Highly sensitive refractive index sensor based on photonic crystal ring resonators nested in a Mach–Zehnder interferometer

Amir Hossein Abdollahi Nohoji1 · Mohammad Danaie1

Received: 25 February 2022 / Accepted: 13 July 2022 / Published online: 3 August 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
Today, with the rapid development of photonics, optical sensors are being considered as efficient tools for detecting environmental variations and have been regarded as one of the most important fields in photonic research. In this study, we have proposed a two-dimensional photonic crystal refractive index sensor using a combination of Mach–Zehnder interferometers and two ring resonators. Our goal is to increase the sensitivity and figure of merit of the sensor, so that the output transmission spectrum can be considerably shifted by changing the refractive index of the simulated analytes. The proposed photonic crystal sensor consists of a hexagonal array of silicon rods on a SiO2 substrate. The finite difference time domain method is used for the numerical simulation of the structure. In this regard, to validate the simulation results, two different commercial software have been used. The quality-factor and the sensitivity of the proposed structure are 1535 and 1658 nm/RIU, respectively, where RIU stands for the refractive index unit. In general, the structure has advantages such as low fabrication cost, high sensitivity to changes in refractive index and a high Q-factor.

Keywords Micro-ring resonator · Mach–Zehnder interferometer · Refractive index sensor · Sensitivity · Finite difference time domain (FDTD)

1 Introduction

Today rapid growth of photonic nanotechnology sciences has led to development of devices such as sensors, modulators, optical fibres, switches, etc. Refractive index (RI) sensors are used in a wide variety of physical detectors to measure the concentration of liquids and gases (Wo et al. 2012; Sun et al. 2015). Mach-Zehnder’s interferometer (MZI) (Zhao et al. 2017; Du et al. 2019) and micro-loop amplifiers (MRR) (Rahmatiyar et al. 2020; Sumetsky et al. 2007; Wang et al. 2020) are not only widely used in optical circuits, but have also recently been used as optical biosensors. So far, various optical sensors have
been proposed to detect refractive index changes designed from different structures, such as Mach-Zehnder interferometers (Du et al. 2019; Lu et al. 2009; Sun et al. 2016; Pawar and Kale 2016; Wu et al. 2015; Zhao et al. 2017), Ring Resonators (Arunkumar et al. 2017; Jannesari et al. 2016; Radhouene et al. 2017; Hsiao and Lee 2009), Fabry–Perot interferometers (FPI) (Wei et al. 2008). A Mach–Zehnder interferometer can be simulated using FDTD while it consists of an optical y-splitter and a y-combiner waveguide. In Tasaki et al. (2020) the bending radius of Y waveguides at 385 μm and the average free spectral range (FSRs) of 18 nm are optimized for the MZI model. Also, a MZI can be used as an optical switch. A low-consumption MZI have been presented as a photonic crystal switch using a phase change material (PCM) (Kumar, et al. 2020). Also, MRRs can be used in the nonlinear mode as an all-optical switch or sensor to shift the resonant wavelength by changing the refractive index (Rakshita Rakshit et al. 2013).

In this study, we demonstrated the combination of MRR with MZI as a highly sensitive RI sensor. For the presented topology, the transmission spectrum experiences a considerable wavelength shift as a result of analyte’s RI change. In fact, we used two MRRs nested in an MZI and showed that a small change in refractive index could cause a large change in the resonance wavelength of the structure.

2 Structure design

In this structure, an optical splitter and a combiner connected to two straight waveguides are used to design a photonic crystal MZI. The structure is designed using a hexagonal array of silicon rods in an air background. The optical response of the structure is obtained using the Lumerical’s FDTD Solver. Two photonic crystal rings resonators (PhCRR) are located between straights waveguide arms. Typically, each ring resonator is formed by removing rods in the original photonic crystal (PhC) lattice. The structure is shown in Fig. 1. The lattice constant and the diameter of the rods are considered to be Λ = 1 μm and r = 200 nm, respectively. To determine the refractive index of the analyte, the structure can be placed in the analyte. The refractive index of silicon (Li 1980) and water (Hale and...
Querry 1973; Thormählen et al. 1985) as analytes are approximately 3.436 and 1.33 at the wavelength range of 2900 to 3100 nm, respectively.

In fact, each of the PhCRR arms acts separately in both through and drop ports (Sreenivasulu et al. 2018; Robinson and Nakkeeran 2013). Figure 2 shows a PhCRR designed in the PhC lattice. Using the splitter, half of the source wave is divided in each of the straight waveguide arms. Each arm plays the role of through and drop relative to each other (Fig. 2). In the photonic crystal ring resonator nested in Mach–Zehnder interferometer (RR-MZI), light is evenly distributed on both splitter arms and then coupled to the PhCRRs from each side up and down. Actually, at the resonant wavelength, both PCRRs act as one meta-ring resonator.

### 3 Simulation and optimization

The photonic band structure in the normalized frequency range of 0.28 to 0.37 [a/λ] for the transverse magnetic state (TM) is shown in Fig. 3. In fact, wavelengths between 2700 and 3500 nm can pass through the structure’s waveguides.
At the input wavelength of 2971 nm, when the whole structure is immersed in water as an analyte, both RRs are paired. Consequently, light passes through MZI arms and it is later collected in the combinator and transmitted to the output port of MZI. At this wavelength, the maximum amount of light reaches the output port, where the normalized transmission is equal to 0.82. By a 13 nm shift in the input wavelength, the structure will not allow light to pass through, resulting in the MZI output being minimized (Fig. 4a). This results a quality factor (Q-factor) (Siraji and Zhao 2015; Saha and Sen 2018; Kolli et al. 2021; Rebhi and Najjar 2020; Olyaee and Mohebzadeh-Bahabady 2014) approximately equal to 1500. Equation (1) shows the relationship used for calculation of the Q-factor of the photonic crystal ring resonators.

\[
Q_{factor} = \frac{\lambda(\text{peak resonance})}{\text{FWHM Bandwidth}}
\]

where FWHM is the full width at half maximum (measured using the transmission spectrum). For validation, the results obtained using two different commercial software (Rsoft photonics CAD suite and Lumerical) have been superimposed in Fig. 4b. As seen in Fig. 4b, a very good agreement is observed between the results obtained in each case which confirms the validity of the results.

To optimize the structure, four rods (a and b) have been added at the MZI input and output (Fig. 5). The optimum radii of rods a and b were obtained by sweeping as 185 and 100 nm, respectively. The normalized transmission of the optimized structure increased from 0.82 to 0.93 (Fig. 6). Also, the Q-factor increase from 1518 to 1535.

The sensitivity (Olyaee and Mohebzadeh-Bahabady 2014; Zhao et al. 2016; Rindorf and Bang 2008; Aly and Zaky 2019; Liu et al. 2018; Liang et al. 2021) of the structure is also calculated as follows:

\[
S = \frac{\Delta\lambda(\text{peak})}{\Delta n_{\text{analyte}}} \left[ \frac{\text{nm}}{\text{RIU}} \right]
\]

where, \(\Delta\lambda\) is the change in resonance peak while the refractive index of analyte changes with the value of \(\Delta n\). The sensitivity of the structure is about 1658 [nm/RIU], which

---

Fig. 4  a Output normalized transmission at 2971 nm with water as analyte, b The normalized transmission comparison using Rsoft and Lumerical simulators using the FDTD method
indicates a good separation. Figure 7 shows the normalized transmission for different refractive indices.

The figure of merit (Alfimov and Zheltikov 2006; Chowdhury and Maity 2017; Rahman-Zadeh et al. 2019) (FoM) is a parameter for comparing the performance of sensors, which is defined as follows:

$$FOM = \frac{S}{FWMH}$$  \hspace{1cm} (3)

The resonance wavelength and Q-factor for different analyte refractive indices are plotted in Fig. 8a, b, respectively. Also, the sensitivity and FOM of the sensor are shown in Fig. 8c, d, respectively. Actually, with increasing the refractive index of the analyte, the Q-factor increases and the sensitivity and FOM decreases. The FWHM bandwidth for the refractive indexes of the various analytes is about 1.95 nm, and the average FOM of sensor is about 840 RIU$^{-1}$. 

Fig. 5 The optimized structure

Fig. 6 The transmission spectrum for the optimized structure presented in Fig. 5
4 Discussion and comparisons

In this section, the performance of different RI sensors is compared with the proposed structure. The electric field for the optimized structure (shown in the Fig. 5) shows that

![Graph showing normalized transmission vs. wavelength for different refractive indices.](image)

![Graphs showing resonance wavelength, Q-factor, sensitivity, and FOM vs. refractive index.](image)
at the input wavelength of 2959 nm, both PCRRs are coupled together and light passes through the straight waveguides and it is transmitted to the MZI output port. Instead, at 2946 nm, no signal is directed to MZI output. The electric field intensities though the structure are shown in Fig. 9a, b.

Some of the best refractive index sensors are listed in Table 1, where the resolution of the sensors is determined by the following equation:

$$R = \frac{\Delta n_{\text{analyte}} \times \Delta \lambda_{\text{min}}}{\Delta \lambda_{(\text{peak})}} \text{(RIU)}$$  \hfill (4)

As seen in Fig. 10, two nested ring resonators are used in a Mach–Zehnder to create a large ring resonance at the sensor detection wavelength. As a result, the structure has a higher sensitivity and quality factor than the other works mentioned in the Table 1. Based on the knowledge of the authors, coupling both arms or a Mach–Zehnder to central resonators has not been proposed before. In this case the two small PhC resonators are combined to form a large-scale super resonator, which incorporates Mach–Zehnder arms as part of the resonator loop.

To investigate the effect of changes in device length, the number of rods between the two ring resonators and Mach-Zander arms is changed (Fig. 11) and the normalized output spectrum for each case is shown in Figs. 12 and 13, respectively. To have the maximum bandwidth around the main wavelength of the sensor, a centrality index is defined as follows:

Fig. 9 The electric field intensity for the optimized structure, a at the wavelength of 2959 nm, b at the wavelength of 2946 nm
Table 1  Performance comparison of Refractive Index Sensitive Sensor based on Photonic Crystal

| Structure                                    | RI Range (RIU) | Sensitivity (nm/RIU) | Resolution (RIU) | Q-factor          | Figure of merit (RIU − 1) | Refs.                                      |
|----------------------------------------------|----------------|----------------------|------------------|-------------------|---------------------------|--------------------------------------------|
| Ring cavity                                 | 1.33–1.44      | 536–600              | 1.24×10−4        | 1432–2081         | 487                       | Rahman-Zadeh et al. (2019)                 |
| PCF with up-tapered joints                   | 1.33–1.379     | 252                  | 8×10−5           | _                 | _                         | Zhao et al. (2015)                        |
| PCF-MZI with two HTCRS                       | 1.3333–1.3574  | 181.96               | _                | _                 | _                         | Zhao et al. (2017a)                       |
| Cladding Etched PFC MZI                      | 1.333–1.381    | 359.37               | 4.73×10−5        | _                 | _                         | Du et al. (2019)                          |
| H-shaped PCF coated with silver and graphene | 1.33–1.36      | 2770                 | 3.61×10−6        | _                 | _                         | Li et al. (2020)                          |
| T-shaped PC                                  | 1.05–1.10      | 1040                 | _                | _                 | _                         | Turduev et al. (2017)                     |
| ring-shaped slotted PC                       | 1–1.5          | 1450                 | _                | _                 | _                         | Kassa-Baghdouche and Cassan (2019)        |
| MIM-plasmonic ring shaped                    | 1–1.2          | 636                  | _                | 269               | 211.3                     | Danaie and Shahzadi (2019)                |
| Fano resonance                               | 1–1.4          | 1060                 | _                | 145               | 176.7                     | Zafar and Salim (2015)                    |
| PCF-MZI                                      | 1.3735–1.3994  | 252.88               | _                | _                 | _                         | Dong et al. (2022)                       |
| Current work                                 | 1.33–1.37      | 1658                 | 6×10–5           | 1535              | 840                       |                                            |
where $\lambda_c$ is the main wavelength of the sensor and $\lambda_{\text{max}}$ and $\lambda_{\text{min}}$ show the maximum and minimum peaks around the main wavelength, respectively, so that in the $D\lambda$ range, the sensor is considered as a single mode device (Fig. 14).

The results of the study on the effect of device length on the sensitivity index and centrality of the transmission spectrum for changes in the number of rods between the two ring resonators and Mach-Zander’s arms are given in Tables 2 and 3 respectively. As mentioned in these tables, the optimal state is for the distance between the two ring resonators with 6 rods (a 6A distance) and the number

\[
\text{Centrality index\%} = \left(1 - \frac{\lambda_c - \frac{D\lambda}{2}}{D\lambda}\right) \times 100
\]  

(5)

where

\[
D\lambda = \lambda_{\text{max}} - \lambda_{\text{min}}
\]  

(6)

Fig. 10 Schematic representation of the creation of a super resonator at the wavelength of 2959

Fig. 11 The effect of optimized structure length, $D$ and $L$ determine the number of rods in the space between the two ring resonators and Mach-Zander’s arms, respectively
of rods in the MZI arms is 27. For this case, it has a sensitivity of 1658 (nm/RIU) and a centrality index of 98.77%. It is also clear from the results that the RI sensitivity is weakly dependent on the length of the device. Also, by changing the lattice constant, the main wavelength of the device can be easily adjusted in the range of 1550 or 1310 nm. For this purpose, the lattice constant for the wavelengths of 1550 and 1310 nm should be considered to be 522 and 440 nm, respectively, and the transmission spectrum for each are shown in Fig. 15a, b.
Conclusions

We have proposed a sensitive refractive index sensor based on photonic crystal ring resonators nested in a Mach–Zehnder interferometer. The sensor structure is simulated using FDTD method and has a good quasi-linear sensitivity to changes in the refractive index of the analyte. In the RI range of 1.33 to 1.37 the average values of Q-factor and

---

**Table 2** Centrality and sensitivity index in terms of the number of rods between the two ring resonators

| Number of rods between two ring resonators (D) | Centrality index % | Δλ (nm) | Sensitivity (nm/RIU) |
|-----------------------------------------------|-------------------|---------|---------------------|
| 2D                                            | 90.38             | 52      | 1631                |
| 3D                                            | 97.72             | 44      | 1649                |
| 4D                                            | 91.02             | 39      | 1609                |
| 5D                                            | 96.34             | 41      | 1622                |
| 6D                                            | 98.77             | 61      | 1658                |
| 7D                                            | 96.93             | 49      | 1614                |
| 8D                                            | 90.81             | 49      | 1597                |
| 9D                                            | 96.15             | 39      | 1627                |

**Table 3** Centrality and sensitivity index in terms of the number of rods of MZI arms

| Number of rods between MZI arms (L) | Centrality index % | Δλ (nm) | Sensitivity (nm/RIU) |
|-------------------------------------|-------------------|---------|---------------------|
| 23L                                 | 84.66             | 75      | 1698                |
| 25L                                 | 99.57             | 35      | 1654                |
| 27L                                 | 99.77             | 61      | 1658                |
| 29L                                 | 89.47             | 38      | 1695                |
| 31L                                 | 92.85             | 49      | 1626                |
| 33L                                 | 94.64             | 56      | 1668                |

---

5 Conclusions

We have proposed a sensitive refractive index sensor based on photonic crystal ring resonators nested in a Mach–Zehnder interferometer. The sensor structure is simulated using FDTD method and has a good quasi-linear sensitivity to changes in the refractive index of the analyte. In the RI range of 1.33 to 1.37 the average values of Q-factor and
sensitivity are 1535 and 1658 (nm/RIU), respectively. Also, the average FOM in this work was calculated about 840 RIU$^{-1}$. Finally, the proposed structure is a good candidate for sensor design, to determine the refractive index or to identify different analytes.

**Author contribution** Design, analysis, and investigation: AHAN, Writing—original draft preparation: AHAN, Writing—review and editing: MD, Supervision: MD

**Availability of Data and Materials** The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Conflict of interest** The authors declare no conflict of interests.
Ethical approval

We the undersigned declare that the manuscript entitled “Highly Sensitive Refractive Index Sensor based on Photonic Crystal Ring Resonators Nested in a Mach–Zehnder Interferometer” is original, has not been fully or partly published before, and is not currently being considered for publication elsewhere. Also, results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

References

Alfimov, M.V., Zheltikov, A.M.: The figure of merit of a photonic-crystal fiber beam delivery and response-signal collection for nanoparticle-assisted sensor arrays. Laser Phys. Lett. 4(5), 363 (2006)

Aly, A.H., Zaky, Z.A.: Ultra-sensitive photonic crystal cancer cells sensor with a high-quality factor. Cryogenics 104, 102991 (2019)

Arunkumar, R., Suganya, T., Robinson, S.: Design and analysis of photonic crystal elliptical ring resonator based pressure sensor. Int. J. Photon. Opt. Technol. 1(3), 30–33 (2017)

Chowdhury, S., Maity, A.: Numerical analysis of photonic crystal fiber based hemoglobin sensor. Optik 130, 825–829 (2017)

Danaie, M., Shahzadi, A.: Design of a high-resolution metal–insulator–metal plasmonic refractive index sensor based on a ring-shaped Si resonator. Plasmonics 14(6), 1453–1465 (2019)

Dong, X., Zeng, L., Chu, D., Sun, X.: Highly sensitive refractive index sensing based on a novel Mach–Zehnder interferometer with TCF-PCF composite structure. Infrared Phys. Technol. 123, 104134 (2022)

Du, H., Sun, X., Hu, Y., Dong, X., Zhou, J.: High sensitive refractive index sensor based on cladding etched photonic crystal fiber Mach–Zehnder interferometer. Photon. Sens. 9(2), 126–134 (2019)

Hale, G.M., Querry, M.R.: Optical constants of water in the 200-nm to 200-μm wavelength region. Appl. Opt. 12(3), 555–563 (1973)

Hsiao, F.L., Lee, C.: Novel biosensor based on photonic crystal nano-ring resonator. Procedia Chem. 1(1), 417–420 (2009)

Jannesari, R., Ranacher, C., Consani, C., Lavchiev, V., Grille, T., Jakoby, B.: High-quality-factor photonic crystal ring resonator with applications for gas sensing. Procedia Eng. 168, 375–379 (2016)

Kassa-Baghdouche, L., Cassan, E.: Sensitivity analysis of ring-shaped slotted photonic crystal waveguides for mid-infrared refractive index sensing. Opt. Quant. Electron. 51(10), 1–1 (2019)

Kolli, V.R., Bahaddur, I., Prabhakar, D., Talabattulac, S.: A high Q-factor photonic crystal microring-resonator based sensor. Photon. Nanostruct.-Fundam. Appl. 43, 100870 (2021).

Kumar, K.V. et al.: Photonic crystal mach-zehnder optical switch based on phase change material. In: 2020 IEEE 20th International Conference on Nanotechnology (IEEE-NANO). IEEE, 2020.

Li, H.H.: Refractive index of silicon and germanium and its wavelength and temperature derivatives. J. Phys. Chem. Ref. Data 9(3), 561–658 (1980)

Li, T., Zhu, L., Yang, X., Lou, X., Yu, L.: A refractive index sensor based on H-shaped photonic crystal fibers coated with Ag-graphene layers. Sensors. 20(3), 741 (2020)

Liang, H., Shen, T., Feng, Y., Liu, H., Han, W.: A D-Shaped photonic crystal fiber refractive index sensor coated with graphene and zinc oxide. Sensors. 21(1), 71 (2021)

Liu, C., Su, W., Liu, Q., Lu, X., Wang, F., Sun, T., Chu, P.K.: Symmetrical dual D-shape photonic crystal fibers for surface plasmon resonance sensing. Opt. Express 26(7), 9039–9049 (2018)

Lu, P., Men, L.Q., Sooley, K., Chen, Q.: Tapered fiber Mach-Zehnder interferometer for simultaneous measurement of refractive index and temperature. Appl. Phys. Lett. 94(13), 131110-1-131110–3 (2009)

Olyaei, S., Mohebzedeh-Bahabady, A.: Two-curve-shaped biosensor using photonic crystal nano-ring resonators. J. Nanostruct. 4(3), 303–308 (2014)

Pawar, D., Kale, S.N.: Birefringence manipulation in tapered polarization-maintaining photonic crystal fiber Mach-Zender interferometer for refractive index sensing. Sens. Actuators A 252, 180–184 (2016)

Radhouene, M., Chhipa, M.K., Najjar, M., Robinson, S., Suthar, B.: Novel design of ring resonator based temperature sensor using photonic technology. Photon. Sens. 7(4), 311–316 (2017)

Rahman-Zadeh, F., Danaie, M., Kaatuzian, H.: Design of a highly sensitive photonic crystal refractive index sensor incorporating ring-shaped GaAs cavity. Opto-Electron. Rev. 27(4), 369–377 (2019)

Rahmatiyar, M., Afshari, M., Danaie, M.: Design of a refractive index plasmonic sensor based on a ring resonator coupled to a MIM waveguide containing tapered defects. Plasmonics 15(6), 2169–2176 (2020)
Rakshita Rakshit, J., Chattopadhyay, T., Roy, J.: Design of ring resonator based all optical switch for logic and arithmetic operations—a theoretical study. Optik 124, 6048–6057 (2013)
Rebhi, S., Najjar, M.: High Q-factor optical filter with high refractive index sensitivity based on hourglass-shaped photonic crystal ring resonator. Optik 202, 163663 (2020)
Rindorf, L., Bang, O.: Sensitivity of photonic crystal fiber grating sensors: biosensing, refractive index, strain, and temperature sensing. JOSA b. 25(3), 310–324 (2008)
Robinson, S., Nakkerean, R.: Photonic crystal ring resonator-based add drop filters: a review. Opt. Eng. 52(6), 060901 (2013)
Saha, P., Sen, M.: A slotted photonic crystal nanobeam cavity for simultaneous attainment of ultra-high Q-factor and sensitivity. IEEE Sens. J. 18(9), 3602–3609 (2018)
Siraji, A.A., Zhao, Y.: High-sensitivity and high-Q-factor glass photonic crystal cavity and its applications as sensors. Opt. Lett. 40(7), 1508–1511 (2015)
Sreenivasulu, T., Bhownick, K., Samad, S.A., Yadunath, T.I., Badrinarayana, T., Hegde, G.M., Srinivas, T.: Photonic crystal ring resonator-based four-channel dense wavelength division multiplexing demultiplexer on silicon on insulator platform: design and analysis. Opt. Eng. 57(4), 046109 (2018)
Sumetsky, M., Windeler, R.S., Dulashko, Y., Fan, X.: Optical liquid ring resonator sensor. Opt. Express 15(22), 14376–14381 (2007)
Sun, X.Y., Dong, X.R., Hu, Y.W., Li, H.T., Chu, D.K., Zhou, J.Y., et al.: A robust high refractive index sensitivity fiber Mach-Zehnder interferometer fabricated by femtosecond laser machining and chemical etching. Sens. Actuators A 230, 111–116 (2015)
Sun, X.Y., Chu, D.K., Dong, X.R., Zhou, C., Li, H.T., Zhi, L., et al.: Highly sensitive refractive index fiber inline Mach-Zehnder interferometer fabricated by femtosecond laser micromachining and chemical etching. Opt. Laser Technol. 77, 11–15 (2016)
Tasaki, K., et al.: Nested Mach-Zehnder interferometer optical switch with phase generating couplers. Jpn J. Appl. Phys. 59, 1 (2020)
Thormählen, I., Straub, J., Grigull, U.: Refractive index of water and its dependence on wavelength, temperature, and density. J. Phys. Chem. Ref. Data 14(4), 933–945 (1985)
Turduev, M., Giden, I.H., Babayiğit, C., Hayran, Z., Bor, E., Boztuğ, Ç., Kurt, H., Staliunas, K.: Mid-infrared T-shaped photonic crystal waveguide for optical refractive index sensing. Sens. Actuators, B Chem. 245, 765–773 (2017)
Wang, Q., Hamadeh, A., Verba, R., Lomakin, V., Mohseni, M., Hillebrands, B., Chumak, A.V., Pirro, P.: A nonlinear magnonic nano-ring resonator. NPJ Comput. Mater. 6(1), 1–7 (2020)
Wei, T., Han, Y.K., Li, Y.J., Tsai, H.L., Xiao, H.: Temperature-insensitive miniaturized fiber inline Fabry–Perot interferometer for highly sensitive refractive index measurement. Opt. Express 16(8), 5764–5769 (2008)
Wu, D., Zhao, Y., Li, J.: PCF taper-based Mach-Zehnder interferometer for refractive index sensing in a PDMS detection cell. Sens. Actuators B Chem. 213, 1–4 (2015)
Zafar, R., Salim, M.: Enhanced figure of merit in Fano resonance-based plasmonic refractive index sensor. IEEE Sens. J. 15(11), 6313–6317 (2015)
Zhao, Y., Li, X.G., Cai, L., Yang, Y.: Refractive index sensing based on photonic crystal fiber interferometer structure with up-tapered joints. Sens. Actuators, B Chem. 221, 406–410 (2015)
Zhao, Y., Xia, F., Li, J.: Sensitivity-enhanced photonic crystal fiber refractive index sensor with two waistbroadened tapers. J. Lightwave Technol. 34(4), 1373–1379 (2016)
Zhao, Y., Xia, F., Hu, H.F., Chen, M.Q.: A novel photonic crystal fiber Mach–Zehnder interferometer for enhancing refractive index measurement sensitivity. Opt. Commun. 402, 368–374 (2017)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.