FIB-milled Gold-coated Singlemode-Multimode-Singlemode Fiber Tip Refractometer

Ming Ding, Pengfei Wang, Junlong Wang and Gilberto Brambilla

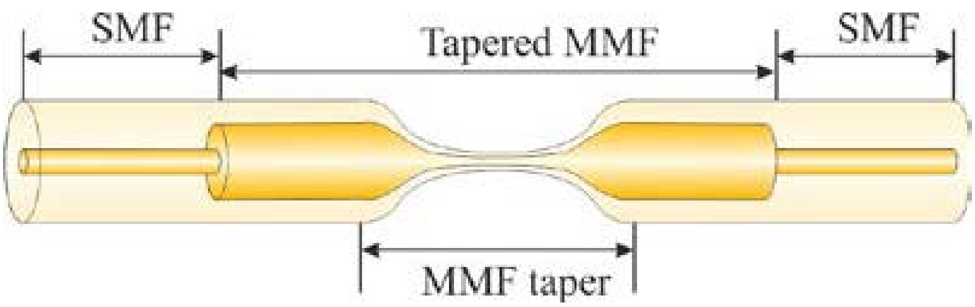
A compact singlemode-multimode-singlemode fiber tip (SMST) refractive index sensor is demonstrated. Focused ion beam (FIB) milling is exploited to have a clean fiber tip cut which is then coated by a layer of gold to increase reflection. An average sensitivity of 265 nm/RIU and a resolvable index change of 3.77×10^{-5} are obtained experimentally with a ~2.94 µm diameter SMST. Because of its compactness, ease of fabrication, linear response, good sensitivity, easy connectivity to other in-fiber optical components and low cost, this refractometer could find various applications in chemical and biological sensing.

I

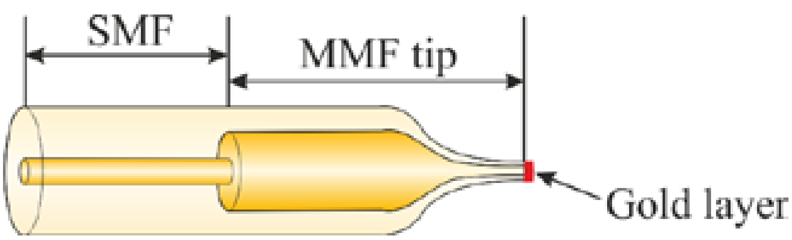
M. Ding and G. Brambilla are with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ U.K. (e-mail: md20g09@orc.soton.ac.uk; gb2@orc.soton.ac.uk).
P. Wang is with the Photonic Research Centre, Dublin Institute of Technology, Kevin Street, Dublin 8, Dublin Ireland. (e-mail: pengfei.wang@dit.ie)
J. Wang is with Beijing Aerospace Times Optical-electronic technology Co., No.1 Fengying East Road, Haidian district, Beijing, 100094, P.R. China (e-mail: junl_wang@126.com).

I. INTRODUCTION

Fiber optic sensors represent a technology which finds applications in a multitude of fields. Most physical properties can be sensed optically with fibers. Light intensity displacement, temperature, pressure, rotation, sound, strain, magnetic field, electric field, radiation, flow, liquid level, chemical analysis, and vibration are just few examples [1]. They offer numerous advantages over conventional sensors due to their immunity to electromagnetic interference, resistance to erosion, small size, high sensitivity and capability of remote sensing. In the past years, several types of refractive index (RI) optical fiber sensors have been developed. The most common approaches rely on etched or titled fiber Bragg gratings (FBGs) [2,3], long period gratings (LPGs) [4-6], surface plasmons [7], Fabry-Perot interferometers [8,9], and microfiber coil resonators [10]. However, the grating (FBGs and LPGs) based sensors often require special fibers, hydrogen loading, a cumbersome grating writing equipment working with toxic gases and post fabrication treatments.



(a)



(b)
Fig. 1 Schematic of (a) STMS structure; (b) gold-coated SMST.

Recently, all-fiber interferometers have been intensively studied due to their simple fabrication method, high sensitivity and small size. These include mode interferometers based on two peanut-shape structures [11], tapered fibers [12-14], and core diameter mismatch [15-19]. All these approaches have in common the focus on the interference between the dominant cladding mode and the core mode. In 2006, a singlemode-multimode-singlemode (SMS) fiber based sensor utilizing multimode interference in the multimode fiber (MMF) core section has been proposed [20-23]. Concurrently, significant effort has been devoted to develop tapered fiber devices because of a range of advantages such as a large evanescent field, strong confinement, smart footprint, compact physical size and fast response [24]; hence tapering offers the potential both to improve the performance and to reduce the physical size of the SMS structure based fiber sensor mentioned above. Wang et al. demonstrated a singlemode-tapered multimode-singlemode (STMS) fiber sensor with 1900 nm/RIU sensitivity at a RI~1.44 (Fig. 1 (a)) [25]. The STMS sensor consists of an input singlemode fiber (SMF), a tapered multimode fiber (MMF) section, and an output SMF. Within the tapered MMF section, the excited modes of LP_{0m} in the MMF core is partly coupled to the high-order cladding modes at the beginning of the fiber taper region, and this increases the fraction of power in the evanescent wave within the region of the MMF cladding. However, given that a long portion of an MMF needs to be exposed to the surrounding medium in order to achieve a large RI change, the MMF device results to be several centimeters long.

In this letter, a compact fiber refractometer based on a singlemode-multimode-singlemode fiber tip (SMST) is presented (Fig. 1(b)). The structure consists of an input/output SMF, an MMF half taper section and a gold film at the end of the tip as a reflection mirror. In both the conical transition region and tip sections, the effective index of the guided mode (thus multimode interference) is affected by the external medium RI, thus the MMF tip can be potentially used as a highly sensitive refractometer. Due to the small size, the SMST has a good spatial resolution and could be inserted into narrow orifices.

II. GOLD-COATED SMST REFRACTOMETER FABRICATION

The SMS sample was manufactured from a 42 mm long Thorlabs AFS105/125Y step-index MMF, which was stripped, cleaved, and then spliced between two standard SMFs. As shown in Fig.2, a CO_2 laser (Synrad, Model 48-2KWL, with maximum power of 30 W at the wavelength λ=10.6 µm) was used to fabricate the SMST. A ZnSe cylindrical lens with focal length of 254mm ±0.5% focused the CO_2laser beam down to~150 µm. The SMS fiber device was fixed vertically on a support and a weight (~30 g) was used to apply a constant tension to the end of the SMS. When the middle of the MMF section was exposed to the CO_2laser beam with an average output power of 15 W, tapering occurred because of the tension applied to the fiber end by the weight. Fig.3(a) presents the microscope image of the SMST. The light which is launched into the SMST can be potentially reflected by Fresnel effect tip end. However, the reflectivity of this SMST is very weak and cannot be detected.

In order to increase its reflectivity, the device tip was flat cut with a focus ion beam (FIB) system “Helios600” (FEI Inc., Hillsboro, USA). A 50 nm layer of gold was deposited on the SMST surface before FIB milling using an electron beam evaporator, to avoid charging during FIB milling. The Gallium ion beam accelerating voltage and current were set to 30.0 kV and 93pA, respectively. FIB beam sizes smaller than 30 nm can be easily obtained, thus tip end sizes can be controlled with a good degree of precision. Fig.3(b) shows the SEM image of the SMST which was milled by FIB and resulted to be d~2.94 µm. After FIB milling, the gold layer was removed by gold-etching solvent which contains iodine and potassium iodide. Then another 40nm layer of gold was coated on the milled SMST to increase the reflectivity.

The reflection spectrum of the FIB-milled gold-coated SMST in air in the range from λ=1350 nm to 1650 nm is shown in Fig.4. Several dips appear in the spectrum, as expected from multimode interference. The reflectivity dips show extinction ratio >10dB. Compared to the reflectivity obtained in ref. [26], which was less than -50dB, the reflectivity after FIB milling shows an extraordinarily large improvement of ~40 dB. By FIB milling and gold coating, the reflection can be improved and the measurement accuracy increased.

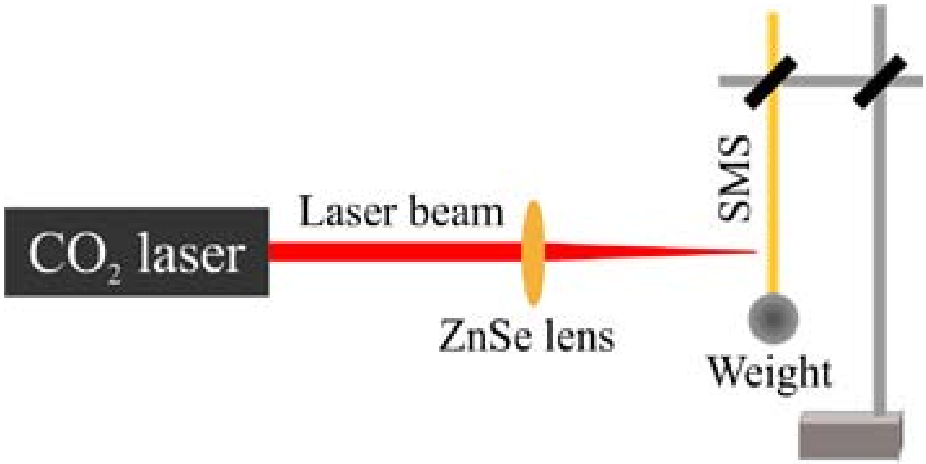
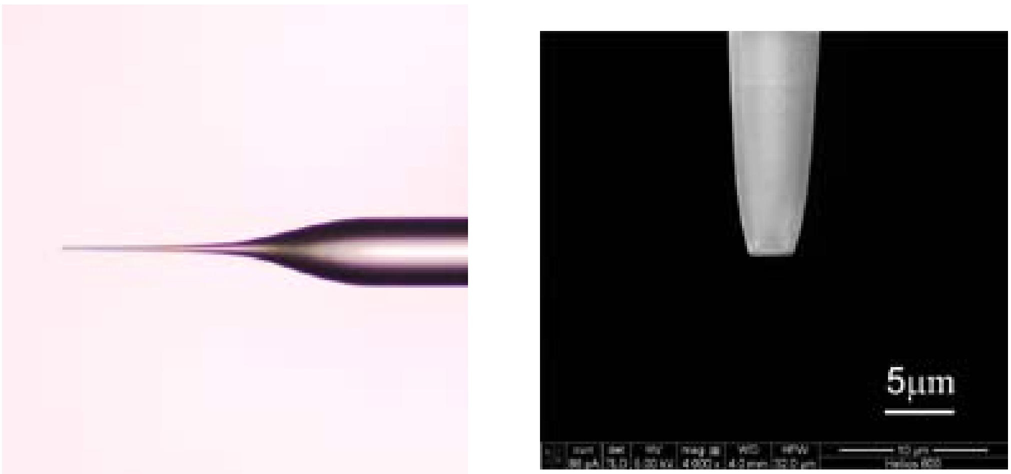


Fig.2 Schematic of set-up for fabricating SMST.



(a) (b)

Fig.3(a) Microscope image of SMST;(b) SEM image of FIB-milled SMST. The tip end size is d~2.94 μm.

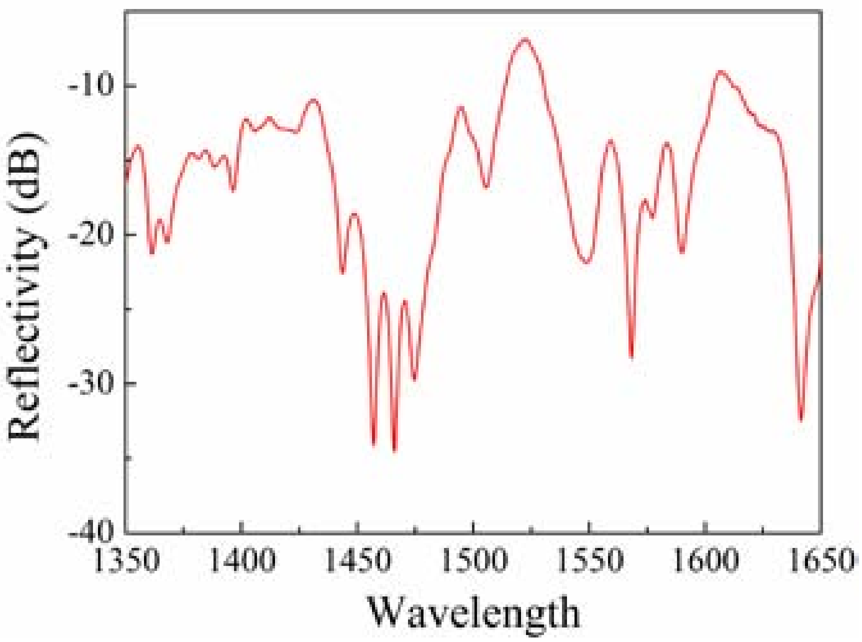


Fig.4 Reflectivity of SMST in air after FIB milling and gold coating.

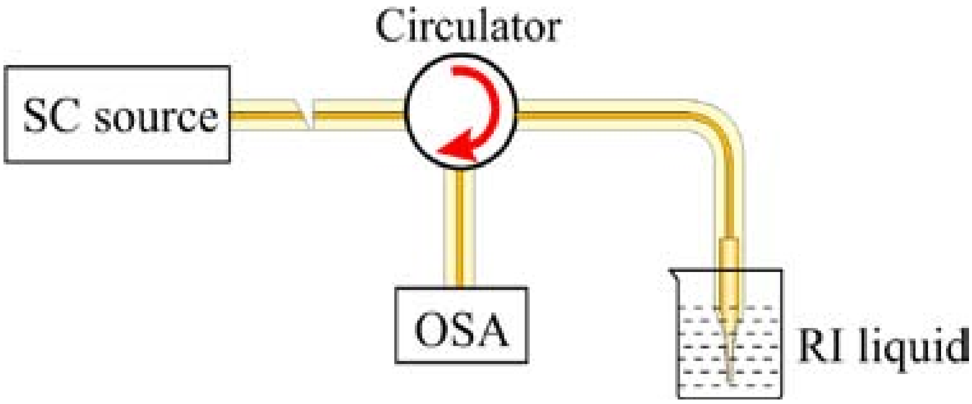
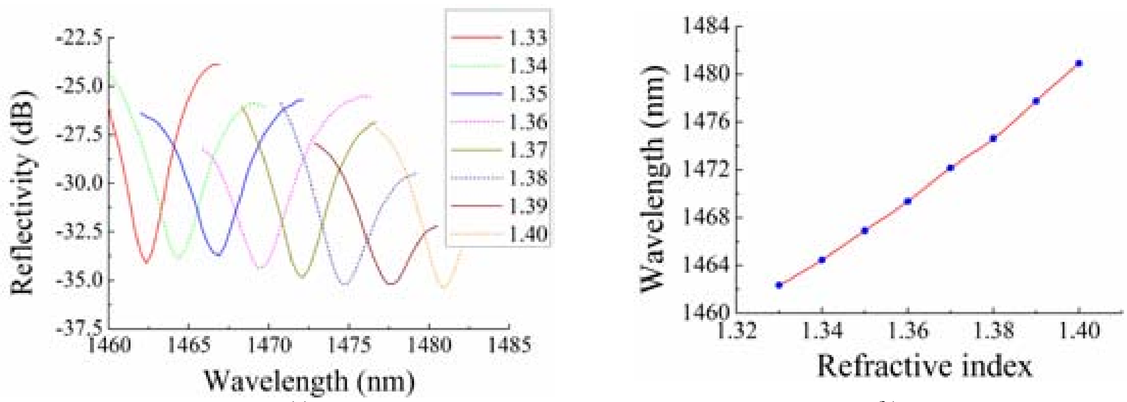


Fig.5 Experimental set-up for RI measurement.

III. SMST REFRACTOMETER CHARACTERIZATION

The RI sensing measurement was performed at room temperature(~25°C) with a series of RI liquids (1.33~1.40 with an interval of 0.01, RI error ±0.0002). The measurement set-up is shown in Fig.5. A supercontinuum (SC) source (Fianium Ltd, Southampton, U.K.) was used to deliver light over a rather broad range of wavelengths (450 nm-1800 nm) with maximum pulse energy of 50nJ. The in-fiber laser output was angle-cleaved to avoid back reflections from the optical components. The SMST was inserted into RI liquids. The reflection spectra from SMST were measured and recorded by an optical spectrum analyzer (OSA) (AQ6317, Yokogawa, Japan) via an optical circulator.

Fig.6(a) shows the spectral shift of the peak at ~1460nm for refractive indices increasing from 1.33 to 1.40. As the RI increases, the spectrum shows a redshift. The peak wavelength shift as a function of RI is plotted in Fig.6(b). An average sensitivity of 265nm/RIU (RI unit) is achieved, resulting in are solvable index change of 3.77×10^{-5} for a resolvable wavelength change of 0.01 nm. Temperature dependence of the similar fiber refractometer has been presented in ref.[26], therefore the temperature compensation is possible during the RI measurements. Higher sensitivity can be achieved by implementing few improvements to the manufacturing technology, including: 1) writing a series of nanoslots or nanogratings on the fiber tip using FIB milling; 2) reducing the tip diameter and 3) using another peak in the reflection spectrum at longer wavelengths.



(a) (b)

Fig. 6 (a) Spectral shift of the peak at ~1460nm for RI increasing from 1.33 to 1.40; (b) The wavelength shift of the peak as a function of RI.

IV. CONCLUSION

In summary, a compact refractometer which uses a FIB-milled and gold-coated SMST has been demonstrated. The refractometer has an average sensitivity of 265 nm/RIU and a resolvable index change of 3.77×10^{-5} for a resolvable wavelength change of 0.01 nm, experimentally with a ~2.94μm diameter SMST. The sensitivity can be improved by optimizing the profile of the SMST. This fiber sensor offers several advantages, including compact size which would allow for good spatial resolution, but also ease of fabrication, linear response, good sensitivity, ease of interconnection with other in-fiber optical components and low cost. The device is promising in various chemical and biological applications.

ACKNOWLEDGEMENTS

GB gratefully acknowledges the Royal Society (London, UK) for his University Research Fellowship. P. Wang is funded by the Irish Research Council for Science, Engineering and Technology, co-funded by the Marie-Curie Actions under FP7.

REFERENCES

[1] B. Lee, "Review of the present status of optical fiber sensors," *Opt. Fiber Technol.*, vol. 9, pp. 57-79, Apr. 2003.
[2] M. Han, F. W. Guo, and Y. F. Lu, "Optical fiber refractometer based on cladding-mode Bragg grating," *Opt. Lett.*, vol. 35, pp. 399-401, Feb. 2010.
[3] H. Y. Meng, W. Shen, G. B. Zhang, C. H. Tan, and X. G. Huang, "Fiber Bragg grating-based fiber sensor for simultaneous measurement of refractive index and temperature," *Sensor. Actuat. B-Chem.*, vol. 150, pp. 226-229, Sep. 2010.
[4] J. L. Li, W. G. Zhang, S. C. Gao, P. C. Geng, X. L. Xue, Z. Y. Bai, and H. Liang, "Long-Period Fiber Grating Cascaded to an S Fiber Taper for Simultaneous Measurement of Temperature and Refractive Index," *IEEE Photon. Technol. Lett.*, vol. 25, pp. 888-891, May. 2013.
[5] Q. Han, X. W. Lan, J. Huang, A. Kaur, T. Wei, Z. Gao, and H. Xiao, "Long-Period Grating Inscribed on Concatenated Double-Clad and Single-Clad Fiber for Simultaneous Measurement of Temperature and Refractive Index," *IEEE Photon. Technol. Lett.*, vol. 24, pp. 1130-1132, Jul. 2012.
[6] C. Trono, F. Baldini, M. Brenci, F. Chiavaioli and M. Mugnaini, "Flow cell for strain- and temperature-compensated refractive index measurements by means of cascaded optical fibre long period and Bragg gratings," *Meas. Sci. and Technol.*, vol. 22, p. 075204, Jun. 2011.
[7] H. M. Liang, H. Miranto, N. Granqvist, J. W. Sadowski, T. Viitala, B. C. Wang, and M. Yliperttula, "Surface plasmon resonance instrument as a refractometer for liquids and ultrathin films," *Sensor. Actuat. B-Chem.*, vol. 149, pp. 212-220, Aug. 2010.
[8] C. R. Liao, T. Y. Hu and D. N. Wang, "Optical fiber Fabry-Perot interferometer cavity fabricated by femtosecond laser micromachining and fusion splicing for refractive index sensing", *Opt. Express*, vol. 20, pp.22813-22818, Sep. 2012.
[9] J. L. Kou, J. Feng, Q. J. Wang, F. Xu, and Y. Q. Lu, "Microfiber-probe-based ultrasmall interferometric sensor," *Opt. Lett.*, vol. 35, pp. 2308-2310, Jul. 2010.
[10] F. Xu and G. Brambilla, "Demonstration of a refractometric sensor based on optical microfiber coil resonator," *Appl. Phys. Lett.*, vol. 92, Mar. 2008.
[11] D. Wu, T. Zhu, K. S. Chiang, and M. Deng, "All Single-Mode Fiber Mach-Zehnder Interferometer Based on Two Peanut-Shape Structures," *J. Lightwave Technol.*, vol. 30, pp. 805-810, Mar. 2012.
[12] P. Lu, L. Q. Men, K. Sooley, and Q. Y. Chen, "Tapered fiber Mach-Zehnder interferometer for simultaneous measurement of refractive index and temperature," *Appl. Phys. Lett.*, vol. 94, Mar. 2009.
[13] Z. B. Tian, S. S. H. Yam, J. Barnes, W. Bock, P. Greig, J. M. Fraser, H. P. Loock, and R. D. Oleschuk, "Refractive index sensing with Mach-Zehnder interferometer based on concatenating two single-mode fiber tapers," *IEEE Photon. Technol. Lett.*, vol. 20, pp. 626-628, Apr. 2008.
[14] D. Wu, T. Zhu, M. Deng, D. W. Duan, L. L. Shi, J. Yao, and Y. J. Rao, "Refractive index sensing based on Mach-Zehnder interferometer formed by three cascaded single-mode fiber tapers," *Appl. Optics*, vol. 50, pp. 1548-1553, Apr. 2011.
[15] L. V. Nguyen, D. Hwang, S. Moon, D. S. Moon, and Y. J. Chung, "High temperature fiber sensor with high sensitivity based on core diameter mismatch," *Opt. Express*, vol. 16, pp. 11369-11375, Jul. 2008.
[16] T. H. Xia, A. P. Zhang, B. B. Gu, and J. J. Zhu, "Fiber-optic refractive-index sensors based on transmissive and reflective thin-core fiber modal interferometers," *Opt. Commun*, vol. 283, pp. 2136-2139, May. 2010.
[17] L. C. Li, L. Xia, Z. H. Xie, L. N. Hao, B. B. Shuai, and D. M. Liu, "In-line fiber Mach-Zehnder interferometer for simultaneous measurement of refractive index and temperature based on thinned fiber," *Sensor. Actuat. A-Phys.*, vol. 180, pp. 19-24, Jun. 2012.
[18] L. C. Li, L. Xia, Z. H. Xie, and D. M. Liu, "All-fiber Mach-Zehnder interferometers for sensing applications," *Opt. Express*, vol. 20, pp. 11109-11120, May. 2012.
[19] Y. Ma, X. G. Qiao, T. Guo, R. H. Wang, J. Zhang, Y. Y. Weng, Q. Z. Rong, M. L. Hu, and Z. Y. Feng, "Mach-Zehnder Interferometer Based on a Sandwich Fiber Structure for Refractive Index Measurement," *IEEE Sens. J.*, vol. 12, Jun. 2012.
[20] A. M. Hatta, G. Rajan, Y. Semenova, and G. Farrell, "SMS fibre structure for temperature measurement using a simple intensity-based interrogation system," *Electron. Lett.*, vol. 45, pp. 1069-1070, Oct. 2009.
[21] P. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, and G. Farrell, "Investigation of single-mode-multimode-single-mode and single-mode-tapered-multimode-single-mode fiber structures and their application for refractive index sensing," *JOSA B*, vol. 28, pp. 1180-1186, May. 2011.
[22] Q. Wang and G. Farrell, "All-fiber multimode-interference-based refractometer sensor: proposal and design," *Opt. Lett.*, vol. 31, pp. 317-319, Feb. 2006.
[23] P. Wang, G. Brambilla, M. Ding, T. Lee, L. Bo, Y. Semenova, Q. Wu, and G. Farrell, "Enhanced refractometer based on periodically tapered small core singlemode fiber," *IEEE Sens. J.*, vol. 13, pp. 180-185, Jan. 2013.
[24] G. Brambilla, "Optical fibre nanowires and microwires: a review," *J. Opt.*, vol. 12, Apr. 2010.
[25] P. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, and G. Farrell, "High-sensitivity, evanescent field refractometric sensor based on a tapered, multimode fiber interference," *Opt. Lett.*, vol. 36, pp. 2233-2235, Jun. 2011.
[26] P. Wang, M. Ding, L. Bo, Y. Semenova, Q. Wu, G. Farrell, and G. Brambilla, "Fiber tip high temperature sensor based on multimode interference" *Opt. Lett.*, vol. 38, pp, 4617-4620, Nov. 2013.