A whispering gallery mode microsphere resonator coupled by anti-resonant reflecting guidance mechanism

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Abstract：A whispering gallery mode microsphere resonator is proposed and demonstrated. The device is fabricated by splicing a single-mode fiber with a capillary tube and, by properly adjusting the discharging current and the splicing position of the fiber and capillary tube, an expanded hollow sphere cavity is formed at the splicing junction. A microsphere is inserted into the hollow sphere cavity and positioned in close touch with the cavity wall to excite whispering gallery mode resonance via the coupling of evanescent field of the anti-resonant reflecting guidance mode produced in the cavity wall. The device has a quality factor of 3.725×10^3 and is compact, simple in fabrication, easy in packaging, convenient in operation and of low cost.

Key words：Resonator, microcavity, optical fiber device

PACS：

反谐振反射模式耦合的回音壁模式微球谐振器

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摘要：本文提出并演示了一种回音壁模式微球谐振器。该装置的制备是将单模光纤与毛细管熔接,通过适当调节放电电流和光纤与毛细管的熔接位置,形成一个膨胀的空心球腔。微球被插入空心球腔中,并与腔壁紧密接触,通过渐逝场的耦合在腔壁中产生的反谐振导向机制来激发回音壁模式共振。该设备的品质因数为 3.725×10^3,结构紧凑,制造简单,易于封装,操作方便,成本低。

关　键　词：谐振器；微腔；光纤器件

1　Introduction

Whispering gallery mode（WGM）is the specific resonance（or mode）of a wave field that is confined inside a given resonator by use of continuous total internal reflection（TIR）. A WGM resonator has high Q-factor（or narrow linewidth）and small mode volume, hence supporting widespread applications in sensors, filters, microlasers, and modulators［1-5］. The common WGM excitation schemes are generally based on phase-matching of the evanescent fields, to couple light from the outside into the WGM resonators. Currently, the main coupling techniques include prism, planar waveguide, side polished or angle polished optical fiber, and tapered optical fiber［6-10］. The prism coupling is a flexible and efficient means for free space optical operation, but it involves with bulky components and needs a careful alignment. Planar waveguide coupling is compact and robust however, it requires high precision and complicated fabrication techniques and is not compatible with optical fiber. Although the side polished or angle polished fiber coupling is compatible with optical fiber and convenient for use, its fabrication is relatively difficult and has relatively low coupling efficiency. The highest coupling efficiency can be realized by use of tapered optical fiber coupling however, the tapered fiber is fragile in structure, which results in long term operation instability of the device.

WGM resonators based on commercially available microsphere are featured with high compactness, flexible and convenient operation and low cost, and have attracted a lot of research attention in recent years. A WGM microsphere resonator is suitable for the coupling schemes such as the use of chemically etched photonic crystal fiber（PCF）or capillary tube, and tapered hollow annular

core fiber [11-14]. However, the etched PCF and capillary are fragile and, for the tapered hollow annular core fiber, the WGM resonance is relatively weak due to strong reflection from the Fabry-Perot (FP) cavity.

In this paper, a new coupling method for WGM microsphere resonator is proposed and demonstrated by use of anti-resonant reflecting guidance (ARRG) mechanism [15-16], which is an effect that causes the lossy dips in the transmission spectrum. The device consists of a single-mode fiber (SMF) connected with an expanded hollow sphere cavity of capillary tube, formed in the fusing splicing process. The wall of the hollow sphere cavity can be considered as a FP etalon. Wavelengths that satisfy the resonant condition will leak out of the wall, whereas the other wavelengths can continue to propagate in the wall of capillary tube as the guide modes. When the incident light arrives at the interface of SMF and hollow sphere cavity, part of light enters into the wall of the hollow sphere cavity, and propagates along the wall by following total internal reflection. When the light path is tangential with the microsphere surface at the contacting point, it is coupled into the microsphere and excites WGM if the phase matching condition can be satisfied. Such a WGM microsphere resonator is compact in size, simple in fabrication, low in cost and convenient in operation and have a quality (Q) factor of 3.725×10^3.

2 Device Fabrication

The proposed optical fiber WGM microsphere resonator consists of a SMF and a capillary tube, both are fusion spliced to form an expanded hollow sphere cavity. A microsphere is adhered to the inner wall of the hollow sphere cavity with the help of a tapered fiber.

The fabrication process of the device is illustrated in Fig. 1. Firstly, a section of capillary tube with outer diameter of 149 μm, inner diameter of 75 μm and length of 800 μm is fusion spliced with a SMF, as shown in Fig. 1(a). The other end of the capillary tube is fusion spliced with another section of SMF as shown in Fig. 1(b). By continuously adjusting the splicing position of the capillary tube and the SMF until part of the capillary tube collapses and expands into a hollow sphere cavity with the wall thickness of ~15 μm, as shown in Fig. 1(c). Due to the collapse of the capillary tube at the SMF-capillary tube junction, a thin layer is formed. Next, the capillary tube is cut away at a position distant from the hollow sphere cavity, as shown in Fig. 1(d).

A tapered optical fiber covered with a thin layer of UV adhesive is then used to push a microsphere (Cospheric Inc, BTGMS-4.21, barium titanate) with a diameter of ~73 μm into the capillary tube and then the hollow sphere cavity, as shown in Fig. 1(e).

The position of the microsphere in close touch with the inner wall of the hollow sphere cavity is continuously adjusted by use of the tapered fiber as shown in Fig. 1(f), until the WGM resonance appears in the reflection spectrum of the device. The UV adhesive is then solidified by UV light illumination, to provide a robust structure of the WGM resonator.
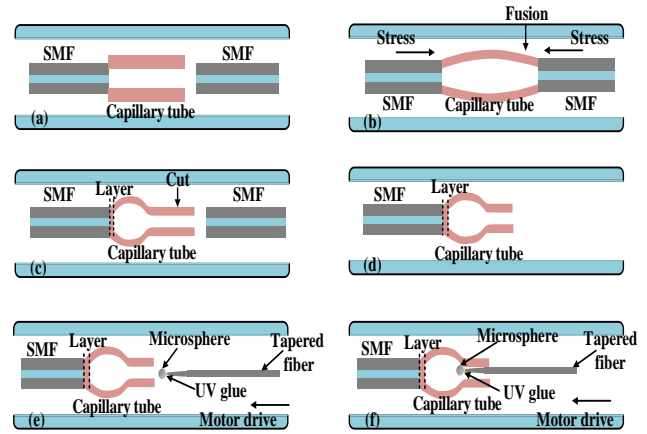

Fig. 1 Schematic diagrams of the fabrication process of the WGM microsphere resonator. (a) One end of the capillary tube is fusion spliced with a SMF; (b) The other end of the capillary tube is fusion spliced with another SMF; (c) The hollow sphere cavity is formed by continuously discharging the SMF-capillary tube junction; (d) The capillary tube is cut at a position distant from the hollow sphere cavity; (e) A tapered fiber covered with UV glue is used to insert the microsphere into the hollow sphere cavity by using a motor drive; (f) The microsphere is positioned in close touch with the inner wall of the hollow sphere cavity.
图1 WGM微球谐振器制备示意图。(a)毛细管的一端与单模光纤熔接;(b)毛细管的另一端与另一段单模光纤熔接;(c)通过在单模光纤毛细管连接处连续放电形成空心球腔;(d)在远离空心球腔的位置切割毛细管;(e)使用覆盖有紫外胶的锥形光纤,通过使用电机驱动器将微球插入空心球腔内;(f)微球放置在与空心球腔的内壁紧密接触的位置。

The function of tapered fiber is to help adjusting the position of the microspheres in the cavity to allow light be coupled into the microspheres efficiently, thereby exciting WGM resonance.
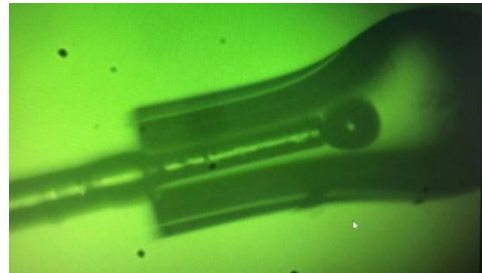

Fig. 2 Microscope image of the WGM microsphere resonator
图2 回音壁模式微球谐振腔的显微图像

The microscope image of the fabricated WGM microsphere resonator is displayed in Fig. 2.

3 OPERATION PRINCIPLE

The operation principle of the device is illustrated in Fig. 3, where it can be observed that there are five possible reflection surfaces: S_1, S_2, S_3, S_4 and S_5 respectively. The front and back surfaces of the thin layer at the SMF-capillary tube junction, S_1 and S_2, the front and back surfaces of microsphere S_3 and S_4, and the end face of the capillary tube, S_5.

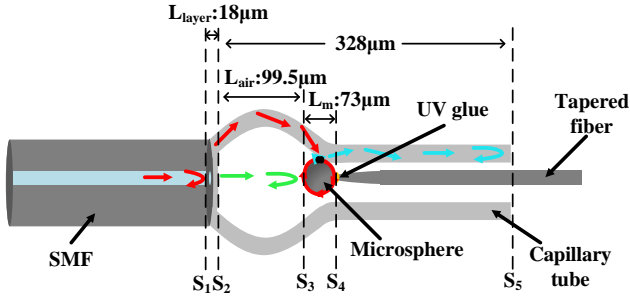Part of incident light traveling along the core of SMF

Fig. 3　Schematic diagram of the WGM microsphere resonator
图3　回音壁模式微球谐振器示意图

is directed into the wall of hollow sphere cavity, and propagates along the cavity wall by experiencing total internal reflection. When the light beam traveling along the wall follows the tangential path of the microsphere, it is coupled into the microsphere at the contacting point, and circulates along the microsphere surface, hence exciting WGM resonance. After propagating along the surface of the microsphere for a period, the light beam leaves the microsphere and propagates along the wall of capillary tube, until it is reflected at the cutting end surface of the capillary tube and finally returns to the core of SMF.

The rest part of the light is reflected sequentially at the thin layer surfaces and the microsphere surfaces and as a result, a cascaded FP interferometer is formed, which may include an FP cavity formed by the surfaces of S_1 and S_2, S_2 and S_3, and S_3 and S_4, with cavity length of L_{layer}, L_{air} and L_m, respectively, as shown in Fig. 3.

The microscope image of the device under red light illumination is displayed in Fig. 4, where the high reflection at the end of capillary tube reveals the ARRG mechanism existed [16]. It can also be observed from the figure that that light circulates along the circumference of the microsphere, which confirms the existence of the WGM resonance.
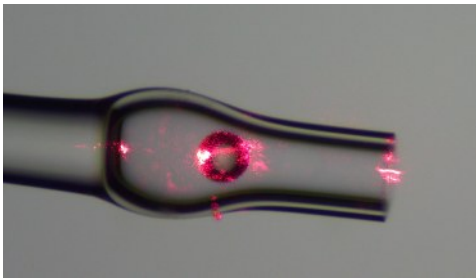

Fig. 4　Microscope image of the device under red light illumination
图4　器件在红光照射下的显微镜图像

The free spectral range（FSR）of the spectrum is given by

$$FSR = \frac{\lambda_1 \lambda_2}{OPD} = \frac{1}{f} \qquad (1)$$

where λ_1 and λ_2 represent the adjacent resonance peak wavelengths, OPD is the optical path difference pro-

duced, and f is the corresponding spatial frequency.

For a WGM microsphere resonator：

$$OPD_{WGM} = n_m \pi D \qquad (2)$$

where n_m is the refractive index and D is the diameter of the microsphere.

For an FP cavity：

$$OPD_{FP} = 2nL \qquad (3)$$

where n is the refractive index of the FP cavity medium, and L is the FP cavity length.

Since FSR is the reciprocal of the spatial frequency and the cavity lengths are known, the OPD or the actual spatial frequency corresponding to each frequency peak can be calculated and used to determine whether the structure operates in a WGM mode or an FP mode, or both.
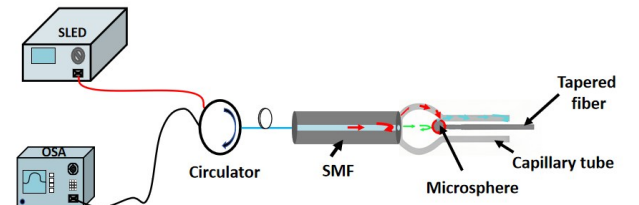
4　Experiment and discussion

Fig. 5　Schematic of the experimental setup
图5　实验装置示意图

To demonstrate the operation of the proposed device, the reflection spectrum of the WGM microsphere resonator needs to be recorded and the experimental setup is shown in Fig. 5. The light from a broadband light source（Haoyuan Optoelectronics, HY-SLE）is introduced into the device through a circulator. The reflected light from the device is directed to the output port of the circulator and received by an optical spectrum analyzer（YOKOGAWA, AQ6370）with a resolution of 0.02 nm, for recording the reflection spectrum.

The reflection spectrum of the expanded hollow sphere cavity device without microsphere is displayed in Fig. 6(a). When the microsphere is inserted, the reflection spectrum of the device is shown in Fig. 6(b), and the corresponding spatial frequency spectrum obtained by implementing fast Fourier transform（FFT）is shown in Fig. 6(c). It can be observed from Fig. 6(c) that a number of peaks A, B, C, D, and E exist in the spatial frequency spectrum, situated at 0.0249, 0.0833, 0.1916, 0.2749 and 0.2916 nm⁻¹ respectively. The OPD value corresponding to the frequency peak A is ~ 59.8 μm, which is close to the OPD value of 51.8 μm for the FP cavity formed by the reflection surfaces of thin layer, S_1 and S_2, as the refractive index of capillary tube is 1.44. The OPD value corresponding to the frequency peak B is ~200.1 μm, which is close to the OPD value of 199 μm for the air FP cavity formed by the reflection surfaces of S_2 and S_3. Since the refractive index of the microsphere is 1.93 and the diameter is ~73 μm, accord-

ing to Eq. (2), the corresponding OPD value of WGM microsphere resonator can be calculated to be ~442. 4 μm, which is close to the OPD value corresponding to the frequency peak C, ~460. 3 μm. Thus our proposed device is indeed a WGM microsphere resonator. Fig. 6 (d) provides an enlarged view of the dashed box in Fig. 6 (b). At the resonance wavelength of 1504 nm, the full-width at half maximum (FWHM) value of the main resonance is ~0. 4038 nm, and the Q factor can be determined as 3.725×10^3. Such a value is slightly better than that reported in [11], but is still lower than those in [12-14]. However, our device has a good robustness due to etching free, and the WGM resonance can be easily established.

The frequency peak D is the sum frequency of peak B and peak C (0. 0833 + 0. 1916 = 0. 2749) and the frequency peak E is the sum of peak D and peak A (0. 2749 + 0. 0249 = 0. 2998). It can be also noticed that the FP resonance between S_3 and S_4 is not found in Fig. 6(c), which is likely due to the weak reflection from the microsphere surfaces.

The device can be used for gas pressure measurement. When the external refractive index varies, the OPD related to the WGM microsphere resonator also changes, thus shifting the reflection spectrum. Considering the refractive index of microsphere of 1. 93 and the measured Q value of 3.725×10^3, the refractive index sensitivity can be achieved in the device is in the order of 10^{-4}.

5 Conclusion

In conclusion, an optical fiber WGM microsphere resonator is demonstrated. The device is fabricated by fusion splicing SMF with a section of capillary tube, which is expanded into a hollow sphere cavity at the SMF-capillary tube junction produced due to the high temperature during the splicing process. A microsphere is inserted into the hollow sphere cavity and in close touch with the cavity wall to excite WGM through the evanescent field coupling between the microsphere and the cavity wall due to anti-resonant reflecting guidance mechanism. The device has a good Q-factor of 3.725×10^3 and is compact, simple in fabrication, easy in packaging, convenient in operation and of low cost.

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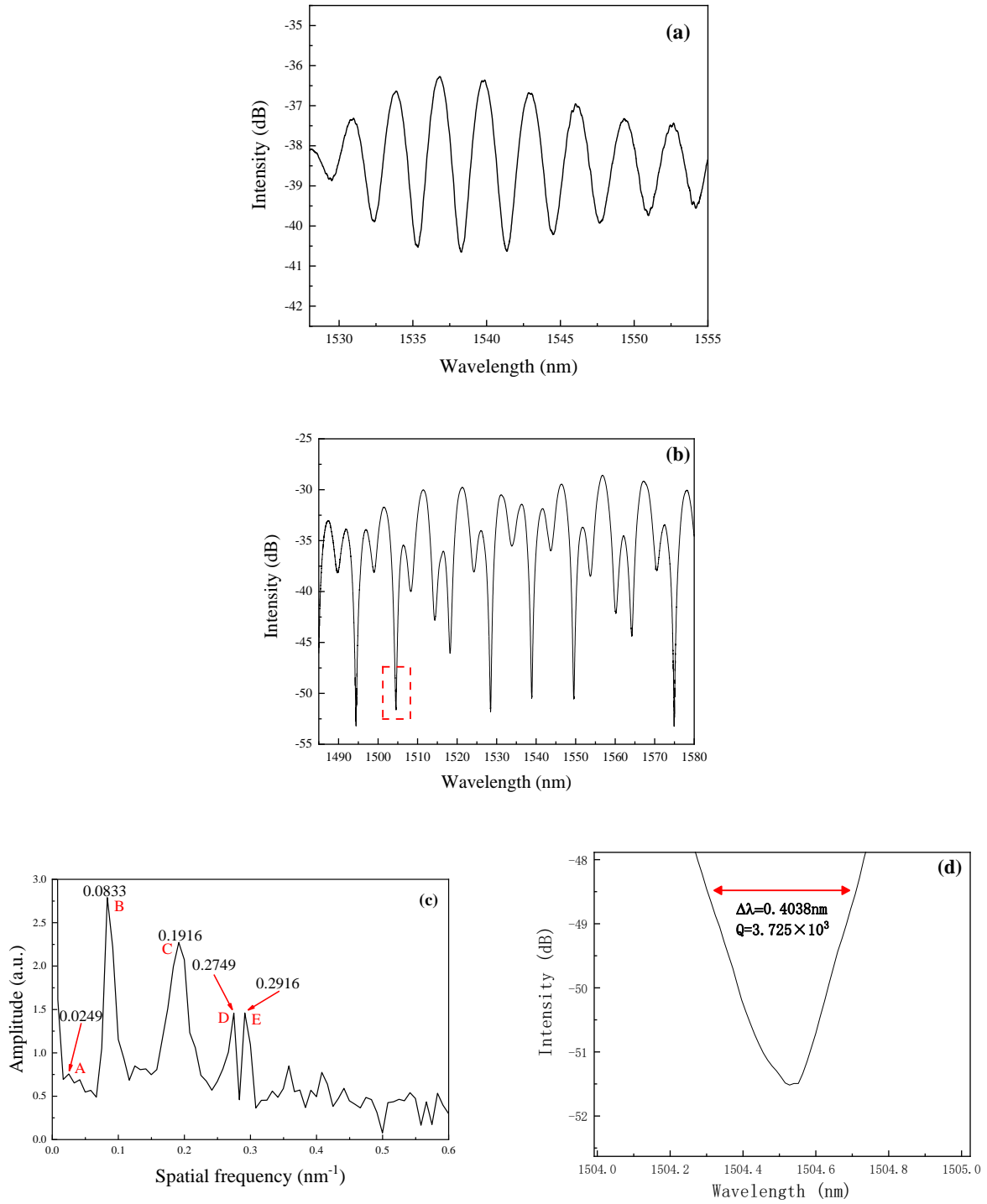ance mechanism

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Fig. 6(a) Reflection spectrum of the hollow sphere cavity without inserting the microsphere; (b) Reflection spectrum of the WGM micro-sphere resonator; (c) FFT of the reflection spectrum; (d) Enlarged view of the dotted box in the reflection spectrum of the WGM micro-sphere resonator.

图6(a) 未插入微球的空心球腔的反射谱；(b)回音壁模式微球谐振器的反射谱；(c)反射谱的快速傅里叶变换；(d)回音壁模式微球谐振器反射谱中虚线框部分的放大图。

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tion photonics technology（GKPT20－04）.

References

［1］B. Matsko, and V. Ilchenko, "Optical resonators with whispering-gallery modes—part I: Basics," IEEE J. Sel. Topics Quantum Electron. 12, 3－14（2006）.

［2］V. S. Ilchenko, and A. B. Matsko, "Optical resonators with whispering-gallery modes-part II: applications," IEEE J. Sel. Topics Quantum Electron. 12, 15－32（2006）.

［3］J. Ward and O. Benson, "WGM micro resonators: sensing, lasing and fundamental optics with microspheres," Laser & photon. 5, 553－570（2011）.

［4］S. Soria, S. Berneschi, M. Brenci, F. Cosi, G. N. Conti, S. Peli and G. C. Righini, "Optical microspherical resonators for biomedical sensing," Sensors. 11, 785－803（2013）.

［5］J. Lin, Y. Xu, J. Song, B. Zeng, F. He, H. Xu, K. Sugioka, W. Fang, and Y. Cheng, "Low-threshold whispering-gallery-mode microlasers fabricated in a Nd: glass substrate by three-dimensional femtosecond laser micromachining," Opt. Lett. 38, 1458－1460（2013）.

［6］A. Mazzei, S. Götzinger, L. S. Menezes, V. Sandoghdar, O. Benson, "Optimization of prism coupling to high-Q modes in a microsphere resonator using a near-field probe," Opt. Commun. 250, 428－433（2005）.

［7］E. Xifré-Pérez, J.D. Domenech, R. Fenollosa, P. Muñoz, J. Capmany, and F. Meseguer, "All silicon waveguide spherical microcavity coupler device," Opt. Express. 19, 3185－3192（2011）.

［8］N. Dubreuil, J. C. Knight, D. K. Leventhal, V. Sandoghdar, J. Hare, and V. Lefèvre, "Eroded monomode optical fiber for whispering-gallery mode excitation in fused-silica microspheres," Opt. Lett. 20, 813－815（1995）.

［9］J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper," Opt. Lett. 22, 1129－1131（1997）.

［10］K. Milenko, I. Konidakis, and S. Pissadakis, "Silver iodide phosphate glass microsphere resonator integrated on an optical fiber taper," Opt. Lett. 41, 2185－2188（2016）.

［11］K. Kosma, G. Zito, K. Schuster, and S. Pissadakis, "Whispering gallery mode microsphere resonator integrated inside a microstructured optical fiber," Opt. Lett. 38, 1301－1303（2013）.

［12］L. Shi, T. Zhu, D. Huang, and M. Liu, "Thermo－Optic Tuning of Integrated Polymethyl Methacrylate Sphere Whispering Gallery Mode Resonator," IEEE Photon. Journal. 8, 1－7（2016）.

［13］X. Zhang, Y. Yang, H. Shao, H. Bai, F. Pang, H. Xiao, and T. Wang, "Fano resonances in cone-shaped inwall capillary based microsphere resonator," Opt. Express. 25, 615－621（2017）.

［14］J. Wang, X. Zhang, M. Yan, L. Yang, F. Hou, W. Sun, X. Zhang, L. Yuan, H. Xiao, and T. Wang, "Embedded whispering-gallery mode microsphere resonator in a tapered hollow annular core fiber," Photon. Res. 6, 1124－1129（2018）.

［15］M. Hou, F. Zhu, Y. Wang, Y.P. Wand, C. R. Liao, S. Liu, and P. X. Lu, "Antiresonant reflecting guidance mechanism in hollow-core fiber for gas pressure sensing," Opt. Express. 24, 27890－27898（2016）.

［16］Y. B. Yang, D. N. Wang, Ben Xu Z. K. Wang, "Optical fiber tip interferometer gas pressure sensor based on Anti-resonant reflecting guidance mechanism", Opt. Fiber Technol. 42, 11－17（2018）.