 7 is the insertion loss of the microfibre drawn under different circumstances. When the microfibre is placed straight, a very low insertion loss confirms the high-quality of microfibre. But if one end of the microfibre is bent toward the other end (no

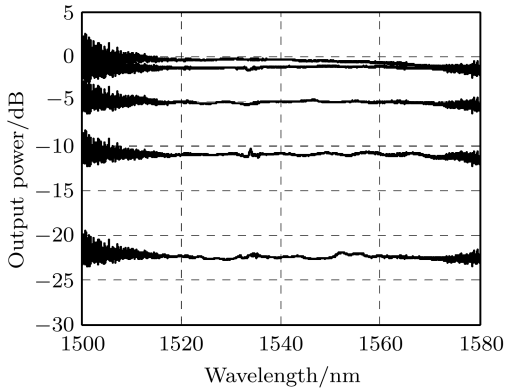


Fig.7. Measured insertion loss of the microfibre. from the top down: (a) Placed straightly; (b) Bent with very big radius; (c) $R = 5\,\mathrm{mm}$ and placed in air; (d) $R = 5\,\mathrm{mm}$ and placed in alcohol; (e) $R = 100\,\mu\mathrm{m}$ and placed in alcohol.

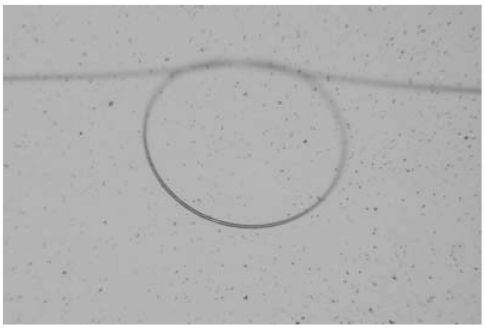


Fig.8. All-fibre micro-ring resonator fabricated by self-coiling of the microfibre.

contacting to provide coupling), significant power attenuation will be introduced with the decreasing bending radius and the increasing external index. In order to avoid deteriorating device performance badly, we set the ring radius at around $500\,\mu$m and coil the microfibre to form the resonator. Figure 8 is the fabricated all-fibre micro-ring resonator.

Then, the transmission spectra of the fabricated all-fibre micro-ring resonator are measured by the broadband Erbium-doped fibre amplifier (EDFA) source and ANDO-AQ6317C optical spectrum analyser. The experimental results shown in Fig.9 verify the wavelength-dependent filtering response given in Fig.2 and demonstrate much shaper resonant characteristics as compared with the results reported in Ref.[6] (Fig.4). This is because our micro-ring resonator is fabricated by a continuous optical fibre, which can provide higher coupling efficiency. Furthermore, by controlling the self-coiling region, the oscillation corresponding to the maximum extinction ratio can be adjusted discretionarily from the longer wavelength to the shorter wavelength.

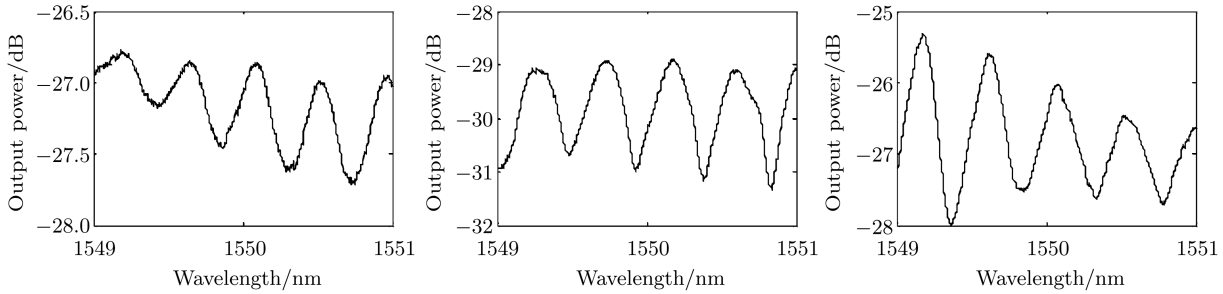


Fig.9. Spectral responses of micro-ring resonator adjusted by controlling self-coiling coupling region.

5. Conclusions

We have designed and fabricated a $500\,\mu$m-radius all-fibre micro-ring resonator by self-coiling method. Good resonant responses were obtained and the oscillation corresponding to the maximum extinction ratio was adjusted by controlling the coupling region. Due to the entire device built on a continuous piece of optical fibre, the all-fibre micro-ring resonator is expected to be able to avoid many problems associated with planar waveguide integration.

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