All-Optical Tuning of Au Nanocluster Functionalized Microfibre Coil Resonator

Yu Yin¹, Shi Li¹ and Pengfei Wang¹,²

¹ Key Laboratory of In-fibre Integrated Optics of Ministry of Education, College of Physics and Optoelectronic Engineering, Harbin Engineering University, Harbin 150001, China.
² Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, 518060, China

Email: m18204313488@163.com, pengfei@tu.dublin.ie

Abstract. An all-optical tunable microfibre coil resonator (MCR) functionalized using Au nanoclusters (AuNCs) was investigated and demonstrated. The MCR was manufactured by winding tapered fibre on a hollow rod of low refractive index polycarbonate (PC) resin to form a fluidic channel, and the AuNCs aqueous solution was injected into the channel to complete the functionalization process. The resonance wavelength and extinction ratio can be tuned using a pump laser with wavelength of 808 nm due to the photo-thermal effect and photon generated carriers from strong absorption of AuNCs at 808 nm, resulting light-matter interaction and providing all-optical tuning properties, including variations of resonance wavelength and extinction ratio. The variation rate of the resonance wavelength and extinction ratio were determined as 69 pm/mW and 0.459 dBm/mW. The response times of the MCR functionalized with the AuNCs are 11.99 s (rising) and 11.41 s (falling). The AuNCs functionalized MCR has several advantages compared to other tunable resonator devices, including easy fabrication, high tuning efficiency, low cost and all-fibre construction.

1. Introduction
The all-optical tuning functionality of optical fibre based on optical nonlinear effects attracted has much attention due to the latent applications including optical signal processing and optical communication [1, 2]. However, due to the low nonlinear coefficient of conventional optical fibres, the tuning ability of optical fibre based devices is restricted. Thus, the nonlinearity can be enhanced by doping the fibres with materials such as rare earths and transition metals. At present, all-optical switching and microwave phase shifters have been realized utilizing doped fibres [3, 4]. In addition, microfibres exhibit a strong evanescent field and high surface intensity field, which can enhance the light matter interaction and provide the possibility for all-optical tuning [5]. Microfibre resonators can be sub-classified into a number of types: microloop (MLR), microknot (MKR) and microcoil based devices and have been applied as fibre sensors [6], fibre lasers [7], fibre couplers [8], add-drop filters [9] and slow light systems [10]. The microfibre coil resonator (MCR) described in this article was fabricated by wrapping the microfibre on a supporting rod to form a coil structure, which has advantages of providing a long coupling length, strong evanescent field, compact size and high stability [11] resulting in potential
applications in all-optical tuning. Through all-optical tuning, the output light has different characteristics compared with the background light, which can suppress the interference of the background light.

All-optical tuning of microfibre devices and microfibre resonators have been fabricated using various materials including magnetic fluid [12], two-dimensional material [13], and photosensitive liquid crystal [14], etc. In recent years, the development, characterization and unique optical properties of nano-metal particles have attracted great attention in many fields, and their excellent photo-thermal property have been combined with optical fibre and applied in gas sensing [15], label-free biochemical measurement [16], water content in ethanol measurement [17] and heavy metal ions detection [18].

The optical properties of nano-metal particles are closely related to factors such as material, size, shape and the surrounding dielectric environment. Among them, Au nanoclusters (AuNCs), as a nanoscale photo-thermal conversion materials, have been used for the detection of glucose [19], heavy metal ions [20] and organophosphorus pesticides [21]. In the case of AuNCs, when illuminated by incident light, the incident photon energy is transferred to excite electrons due to the high photo-thermal effect, which ultimately relaxes the atoms to the ground state and locally generates heat. In addition, in the presence of external light excitation, the refractive index of AuNCs can be changed, which can be used in all-optical tuning.

In this paper, all-optical tuning of the resonance wavelength and extinction ratio of MCR functionalized with AuNCs is demonstrated. The device was fabricated by winding microfibre on a hollow rod made of low refractive index polycarbonate PC resin and then injecting AuNCs aqueous solution under light incident conditions based on a photodeposition method to form an AuNCs functionalized MCR (AMCR). The AMCR was irradiated using an 808 nm laser diode for all-optical tuning due to the photo-thermal effect and photon generated carriers. The resonance wavelength and extinction ratio tunabilities are 69 pm/mW and 0.459 dBm/mW, respectively and the response time was measured to be 12.113s and 11.185s for rising and falling time respectively. The experimental results described in this article indicate that the AMCR has great potential for all-optical tuning. The AMCR has advantages including easy fabrication, high tuning efficiency, low cost and all-fibre fabrication, and has broad application potential as an optical switch, tunable optical filter and all-optical modulator.

2. Experiment

A tapered microfibre with a 2.83 μm diameter was obtained by tapering a standard single-mode fibre (SMF-28) using the fused biconical taper method [22]. A 1 mm-diameter PMMA (polymethyl methacrylate) rod was cut into a 3 cm length and coated using a UV-curable low refractive index PC resin (Luvantix, PC373-LD) and then fully cured using a UV lamp (Lightningcure, LC8). The rod was dipped in acetone for 12 hours to dissolve the PMMA, which resulted in a hollow PC resin cylinder which in turn formed a simple fluidic channel as well as a supporting rod. The microfibre was wound around the supporting rod to form a 4-turn MCR with a gap between adjacent rings packaged using the same resin and cured using the same UV lamp. The MCR was then fixed onto a glass slide coated with the same resin which was fully cured using the same UV lamp to provide mechanical rigidity and facilitate subsequent measurements.

The experimental setup is shown in Fig. 1. The signal was provided by a broadband amplified spontaneous emission (ASE) source (YSL SC-series). The excitation (pump) light was provided by a laser diode (MDL-N-808) with a centre wavelength of 808 nm (LEOPTICS, LE-LS-808-XXFC). The signal and pump light were combined using a 90:10 optical coupler (OC, 1550 FBT Coupler), of which the 10% port was connected to the ASE source and the 90% port to the 808 nm laser. And the output port was connected to the MCR. The output spectra of the MCR were measured using an optical spectrum analyzer (YOKOGAWA, AQ-6370C). The Au nanoclusters (AuNCs) aqueous solution (XFNANO, XFJ62) was injected into the fluidic channel of the MCR using a syringe. The AuNCs were coated using Sodium Citrate, which permits functionalization and adhesion to the MCR. The AuNCs were deposited on the MCR using photodeposition to complete the fabrication of the functionalized.
3. Results and Discussion

The particle size and shape were investigated using transmission electron microscopy (TEM), and the resulting image is shown in Fig. 2(a), with the particles dispersed in liquid. The diameter of AuNCs is about 50 nm and their distribution based on TEM image is found to be homogeneous. The absorption spectrum of AuNCs is shown in Fig. 2(b), which shows a broad band with the peak wavelength located at 800 nm. The pump laser was therefore selected with a wavelength of 808 nm, which was close to the absorption peak for generating photothermal effects.

In the AuNCs functionalization process, the transmission spectrum of MCR was monitored in real time to determine that the AuNCs were adhering to the MCR. As shown in Fig. 3(a), since the AuNCs constantly moves and adheres to the MCR, the refractive index (RI) of the MCR increases and accordingly the transmission spectrum shifts to a longer wavelength. After about 20 minutes from commencement of the deposition process, following an initial rapid rise, the progressive resonance wavelength change became smaller (Fig 3(b)), indicating that the AuNCs in the aqueous solution were completely attached to the MCR.

In order to explore the all-optical tuning mechanism of AuNCs functionalized MCR (AMCR), it was necessary to consider light transmission in the MCR. For the light propagation in the MCR, there are two possible optical transmission paths: one is along the microfibre direction, and the other is through coupling into adjacent microfibre coils via the strong evanescent field, which can be expressed as [23]:
\[
\begin{bmatrix}
A_1(s) \\
A_2(s) \\
A_3(s) \\
\vdots \\
A_{n-2}(s) \\
A_{n-1}(s) \\
A_n(s)
\end{bmatrix}
\frac{d}{ds}
\begin{bmatrix}
A_1(s) \\
A_2(s) \\
A_3(s) \\
\vdots \\
A_{n-2}(s) \\
A_{n-1}(s) \\
A_n(s)
\end{bmatrix}
= \begin{bmatrix}
0 & k & 0 & 0 & \cdots & 0 & 0 & 0 & 1 \\
k & 0 & k & 0 & \cdots & 0 & 0 & 0 & 0 \\
0 & k & 0 & k & \cdots & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & \cdots & k & 0 & k & 0 \\
0 & 0 & 0 & 0 & \cdots & 0 & k & 0 & k \\
0 & 0 & 0 & 0 & \cdots & 0 & 0 & k & 0 \\
0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & k \\
\end{bmatrix}
\begin{bmatrix}
A_1(s) \\
A_2(s) \\
A_3(s) \\
\vdots \\
A_{n-2}(s) \\
A_{n-1}(s) \\
A_n(s)
\end{bmatrix}
\tag{1}
\]

where \(A_j(s)\) is the electric field amplitude of the \(j\)th coil with a space \(s\) around the coil and \(k\) is the coupling coefficient between adjacent two coils. The amplitude transmittance of the MCR can be defined as:

\[
T = \frac{A_n(S)e^{i\beta S}}{A_1(0)}
\tag{2}
\]

where \(\beta\) is the propagation constant of the fundamental mode and \(S\) is the length of each coil. For the fundamental mode, the eigenvalue equation can be expressed as [24]:

\[
\begin{bmatrix}
J_1'(U) + K_1'(W) \\
J_1'(U) + K_1'(W)
\end{bmatrix}
= \begin{bmatrix}
\frac{\beta}{2n_1^2} & V \\
V & \frac{\beta}{2n_1^2}
\end{bmatrix}
\]

\tag{3}

where \(n_1\) is the RI of the fibre, \(n_2\) is the RI of the surrounding environment, and \(d\) is the diameter of the fibre.

As the pump light propagates into the AMCR, the combined action of the photo-thermal effect and photon generated carriers caused by absorption by the AuNCs change \(n_2\), which influences the resonance mode of the MCR and hence the transmission spectrum. The all-optical tuning properties of AMCR using the pump light source are investigated in Fig. 4. The transmission spectra for various pump light output power levels were recorded, as shown in Fig. 4(a). In the experiments, the pump light power was varied from 9.83 mW to 15.05 mW, which resulted in a red-shift of the resonance wavelength and an extinction ratio reduction, as shown in Fig. 4(b) and 4(c). The experimental results of Fig. 4(b) and 4(c) exhibit a linear characteristic with a slope of 69 pm/mW for the resonance wavelength and -0.459 dBm/mW for the extinction ratio.

![Image](a) Transmission spectra of AMCR with different pump output light powers. (b) Resonance wavelength and (c) extinction ratio versus pump light power.
From the above experimental results, the resonance wavelength and extinction ratio have distinct variations when subjected to different pump power light excitation. The physical mechanisms for explaining the phenomena of all-optical tuning can be attributed to the photo-thermal effect and photon generated carriers of AuNCs. Under illumination from the pump source, the temperature of AuNCs increase due to the photo-thermal effect [25] and then the heat will be diffused to the MCR. The real part of the AuNCs RI is affected by the temperature [26]. Therefore, the refractive index of AuNCs is influenced by the external pump light power variation. Furthermore, when the 808 nm laser light is incident, the absorption of AuNCs at 808 nm leads to the excitation of electron-hole pairs, which in turn produces photon carriers. The photon generated carriers cause an RI change in both the real and imaginary parts of the RI of the AuNCs, which leads to a variation in the effective refractive index of the AuNCs [27]. Generally, the photo-thermal effects lead to the resonance wavelength shift, and photon generated carriers play a role in extinction ratio variation.

Response time is an important characteristic for the all-optical tuning properties of AMCR. The experimental setup for measuring response time is based on that shown in Fig. 1, but with the OSA was replaced by a photodetector (Kemai, PDA, 10 GHz) whose voltage output was recorded using an oscilloscope (Tektronix MDO4054-6, 5 GHz/s). A step change of pump power from 0 mW to 12.46 mW was used for response time representation. As seen in Fig. 5, The response time for reaching 90% of the full scale, was measured as 11.99 s (rising) and 11.41 s (falling), which were similar. Actually, the response time depends on the heat transfer rate of AuNCs and the UV-curable low refractive index PC resin. However, the thermal coefficient of the resin is very low (about 0.2 W/(m∙k)), resulting in the longer response time than observed in other work [28, 29]. To further optimize the response time, another low refractive index material with a larger thermal coefficient could be used or the AuNCs could be deposited directly on the surface of the microfibre during the fabrication process.

A comparison of important parameters (including sensitivity of resonance wavelength, extinction ratio and response time) based on different microfibre devices reported in the literature is presented in Table 1. The AMCR exhibits better performance than other microfibre devices combined with different materials. The response time is also smaller than GNR-integrated microfibre. In terms of extinction ratio sensitivity, the AuNCs functionalized MCR has a much larger tuning efficiency than other microfibre devices. In addition, for resonance wavelength tuning, the AMCR is superior to the microfibre devices based on conventional 2D materials. The high tuning efficiency of the AMCR is due to the combined performance of the MCR and AuNCs. The MCR has a longer coupling length which greatly enhances the light-matter interaction, while the AuNCs possess an excellent photo-thermal property, which is combined with the strong evanescent light of MCR. The tuning efficiency could be improved by reducing the fluidic channel thickness, optimizing the microfibre diameter and the AuNCs size.
Table 1. Comparison of various microfibre devices combined with different materials.

| Microfibre devices                  | Resonance wavelength sensitivity (pm/mW) | Extinction ratio sensitivity (dBm/mW) | Response time (s) |
|-------------------------------------|----------------------------------------|--------------------------------------|-------------------|
| Microfibre+graphene [30]            | -                                      | 0.2                                  | -                 |
| Microfibre+MoSe₂ [31]               | -                                      | 0.165                                | 0.6               |
| Microfibre+MXene (Ti₃C₂Tₓ) [32]     | 7.4                                    | -                                    | 0.0041            |
| Microfibre+gold nanorods [33]       | 160                                    | -                                    | 19 and 20         |
| Microfibre MZI+graphene [34]        | 0.856                                  | -                                    | -                 |
| MKR+WS₂ [28]                        | 0.85                                   | 0.4                                  | 0.12              |
| MKR+SnS₂ [35]                       | -                                      | 0.22                                 | 0.0032            |
| MKR+MoTe₂ [36]                      | 7.52                                   | 0.16                                 | ~0.003            |
| MCR+AuNCs (this work)               | 69                                     | 0.459                                | 11.99 and 11.41   |

4. Conclusion

In conclusion, an MCR functionalized using AuNCs was successfully fabricated and characterised and its all-optical tuning properties were experimentally demonstrated. An MCR with fluidic channel was functionalized using AuNCs and exhibits resonance wavelength and extinction ratio tuning when the output light of the 808 nm pump source power was varied. The pump source light interacts with the AuNCs changing their refractive index due to the photo-thermal effect and photon generated carriers and this in turn resulted in a variation of the resonance wavelength and extinction ratio. The variation rate of the resonance wavelength and extinction ratio are 69 pm/mW and 0.459 dBm/mW, respectively, for AMCR. The response time of the AMCR were measured as 11.99 s (rise) and 11.41 s (fall) which can be reduced by replacing the low refractive index material with one with a larger thermal coefficient or by depositing the AuNCs directly on the surface of microfibre. The device has several advantages including high tuning efficiency, easy fabrication, all-fibre construction and has excellent potential to be used as an optical switch, tunable optical filter and an all-optical modulator. The tuning efficiency can be further improved by reducing the fluidic channel thickness, optimizing the microfibre diameter and optimizing the AuNCs size.

References

[1] Agrawal G P, "Nonlinear fiber optics," in Nonlinear Science at the Dawn of the 21st Century(Springer, 2000), pp. 195-211.
[2] Holmes M, Williams D, and Manning R. Highly nonlinear optical fiber for all optical processing applications. IEEE Photonics Technology Letters 1995;7:1045-1047.
[3] Zang Z-G, and Yang W-X. Theoretical and experimental investigation of all-optical switching based on cascaded LPFGs separated by an erbium-doped fiber. Journal of applied physics 2011;109:103106.
[4] Liu W, and Yao J. Ultra-wideband microwave photonic phase shifter with a 360° tunable phase shift based on an erbium-ytterbium co-doped linearly chirped FBG. Optics letters 2014;39:922-924.
[5] Lou J, Wang Y, and Tong L. Microfiber optical sensors: A review. Sensors 2014;14:5823-5844.
[6] Yin Y, Li S, Ren J, Farrell G, Lewis E, and Wang P. High-sensitivity salinity sensor based on optical microfiber coil resonator. Optics express 2018;26:34633-34640.
[7] Li S, Yin Y, Lewis E, Garrell G, and Wang P. A twelve-wavelength thulium-doped fibre laser based on a microfibre coil resonator incorporating black phosphorus. Optics Communications 2019;437:342-345.
[8] Jasim A A, Zulkifli A Z, Muhammad M Z, Ahmad H, and Harun S W. Fabrication and...
characterization of a 2×2 microfiber knot resonator coupler. Chinese Physics Letters 2012;29:084204.

[9] Jiang X, Chen Y, Vienne G, and Tong L. All-fiber add-drop filters based on microfiber knot resonators. Optics letters 2007;32:1710-1712.

[10] Ma C-J, Ren L-Y, Xu Y-P, Wang Y-L, Zhou H, Fu H-W, and Wen J. Theoretical and experimental study of structural slow light in a microfiber coil resonator. Applied optics 2015;54:5619-5623.

[11] Yin Y, Yu J, Jiang Y, Li S, Ren J, Farrell G, Lewis E, and Wang P. Investigation of temperature dependence of microfiber coil resonators. Journal of Lightwave Technology 2018;36:4887-4893.

[12] Liu Y, Shi L, Xu X, Zhao P, Wang Z, Pu S, and Zhang X. All-optical tuning of a magnetic-fluid-filled optofluidic ring resonator. Lab on a Chip 2014;14:3004-3010.

[13] Wang Y, Gan X, Zhao C, Fang L, Mao D, Xu Y, Zhang F, Xi T, Ren L, and Zhao J. All-optical control of microfiber resonator by graphene's photothermal effect. Applied Physics Letters 2016;108:171905.

[14] Chen Z, Hsiao V K, Li X, Li Z, Yu J, and Zhang J. Optically tunable microfiber-knot resonator. Optics express 2011;19:14217-14222.

[15] Monzón-Hernández D, Luna-Moreno D, Escobar D M, and Villatoro J. Optical microfibers decorated with PdAu nanoparticles for fast hydrogen sensing. Sensors & Actuators B Chemical 2010;151:219-222.

[16] Lin H-Y, Huang C-H, Cheng G-L, Chen N-K, and Chui H-C. Tapered optical fiber sensor based on localized surface plasmon resonance. Optics Express 2012;20:21693-21701.

[17] Srivastava S K, Verma R, and Gupta B D. Surface plasmon resonance based fiber optic sensor for the detection of low water content in ethanol. Sensors and Actuators B: Chemical 2011;153:194-198.

[18] Raj D R, Prasanth S, Vineeshkumar T, and Sudarsanakumar C. Surface plasmon resonance based fiber optic sensor for mercury detection using gold nanoparticles PVA hybrid. Optics Communications 2016;367:102-107.

[19] Zhang J, Tu L, Zhao S, Liu G, Wang Y, Wang Y, and Yue Z. Fluorescent gold nanoclusters based photoelectrochemical sensors for detection of H2O2 and glucose. Biosensors & Bioelectronics 2015;67:296-302.

[20] Chansuvarn W, Tuntulani T, and Imyim A. Colorimetric detection of mercury(II) based on gold nanoparticles, fluorescent gold nanoclusters and other gold-based nanomaterials. Trends in Analytical Chemistry 2015;65:83-96.

[21] Yan X, Li H, Hu T, and Su X. A novel fluorimetric sensing platform for highly sensitive detection of organophosphorus pesticides by using egg white-encapsulated gold nanoclusters. Biosensors & Bioelectronics 2017;91:232-237.

[22] Chen G Y, Lee T, Zhang X L, Brambilla G, and Newson T P. Temperature compensation techniques for resonantly enhanced sensors and devices based on optical microcoil resonators. Optics Communications 2012;285:4677-4683.

[23] Sumetsky M. Optical fiber microcoil resonator. Optics Express 2004;12:2303-2316.

[24] Tong L, Lou J, and Mazur E. Single-mode guiding properties of subwavelength-diameter silica and silicon wire waveguides. Optics Express 2004;12:1025-1035.

[25] Bae J J, Yoon J H, Jeong S, Moon B H, Han J T, Jeong H J, Lee G-W, Hwang H R, Lee Y H, and Jeong S Y. Sensitive photo-thermal response of graphene oxide for mid-infrared detection. Nanoscale 2015;7:15695-15700.

[26] Kamikawachi R, Abe I, Paterno A, Kalinowski H, Muller M, Pinto J, and Fabris J. Determination of thermo-optic coefficient in liquids with fiber Bragg grating refractometer. Optics Communications 2008;281:621-625.

[27] Yi X, Zhang J, Yu J, Dong H, Wei Y, Luo Y, Zhong Y, Qiu W, Dong J, and Lu H. Theoretical investigation of optical modulators based on graphene-coated side-polished fiber. Optics
[28] Chen G, Zhang Z, Wang X, Li H, Jiang M, Guan H, Qiu W, Lu H, Dong J, and Zhu W. Highly sensitive all-optical control of light in WS$_2$ coated microfiber knot resonator. Optics express 2018;26:13759.

[29] Zhang D, Guan H, Zhu W, Yu J, Lu H, Qiu W, Dong J, Zhang J, Luo Y, and Chen Z. All light-control-light properties of molybdenum diselenide (MoSe$_2$)-coated-microfiber. Optics Express 2017;25:28536-28546.

[30] Chen J-H, Zheng B-C, Shao G-H, Ge S-J, Xu F, and Lu Y-Q. An all-optical modulator based on a stereo graphene–microfiber structure. Light: Science & Applications 2015;4:e360.

[31] Mao D, Cui X, Gan X, Li M, Zhang W, Lu H, and Zhao J. Passively Q-switched and mode-locked fiber laser based on an ReS$_2$ saturable absorber. IEEE Journal of Selected Topics in Quantum Electronics 2017;24:1-6.

[32] Wu Q, Chen S, Wang Y, Wu L, Jiang X, Zhang F, Jin X, Jiang Q, Zheng Z, and Li J. MZI-Based All-Optical Modulator Using MXene Ti$_3$C$_2$Tx (T=F, O, or OH) Deposited Microfiber. Advanced Materials Technologies 2019;4:1800532.

[33] Yang X, Long Q, Liu Z, Zhang Y, Yang J, Kong D, Yuan L, and Oh K. Microfiber interferometer integrated with Au nanorods for an all-fiber phase shifter and switch. Optics letters 2019;44:1092-1095.

[34] Luo Z-C, Liu M, Luo A-P, and Xu W-C. Two-dimensional materials-decorated microfiber devices for pulse generation and shaping in fiber lasers. Chinese Physics B 2018;27:094215.

[35] Lu H, Wang Z, Huang Z, Tao J, Xiong H, Qiu W, Guan H, Dong H, Dong J, and Zhu W. Resonance-assisted light-control-light characteristics of SnS$_2$ on a microfiber knot resonator with fast response. Photonics Research 2018;6:1137-1143.

[36] Lu H, Tao J, Chen L, Li Y, Liu L, Dong H, Dong J, Qiu W, Zhu W, and Yu J. All-Optical Tuning of Micro-Resonator Overlaid with MoTe$_2$ Nanosheets. Journal of Lightwave Technology 2019.