

# 1 Multi-functional sensor based on photonic 2 crystal fiber using plasmonic material and 3 magnetic fluid

4 MUHAMMAD MUSAVIR BILAL,<sup>1,2,5</sup> SERVANDO LÓPEZ-AGUAYO,<sup>1,\*</sup>  
5 MAŁGORZATA SZCZERSKA,<sup>2,6</sup> AND HAMZA AHMAD MADNI<sup>3,4,7</sup>

6 <sup>1</sup> *Tecnológico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501,*  
7 *Monterrey, N.L. 64849, México.*

8 <sup>2</sup> *Department of Metrology and Optoelectronics, Faculty of Electronics, Telecommunications and*  
9 *Informatics, Gdańsk University of Technology, 11/12 Narutowicza Street, 80-233 Gdańsk, Poland.*

10 <sup>3</sup> *Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, 80-*  
11 *233 Gdansk, Poland.*

12 <sup>4</sup> *Department of Computer Engineering, Khwaja Fareed University of Engineering Information*  
13 *Technology, Rahim Yar Khan, 64200, Pakistan.*

14 <sup>5</sup> *A00829594@tec.mx*

15 <sup>6</sup> *malszcze@pg.edu.pl*

16 <sup>7</sup> *101101770@seu.edu.cn*

17 \* [servando@tec.mx](mailto:servando@tec.mx)

18 **Abstract:** A unique highly sensitive photonic crystal fiber is investigated based on plasmonic  
19 material and magnetic fluid (MF) for the simultaneous measurement of temperature and  
20 magnetic field sensor. The designed sensor is explored by tracing the different parameters such  
21 as birefringence, coupling length, power spectrum, and the peak wavelength of the transmission  
22 intensity. The magnetic field and temperature computation are attained simultaneously by  
23 examining the linear fitting curve and the movement of transmission peaks. The obtained  
24 sensitivity for temperature is 7.1nm/°C with an exposure range of 25°C to 100°C. In contrast,  
25 the magnetic field sensitivity is 12nm/Oe with a detection range of 160-200 Oe. In addition, the  
26 resolutions are -1.245°C, 5.53 Oe for temperature and magnetic field, respectively. Our  
27 inspected sensor is used to detect extremely low and high values of magnetic fields. The  
28 investigated structure is presented with simplification, compactness, easy implementation, and  
29 high sensitivity, which is expected to be a good foundation for the advancement of optical  
30 sensing devices in the future applications of industries, security, small grids, and environmental  
31 systems.

32 © 2022 Optica Publishing Group under the terms of the [OSA Open Access Publishing Agreement](#)

## 33 1. Introduction

34 The surface plasmon resonance (SPR)-based sensing technique has been revealed tremendous  
35 attention for its sensitivity to diverse applications in the fields of chemical sensing, biosensing,  
36 and environmental monitoring [1]. SPR is an optical circumstance happening when an  
37 electromagnetic impulse is produced in the metal surface due to the interface among optical  
38 electromagnetic fields and free electrons of the metal. It creates the stimulation of the surface  
39 plasmon polaritons (SPPs) spreading at the conductor-dielectric interface. The surface  
40 plasmons are extremely sensitive to the surrounding refractive index (RI), which is suitable for  
41 optical sensing applications [2,3]. There are many opportunities related to the SPR perception,  
42 which have been authorized to develop a wide variety of sensors that allocate outstanding  
43 features such as high resolution and a wide range of sensitivity. Furthermore, the linkage of  
44 optical fiber sensors with plasmonic materials adds some new and exciting features to their  
45 remarkable performance of real-time measurements, multiplexing, and the possibility of

46 developing all-fiber systems for remote sensing. SPR sensors have become a research hotspot  
47 because of their potential applications [4,5].

48 In the past, the prism-based SPR method was used. SPR sensors based on prism technology  
49 like slot waveguide and v-groove waveguide have been studied. However, the prism-based  
50 surface plasmon sensor structure is immense, complicated, and expensive because of optical  
51 and mechanical elements that are not appropriate for remote sensing [6].

52 Photonic crystal fiber (PCF) is a modern kind of microstructure optical fiber consisting of  
53 the fiber core, cladding, and metal nanowires in the air hole. The visual function of the PCF  
54 can be reformed by enhancing the periodic layout of the air holes of the fiber cladding, the size  
55 of the air holes, and the form of metal nanowire [7]. In contrast with the traditional optical  
56 fibers, combining the SPR technology with the PCF has been widely studied in the sensing  
57 fields due to their advantages of reliability, stability, small size, remote sensing ability,  
58 immunity to electromagnetic intervention, and extensive range of environmental  
59 monitoring [8]. On the other hand, instantaneous detection of the magnetic field and  
60 temperature is crucial for industrial applications. The accurate measurement of multi-  
61 parameters is almost complex due to the cross-sensitivity effect. Therefore, different functional  
62 plasmonic materials and liquids are added into the cladding or core region of the PCF to detect  
63 more than one parameter. Generally, silver, copper, gold, and aluminum are utilized as  
64 plasmonic materials. In recent years, gold and silver have become a hot topic for PCF-SPR  
65 based sensor techniques, but the performance and the measurement accuracy of silver material  
66 have been reduced due to the oxidation problem [9].

67 Therefore, gold delivers higher sensitivity while encountering the physical parameters. The  
68 high refractive index analyte-like magnetic fluid can be used for magnetic field sensing. As it  
69 is well known, the behaviors of ferromagnetic particles rely on both the external temperature  
70 and the applied magnetic field strength. The refractive index properties could be exploited as  
71 the imaginary basement to acquire the real-time detection of the magnetic field and  
72 temperature [10]. Recently, many researchers studied the surface plasmon resonance  
73 technology based on the photonic crystal fiber for sensing the different parameters and disposed  
74 the characteristics of the structure. The measurement of single parameters has been analyzed  
75 based on the photonic crystal fiber by utilizing the plasmonic materials and highly refractive  
76 index analytes [11,12]. In 2012, the surface plasmon resonances based on the PCF for the  
77 temperature measurement has been designed [13]. The simultaneous measurement of  
78 temperature and magnetic field based on cascaded photonic crystal fibers with surface plasmon  
79 resonance has been investigated [14]. Moreover, the D-shaped photonic crystal fiber (PCF)  
80 sensor based on the plasmonic effect and Sagnac interference technology has been constructed  
81 for measuring the magnetic field and temperature [15]. Similarly, the photonic crystal fiber-  
82 based magnetic fluid and FBG for magnetic field and temperature sensing came to exist [16]  
83 Meanwhile, it has been observed that the previous designs have more complex geometries (such  
84 as dual-core PCF, D-shape PCF, and cascaded PCF) which may create hurdles in the fabrication  
85 process and make it costly. Moreover, in the previous works, the single sensing, and  
86 multifunctional sensing materials have been investigated to measure the physical parameters,  
87 but a need still exists to improve the sensitivity with simple geometric structure at low cost and  
88 easiness.

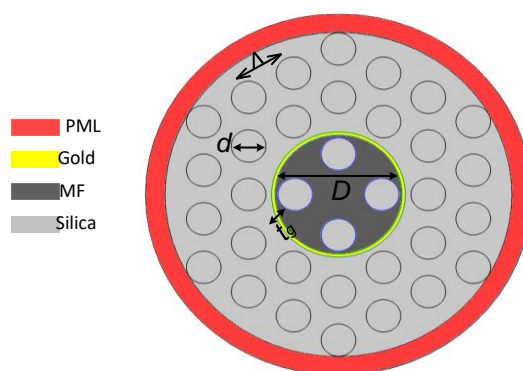
89 In this study, a photonic crystal fiber based on the plasmonic material and magnetic fluid  
90 has been exploited for the simultaneous measurement of temperature and magnetic field. The  
91 effective plasmonic material and sensing fluid are employed at the center of the PCF, which  
92 reduces the construction challenges. In contrast with the previously designed plasmonic  
93 material devices that work on transmission loss, our designed structure works based on the  
94 effective refractive index, birefringence, coupling length, power, and transmission spectrum  
95 attributes by utilizing the finite element method (FEM). The parameters of the designed  
96 structure are appropriately modified to achieve the best sensitivity of the proposed model. The  
97 achieved sensitivities are 12nm/Oe and 7.1nm/°C for magnetic field and temperature,



98 respectively. Furthermore, the figure of merit (FOM) and resolution for the proposed sensor  
99 have been calculated which is 665 Oe and 5.53 Oe, respectively. Our theoretical results are  
100 supported by a simulations study based on the COMSOL multiphysics software.

## 101 2. Design and fabrication

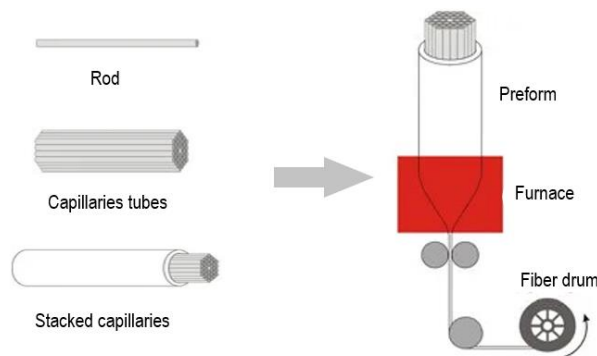
102 The geometrical structure of the photonic crystal fiber based on the plasmonic material is shown  
103 in Fig. 1. The cladding region is arranged with the air holes, and the size of each air hole is  
104 denoted by  $d$  ( $0.4\mu\text{m}$ ). The distance between two adjacent air holes is expressed with pitch  $\Lambda$   
105 ( $0.60\mu\text{m}$ ). The core region consists of the four air holes surrounded by a gold layer and is  
106 mentioned with  $D$  ( $1.46\mu\text{m}$ ). The core region is filled with magnetic fluid except for the air  
107 holes. The interaction of MF and plasmonic material leads to causes the external sensing  
108 schemes. A thin layer of gold is coated as a plasmonic material around the fiber that is  
109 chemically stable, has high-quality peak shifts, and it has less possibility of getting oxidized in  
110 the existence of fluid sensing mode. The thickness of the gold layer is mentioned with  $t_g$  (30nm).  
111 The outer layer contains a perfectly matched layer (PML). PML is manipulated to absorb  
112 radiant energy, which incident at several angles. All the sensor parameters are considered in  
113 such a way for better performance.



114  
115

Fig. 1. The geometrical structure of the proposed PCF.

116 The advantage of this type of fiber is a simple structure in manufacturing, and more air  
117 holes enclosed to the center enhance the less leakage of light. The designed geometry can be  
118 fabricated by applying a high-temperature furnace in a standard fiber drawing tower. After  
119 formulating fiber preform, silica rods and capillaries are assembled together using stack and  
120 draw technique [17]. Moreover, the fabrication process of the proposed structure and steps  
121 involved in designing have been shown in Fig. 2.



122  
123

Fig. 2. Fabrication Process of the proposed structure.



124 Combining the gold layer with PCF is a crucial matter that requires high temperature in  
 125 some deposition techniques like radio frequency, sputtering and thermal evaporation.  
 126 Moreover, chemical vapor deposition (CVD) is the most common and popular method that can  
 127 be exploited to deposit the gold layer effectively [18].

### 128 3. Materials and method

129 In the proposed structure, cladding region mostly consists of air holes with a refractive index  
 130 of 1, and silica is used as background material in the remaining parts of the cladding area. The  
 131 Sellmeier equation is applied to calculate the refractive index of silica. MF is a water-based  
 132 liquid consisting of ferromagnetic nanoparticles that are highly influenced by the external  
 133 magnetic field. Thus, changes in the refractive index of the MF lead to the shift in optical  
 134 properties. Therefore, the output spectrum of the fiber mode interferometer fluctuates due to  
 135 the interference between the evanescent mode field and the sensing material.

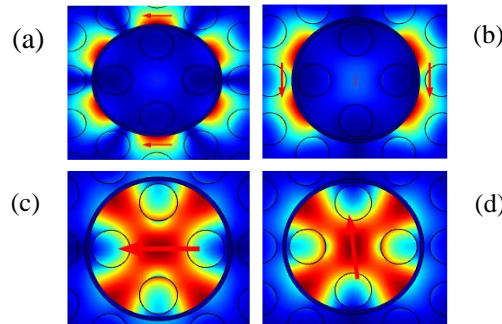
136 Moreover, the performances of ferromagnetic particles are dependent on both the external  
 137 temperature and applied magnetic field [19]. The tunable RI feature can be used to attain the  
 138 simultaneous measurement of temperature and magnetic field. Whereas the refractive index of  
 139 the magnetic fluid can be defined as a function of temperature and external magnetic field by  
 140 using the empirical equation of the Langevin method [20].

$$141 \quad n_{MF} = [n_m - n_0] \left[ \coth \left( a \frac{H - H_{c,n}}{T} \right) - \frac{T}{a(H - H_{c,n})} \right] + n_0, \quad (1)$$

142 where  $H_{c,n}$  is the critical field intensity, after which the refractive index  $n$  starts to change.  $n_0$   
 143 is the refractive index of MF when the magnetic field  $H$  is lower than  $H_{c,n}$ .  $n_m$  is the saturated  
 144 value of the refractive index.  $T$  denotes the temperature of MF.  $a$  is the fitting parameter. Next,  
 145 the gold layer enhances the detection capability of the sensor. The material dispersion of Au to  
 146 achieve the dielectric function is characterized by the Drude-Lorentz model [21].

$$147 \quad \epsilon_{Au} = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\epsilon \Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L \omega}, \quad (2)$$

148 where  $\epsilon_{Au}$  is the permittivity of gold,  $\epsilon_\infty = 5.9673$  is the permittivity of gold at high frequency,  
 149  $\omega = 2\pi c/\lambda$  is known as the angular frequency where  $c$  is the velocity of light,  $\omega_D = 2113.6 \text{ THz}$   
 150  $\times 2\pi$  is known as plasma frequency,  $\gamma_D = 15.92 \text{ THz}$  is known as damping frequency and  $\Delta\epsilon =$   
 151  $1.09$  is denoted by the weighting factor.  $\Omega_L = 650.07 \times 2\pi \text{ THz}$  and  $\Gamma_L = 104.86 \times 2\pi \text{ THz}$  are  
 152 known as Lorentz oscillator strength and spectral width, respectively.

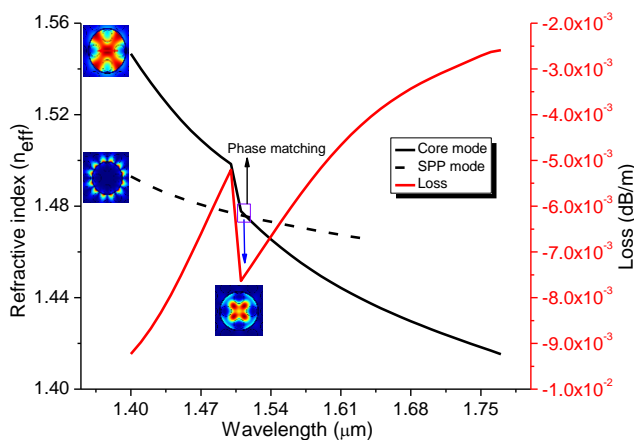


153 **Fig. 3.** Electric field distribution of proposed sensor, SPP mode: (a) X- and (b) Y-polarization; fundamental mode: (c)  
 154 X- and (d) Y-polarization, red arrows indicate the direction of light.  
 155

156 Finite element method (FEM) based on COMSOL multiphysics software is manipulated to  
 157 fabricate and evaluate the spreading mode of the proposed sensor. In computation, the physics-  
 158 controlled way of the meshing system is studied, and the more acceptable method of mesh size  
 159 is selected for better simulation results. Fig. 3(a,b) indicates the phenomena of light

160 transmission of SPP mode for  $X$  and  $Y$  polarization. Arrows indicated the direction of lights. It  
 161 can be clearly seen that the light is totally enclosed at the metal surface. SPP mode is an  
 162 electromagnetic excitation at the metal layer to display the resonance at the plasmonic surface.  
 163 On the other hand, Fig. 3(c,d) shows the core guided mode in which the light is strongly  
 164 confined at the center of the PCF due to the high refractive index of the magnetic fluid.

165 Fig. 4 shows the dispersion of the light spectrum between the fundamental mode and SPP  
 166 mode. In this graph, the effective index of the real part is taken from the left side and  
 167 confinement loss from the right side. The black solid and dotted lines show the core and SPP  
 168 mode variation, respectively. The red line shows the loss curve. It has been seen that at the  
 169 wavelength of  $1.5\mu\text{m}$ , the phase matching point occurred. At this point, the light is shifted from  
 170 SPP mode to fundamental mode, where the maximum loss has been observed. Usually, SPP  
 171 mode operates at visible radiation and fundamental mode operates at infrared radiation. Due to  
 172 the combination of analytes (MF) with a high refractive index of plasmonic material, the  
 173 resonance wavelength is received at  $1.5\mu\text{m}$  (IR) band as the energy is transferred from SPP  
 174 mode to fundamental mode. The effective refractive index ( $n_{eff}$ ) for core and SPP mode is  
 175 gradually decreased with the increase of wavelength. So, at the minimum wavelength, a higher  
 176 refractive index is achieved for  $X$ -polarization. A similar mechanism also happens for the  $Y$ -  
 177 polarized core-guided mode. But it illustrates the low loss intensity as compared to the  $X$ -  
 178 polarized core-guided mode. Due to the high intensity of the magnetic fluid and more  
 179 confinement of light, only the  $X$ -polarized core-guided mode is counted to assess the sensor  
 180 schemes.



181  
 182 **Fig. 4.** Dispersion relation of the core guided and SPP mode.

183 In this simulation study, energy coupling changes its position from the core mode to the  
 184 surface plasmon polarization (SPP) mode. The highest loss occurs at the resonance wavelength.  
 185 Basically, the calculation and discussions of the proposed PCF have been analyzed based on  
 186 the birefringence, coupling length, power spectrum, and transmission intensity, whereas the  
 187 confinement loss (CL) is the critical factor in assessing the performance of the sensor. The  
 188 following equation analyzes the model loss in dB/m of the fundamental core guided mode  
 189 [22,23].

190 
$$CL \left( \frac{dB}{m} \right) = 8.686 \times \left( \frac{2\pi}{\lambda} \right) \times Im [n_{eff}] \times 10^6, \quad (3)$$

191 The mechanism of confinement loss spectrum for  $X$  polarization core mode has been shown  
 192 in Fig. 5. After applying the external magnetic field strength, a peak loss curve has appeared at  
 193 the specific wavelength ( $1.53\mu\text{m}$ ) due to the influence of light with the change of the refractive  
 194 index. It has been seen that as the magnetic field is increased, the loss curve is also increased

195 regarding the wavelength. Additionally, at the maximum magnetic field strength, the loss will  
 196 be higher. After that, there is a linear curve occurred from the wavelength of  $1.54\mu\text{m}$  to  $1.8\mu\text{m}$ .

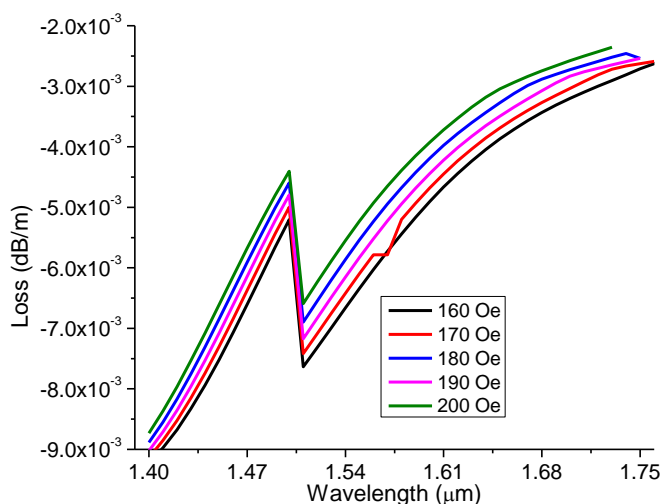


Fig. 5. The loss spectrum concerning with magnetic field.

197  
198

#### 199 4. Results and Discussions

200 In this model, for the whole process, the operating wavelength is taken from  $1.6\mu\text{m}$  to  $2.1\mu\text{m}$ .  
 201 The light spectrum between the X and Y polarization generates interference at a different  
 202 wavelength by applying the external parameters. This interference relates to the change of the  
 203 effective refractive index. The effective refractive index difference between the X and Y  
 204 polarization beams of light results in an optical phase difference. Filling the MF solution into  
 205 the center of the PCF reduces the effective refractive index. The low refractive index difference  
 206 is reliable for high sensitivity. Birefringence can be evaluated by using the following equation  
 207 [24].

$$208 \quad B = |n_x - n_y|, \quad (4)$$

209 where  $B$  is the birefringence,  $n_x$  and  $n_y$  are the differences in effective refractive index.

210 The intended sensor works based on the light intensity modulation. It is recognized that the  
 211 refractive index of the PCF background material (Silica) is not responsive to the magnetic field.  
 212 However, the casually consistent structure of magnetic particles changes under an external  
 213 magnetic field. Therefore, the relocation of  $Fe_3O_4$  nanoparticles leads to the refractive index  
 214 deviation accordingly. Commonly,  $n_{eff}$  increases with the magnetic field, which causes the shift  
 215 of peaks and dips of the proposed structure [25].

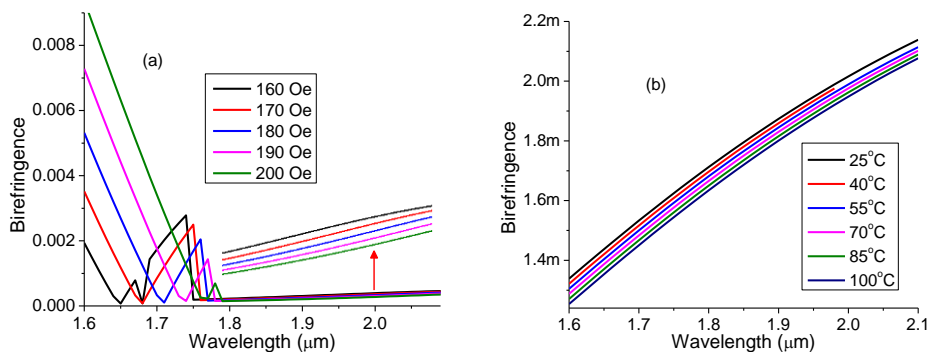


Fig. 6. The variation between the birefringence and wavelength by applied a) magnetic field and b) temperature.

216  
217

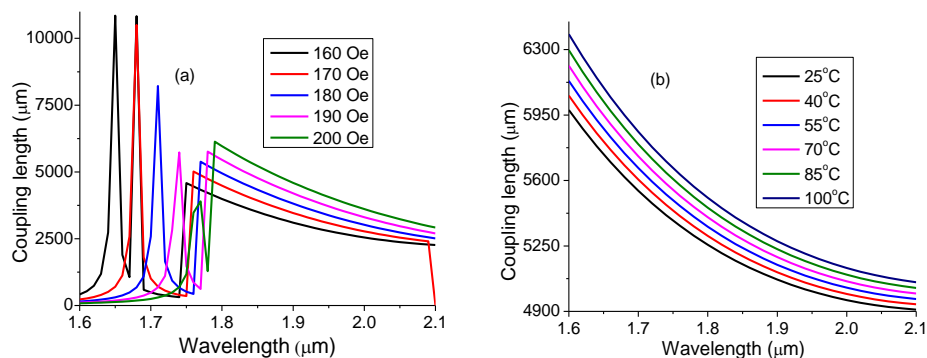


218 For sensing the magnetic field, the temperature has been kept constant at 25°C. The  
 219 variation between the birefringence and wavelength as a function of the external magnetic field  
 220 has been shown in Fig. 6(a). The range of the applied magnetic field is from 160 Oe to 200 Oe.  
 221 The measurement of the weak magnetic field has been analyzed before in many articles. In this  
 222 simulation study, the maximum range has been taken which is 200 Oe after that, the wavelength  
 223 shift of the designed sensor tends to be stable for the agglomerations saturations of magnetic  
 224 particles [26].

225 At the minimum wavelength, the maximum birefringence is obtained. The peak spectrum  
 226 has occurred at the wavelength of 1.75μm due to the effect of the magnetic fluid. Here, it has  
 227 been noticed that as the external magnetic field increases, the birefringence and wavelength  
 228 decrease. After that, there is a linear spectrum happened from 1.80μm to 2.1μm. Next, the  
 229 temperature mechanism with respect to birefringence and wavelength has been shown in Fig.  
 230 6(b). This graph illustrates that there is a constant increment of birefringence with the increase  
 231 of wavelength. By increasing the temperature, the birefringence is gradually decreased. The  
 232 values of temperature are taken from 25°C to 100°C. In accordance with the need for  
 233 applications in the real world, our chosen range of temperature is a bonus point to accept the  
 234 validity of our work as it is the environmental temperature. Thus, our designed sensor is best  
 235 for measuring ecological temperature. Another essential factor is known as coupling length,  
 236 which influences the performance of the sensor. Coupling length is associated with  
 237 birefringence, which can be measured by using the following equation [27].

238 
$$L = \frac{\lambda}{2 \times B}, \quad (5)$$

239 Here  $L$  is the coupling length,  $\lambda$  is the operating wavelength, and  $B$  is the birefringence.



240  
 241 **Fig. 7.** The relationship of a coupling length and wavelength as a function of a) magnetic field and b) temperature.

242 Fig. 7(a) shows the relation between the coupling length and the operating wavelength as  
 243 an external magnetic field function. This graph depicts the inverse reaction of the birefringence.  
 244 At the beginning of wavelength, a dip spectrum has been observed by varying the outer  
 245 magnetic field strength. Whereas, at the minimum magnetic field strength, the highest peak of  
 246 coupling length has been realized and then gradually decreases as the magnetic field increases.  
 247 After that, a constant light spectrum was received from the wavelength of 1.8μm to 2.1μm. It  
 248 is viewed that with the

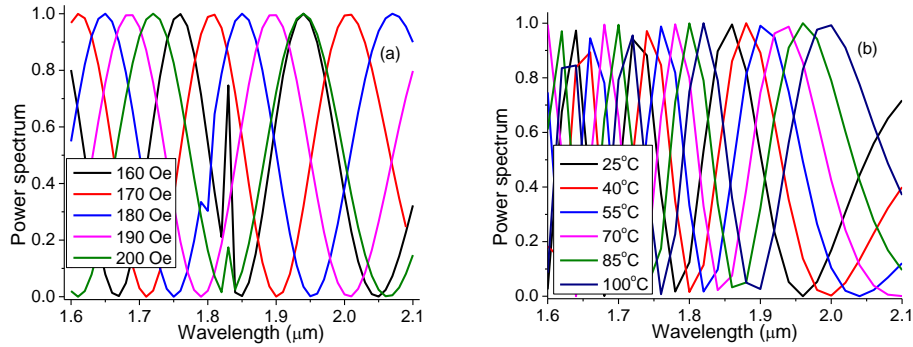
249 increasing of wavelength, the coupling length is slightly going to decrease. The same  
 250 phenomenon is represented in Fig. 7(b) by applying the temperature, but no peak wavelength  
 251 has been detected. Here, it is clearly shown that a linear spectrum has transpired between the  
 252 wavelength and the coupling length. The maximum coupling length has been attained at the  
 253 minimum wavelength and then steadily decreases by increasing the wavelength.

254 Based on the coupling-mode theory, the optical power changes from one mode to another,  
 255 along with the proposed sensor. The term coupling length can describe the power spectrum as

256 it is highly associated with birefringence. The power spectrum ensures the sensor proficiency,  
 257 which is determined by using the equation [28].

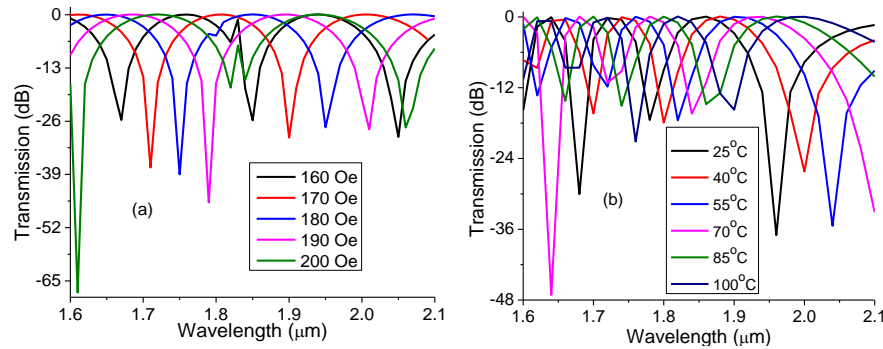
258 
$$P(out) = \sin^2\left(\frac{B \times \pi \times L}{\lambda}\right), \quad (6)$$

259 Where  $B$  is the birefringence,  $L$  is the coupling length, and  $\lambda$  is the operating wavelength.



260  
 261 **Fig. 8.** The variation of the power spectrum to wavelength in terms of a) magnetic field and b) temperature.

262 At the maximum power spectrum, the peak wavelength shift is occurred by applying the  
 263 external magnetic field strength has been shown in Fig. 8(a). Thus, the variation of light signals  
 264 has been achieved between the wavelength and power spectrum. As the wavelength is  
 265 increased, the shift of the power spectrum is moving at the maximum wavelength. On the other  
 266 hand, the same phenomena have been found after applying the external temperature. Fig. 8(b)  
 267 shows the peak shift which has been appeared at the maximum power spectrum. As the  
 268 temperature is going to increases, the peak shift moves to a higher wavelength.



269  
 270 **Fig. 9.** Comparison of a transmission spectrum with a) magnetic field and b) temperature.

271 Additionally, the transmission spectrum is the significant parameter to calculate the  
 272 sensitivity of the temperature and the magnetic field. The intensity modification of pulse  
 273 propagation has been exploited. The overall plasmonic impact significantly varies on the  
 274 transmittance. However, the wavelength sensitivity of the intended sensor can be computed  
 275 through the shift of the sharp peak of the transmittance curve on a specific wavelength for the  
 276 absolute deviation of the refractive index. The transmittance spectrum can be assessed by using  
 277 the following equation [28].

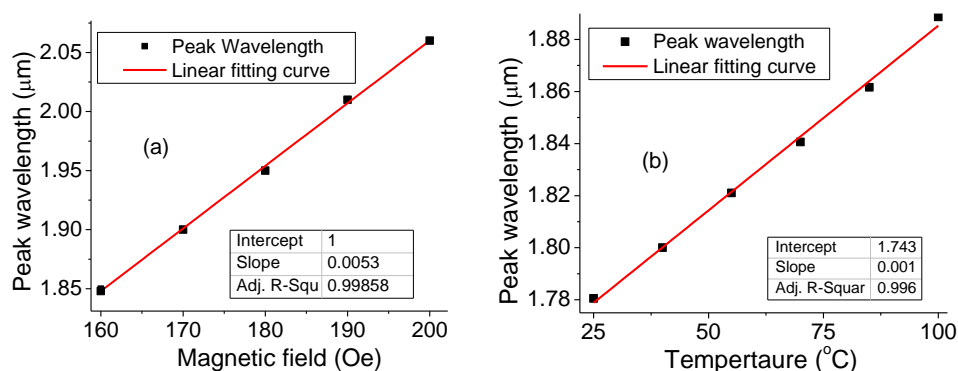
278 
$$T_r(dB) = 10 \times \log_{10}\left(\frac{P_{out}}{P_{in}}\right), \quad (7)$$

279 where  $T_r$  (dB) is the transmittance spectrum,  $P_{out}$  and  $P_{in}$  are the maximum output and input  
 280 power functions.



281 The comparison graph between transmission and wavelength as a serve of the external  
 282 magnetic field has been shown in Fig. 9(a). When the external magnetic field is applied,  
 283 different peak spectrums appear at different wavelengths. The transmittance outline fluctuates  
 284 from 0dB to -70dB, displaying a solid descending peak for each value of external magnetic  
 285 field strength. Furthermore, the maximum and minimum feasible transmittance outlines are -  
 286 70dB, -25dB for 200 Oe, and 160 Oe magnetic field strength, respectively. Next, Fig. 9(b)  
 287 shows the transmittance for the temperature 25°C–100°C. By varying the temperature, peak  
 288 shift has been displayed at different wavelengths. The transmittance summary modifies from 0  
 289 to -50dB, illustrating a sharp downward climax for each value of applied temperature. The  
 290 maximum transmission spectrum has been achieved at -49dB for the value of 70°C.

291 Based on the beyond consequence, the correlation among peak shifts and variation of  
 292 temperature and magnetic field has been depicted in Fig. 10(a) and (b), respectively. The linear  
 293 response of the wavelength alteration with the applied magnetic field and temperature is  
 294 exposed. The links of fitting curves are 0.99, signifying good linear connections. The best-  
 295 matched regression line reveals the best execution with a highly linear reaction. According to  
 296 Fig. 10, the variation of peak factors of the resonance wavelength precisely relies on the shift  
 297 of phase difference, which is induced by the change of effective RI. The linear fitting functions  
 298 of intercept and slope are 1, 0.0053, and 1.74, 0.0014 for magnetic field and temperature  
 299 sensing, respectively.



300  
 301 **Fig. 10.** The dip wavelength versus a) magnetic field and b) temperature effects.

302 Furthermore, the sensitivity rises and falls depending on the peak wavelength variation and  
 303 the change of external parameters. The following equations can be employed to determine the  
 304 sensitivities for both magnetic field and temperature [29,30].

305 
$$S(H) = \frac{\Delta\lambda_{peak}}{\Delta H_{Oe}}, \quad (8)$$

306 
$$S(^{\circ}C) = \frac{\Delta\lambda_{peak}}{\Delta T}, \quad (9)$$

307 Here,  $\Delta\lambda_{peak}$  is peak wavelength differences.  $\Delta H_{Oe}$  and  $\Delta T$  are the external magnetic field and  
 308 temperature variation, respectively. The obtained sensitivity was 12nm/Oe and 7.1nm/°C for  
 309 magnetic field and temperature. The acquired outcomes confirm that the proposed sensor can  
 310 be manipulated for simultaneous measurement. The RI of the MF material is the role of  
 311 temperature and the magnetic field change. The impact of this cross-sensitivity should not be  
 312 ignored. Nevertheless, it should be involved in the description model of the sensor.

313 The figure of merit (FOM) is the key metric to assess the operation of any SPR sensor which  
 314 can be evaluated using the following equation [31]

315 
$$FOM = \frac{S_{\lambda}}{FWHM}, \quad (10)$$



316 where  $S_s$  is the wavelength sensitivity determined in  $nm/Oe$  and FWHM is the full width at half  
 317 maximum calculated in  $nm$  from the transmission intensity. Higher FOM signifies better  
 318 sensing accuracy. Usually, a high-functioning sensor can be achieved when the sensitivity  
 319 increases with a consistent decrease in FWHM. The highest figure of merit (FOM) is achieved  
 320 as 665 Oe within the magnetic field range of 160 to 200 Oe. Similarly, another vital sensing  
 321 factor is the resolution of a sensor that implies the smallest refractive index change or variation  
 322 of sensing capacity. The resolution is identified as [32].

323 
$$R(Oe) = \Delta H \frac{\Delta\lambda_{min}}{\Delta\lambda_{peak}}, \quad (11)$$

324 where  $\Delta H$  indicates the alteration of external magnetic field strength,  $\Delta\lambda_{min}$  shows the  
 325 minimum difference between two peak wavelengths, and  $\Delta\lambda_{peak}$  is the maximum peak  
 326 wavelength shift. The maximum resolution was 5.53 Oe for the magnetic field strength of  $\Delta H$   
 327 = 180 Oe,  $\Delta\lambda_{min} = 0.06\mu m$ , and  $\Delta\lambda_{peak} = 1.95\mu m$ . The proposed sensor will be crucial in the  
 328 practical applications and in the advancement of optical sensing devices in a variety of contexts.  
 329 Table 1 shows the comparison results of temperature and magnetic field sensitivity  
 330 performances with those reported previously. This designed sensor has achieved the highest  
 331 sensitivity performance with the highest detection range than previous work done.

332 **Table 1. Comparatively results with the previous study.**

Sensing structures	Materials	Wavelength (nm)	Range		Sensitivity		Ref.
			H	T	H	T	
Mach-Zehnder interferometer	Magnetic fluid	1520-1620	0-7 Gs	20-60°C	0.72nm/Gs	-0.08nm/°C	[33]
Temperature-insensitive magnetic field sensor	Magnetic fluid	1520-1600	0.01-2.03 KOe	30-100°C	2.36pm/Oe	3.2pm/°C	[34]
Fiber Bragg grating	Magnetic fluid	1540-1570	0-9 mT	15-45°C	9.2pm/mT	11.9pm/°C	[35]
Twin-core photonic crystal fiber	MF, silver, graphene	550-700	0-50 mT	20-50°C	0.44nm/mT	-0.37nm/°C	[36]
Whispering gallery modes in a photonic crystal fiber	Magnetic fluid	1520-1560	0-38 mT	-----	110pm/mT	-----	[37]
Novel nested anti-resonant fiber-based magnetic fluids	Magnetic fluid	600-1000	100-400 Oe	-----	6.8nm/Oe	-----	[38]
Plasmonic material and magnetic fluid-based PCF	MF, gold	1400-2000	160-200 Oe	25-100°C	12nm/Oe	7.1nm/°C	Proposed work

333 **5. Conclusion**

334 In conclusion, our work illustrates multi-parameter sensing by exploiting the highly refractive  
 335 index sensing material. The photonic crystal fiber (PCF) based on coated plasmonic material  
 336 and magnetic fluid (MF) filled into the core region is designed and studied to realize the  
 337 simultaneous temperature and magnetic field measurement. The optical field scattering and loss  
 338 spectra at different wavelengths are studied based on the COMSOL Multiphysics software by  
 339 using the finite element method (FEM). The surface plasmon resonance (SPR) wavelength  
 340 demonstrates high sensitivity due to the solid dispersion between the SPR attenuated modes

341 and the magnetic fluid. Temperature and magnetic field depend on the base of the MF refractive  
342 index. The sensitivity of the spectral reaction of the device to the magnetic field and temperature  
343 is considered. By tracing the peak wavelength shift, the achieved sensitivity was 12nm/Oe and  
344 7.1nm/°C for the magnetic field and temperature sensor, respectively. The achieved figure of  
345 merit (FOM) and resolution for the proposed sensor is 665 Oe and 5.53 Oe, respectively. Our  
346 investigated structure is presented with simplification and compactness to achieve better  
347 sensitivity. In this way, a new area of enhancement for combining the SPR and magnetic fluid  
348 is reviewed to develop the field of plasmonic-based technologies. The proposed sensor is  
349 straightforward, practical, and suitable for industries, security, small grids, and environmental  
350 applications. The formation can be further improved by alternating the parameters and sensing  
351 materials to obtain better results.

352 **Disclosures.** The authors declare that there is no conflict of interest.

353 **Data availability.** Data implicit in the results submitted in this report are not publicly accessible at this time but may  
354 be obtained from the authors upon reasonable request.

355 **Funding:** This research was funded by the Instituto Tecnológico y de Estudios Superiores de Monterrey (Tecnológico  
356 de Monterrey), N.L. 64849, México. This work is also partially supported by the funds of the DS Programs of Faculty  
357 of Electronics, Telecommunications, and Informatics of the Gdańsk University of Technology.

358 **Acknowledgment:** This research was supported by the Tecnológico de Monterrey, Monterrey, N.L. 64849, México.  
359 This work is also partially supported by the funds of the DS Programs of Faculty of Electronics, Telecommunications,  
360 and Informatics of the Gdańsk University of Technology, as well as of the funds of the National Science Centre, Poland  
361 [2021/41/N/ST7/03801].

## 362 **References**

- 363 1. M. I. A. Isti, H. Talukder, S. R. Islam, S. Nuzhat, A. S. Hosen, G. H. Cho, and S. K. Biswas, "Asymmetrical  
364 D-channel photonic crystal fiber-based plasmonic sensor using the wavelength interrogation and lower  
365 birefringence peak method," *Results in Physics* **19**, 103372 (2020).
- 366 2. E. Rodríguez-Schwendtner, N. Díaz-Herrera, M. C. Navarrete, A. González-Cano, and Ó. Esteban,  
367 "Plasmonic sensor based on tapered optical fibers and magnetic fluids for measuring magnetic fields,"  
368 *Sensors and Actuators A: Physical* **264**, 58–62 (2017).
- 369 3. X. D. Wang, and O. S. Wolfbeis, "Fiber-Optic Chemical Sensors and Biosensors (2013-2015)," *Analytical  
370 Chemistry* **88**(1), 203–227 (2016).
- 371 4. H. Talukder, M. I. A. Isti, S. Nuzhat, and S. K. Biswas, "Ultra-High Negative Dispersion Based Single Mode  
372 Highly Nonlinear Bored Core Photonic Crystal Fiber (HNL-BCPCF): Design and Numerical Analysis,"  
373 *Brazilian Journal of Physics* **50**(3), 263–270 (2020).
- 374 5. F. Haider, R. A. Ahmmed, R. Ahmed, W. J. Chew, and G. A. Mahdiraji, "Alphabetic-Core Assisted  
375 Microstructure Fiber Based Plasmonic Biosensor," *Plasmonics* **15**(6), 1949–1958 (2020).
- 376 6. K. M. Rahman, M. S. Alam, R. Ahmed, and M. A. Islam, "Irregular hexagonal core based surface plasmon  
377 resonance sensor in near-infrared region," *Results in Physics* **23**, 103983 (2021).
- 378 7. M. M. Bilal, W. Bi, X. Liu, L. Yang, J. Wa, and H. A. Madni, "Magnetic field sensor based on the magnetic  
379 fluid infiltration into the cladding air holes of the solid-core photonic crystal fiber," *Optical Engineering*  
380 **58**(9), 096107 (2019).
- 381 8. A. A. Nair, C. S. Boopathi, M. Jayaraju, and M. S. M. Rajan, "Numerical investigation and analysis of  
382 flattened dispersion for supercontinuum generation at very low power using hexagonal shaped photonic  
383 crystal fiber," *Optik* **179**, 718–725 (2019).
- 384



- 385 9. M. M. Rahman, M. M. Rana, M. S. Anower, M. S. Rahman, and A. K. Paul, "Design and analysis of photonic  
386 crystal fiber-based plasmonic microbiosensor: an external sensing scheme," *SN Applied Sciences* **2**(7), 1–11  
387 (2020).
- 388 10. Y. Zhao, D. Wu, R. Q. Lv, and Y. Ying, "Tunable characteristics and mechanism analysis of the magnetic  
389 fluid refractive index with applied magnetic field," *IEEE Transactions on Magnetics* **50**(8), 1–5 (2014).
- 390 11. M. A. Mollah, S. M. R. Islam, M. Yousufali, L. F. Abdulrazak, M. B. Hossain, and I. S. Amiri, "Plasmonic  
391 temperature sensor using D-shaped photonic crystal fiber," *Results in Physics* **16**, 102966 (2020).
- 392 12. Y. Liu, X. Jing, S. Li, Y. Guo, S. Wang, J. Wang, and P. Yu, "High-sensitivity plasmonic temperature sensor  
393 based on gold-coated D-shaped photonic crystal fiber," *Applied Optics* **58**(18), 5115–5121 (2019).
- 394 13. Y. Peng, J. Hou, Z. Huang, and Q. Lu, "Temperature sensor based on surface plasmon resonance within  
395 selectively coated photonic crystal fiber," *Appl. Opt.* **51**(26), 6361–6367 (2012).
- 396 14. H. Liu, Y. Wang, C. Tan, C. Zhu, Y. Gao, H. Ma, and Z. Ren, "Simultaneous measurement of temperature  
397 and magnetic field based on cascaded photonic crystal fibers with surface plasmon resonance," *Optik* **134**,  
398 257–263 (2017).
- 399 15. H. Liu, H. Li, Q. Wang, M. Wang, Y. Ding, and C. Zhu, "Simultaneous measurement of temperature and  
400 magnetic field based on surface plasmon resonance and Sagnac interference in a D-shaped photonic crystal  
401 fiber," *Optical and Quantum Electronics* **50**(11), 1–11 (2018).
- 402 16. Y. Chen, Q. Han, W. Yan, Y. Yao, and T. Liu, "Magnetic-fluid-coated photonic crystal fiber and FBG for  
403 magnetic field and temperature sensing," *IEEE Photonics Technology Letters* **28**(23), 2665–2668 (2016).
- 404 17. M. M. Rahman, M. M. Rana, M. S. Anower, M. S. Rahman, and A. K. Paul, "Design and analysis of photonic  
405 crystal fiber-based plasmonic microbiosensor: an external sensing scheme," *SN Applied Sciences* **2**(7), 1–11  
406 (2020).
- 407 18. Q. M. Kamrunnahar, J. R. Mou, and M. Momtaz, "Dual-core gold coated photonic crystal fiber plasmonic  
408 sensor: Design and analysis," *Results in Physics* **18**, 103319 (2020).
- 409 19. F. Wei, A. K. Mallik, D. Liu, Q. Wu, G. D. Peng, and Y. Semenova, "Magnetic field sensor based on a  
410 combination of a microfiber coupler covered with magnetic fluid and a Sagnac loop," *Scientific Reports* **7**(1),  
411 1–9 (2017).
- 412 20. S. A. Mitu, K. Ahmed, M. Hossain, B. K. Paul, T. K. Nguyen, and V. Dhasarathan, "Design of Magnetic  
413 Fluid Sensor Using Elliptically Hole Assisted Photonic Crystal Fiber (PCF)," *Journal of Superconductivity  
414 and Novel Magnetism* **33**(7), 2189–2198 (2020).
- 415 21. L. Zhao, H. Han, N. Luan, J. Liu, L. Song, and Y. Hu, "A temperature plasmonic sensor based on a side  
416 opening hollow fiber filled with high refractive index sensing medium," *Sensors* **19**(17), 3730 (2019).
- 417 22. K. Ahmed, M. A. Alzain, H. Abdullah, Y. Luo, D. Vigneswaran, O. S. Faragallah, M. Eid, and A. N. Z.  
418 Rashed, "Highly Sensitive Twin Resonance Coupling Refractive Index Sensor Based on Gold-and MgF<sub>2</sub>-  
419 Coated Nano Metal Films," *Biosensors (Basel)* **11**(4), 104 (2021).
- 420 23. D. Vigneswaran, M. S. M. Rajan, B. Biswas, A. Grover, K. Ahmed, and B. K. Paul, "Numerical investigation  
421 of spiral photonic crystal fiber (S-PCF) with supporting high order OAM modes propagation for space  
422 division multiplexing applications," *Optical and Quantum Electronics* **53**(2), 1–11 (2021).
- 423 24. N. Ayyanar, D. Vigneswaran, M. Sharma, M. Sumathi, M. M. Rajan, and S. Konar, "Hydrostatic pressure  
424 sensor using high birefringence photonic crystal fibers," *IEEE Sensors Journal* **17**(3), 650–665 (2016).
- 425 25. M. Taghizadeh, F. Bozorgzadeh, and M. Ghorbani, "Designing magnetic field sensor based on tapered  
426 photonic crystal fibre assisted by a ferrofluid," *Scientific Reports* **11**(1), 1–9 (2021).



- 427 26. X. Bai, J. Yuan, J. Gu, S. Wang, Y. Zhao, and S. Pu, and X. Zeng, "Magnetic field sensor using fiber ring  
428 cavity laser based on magnetic fluid," *IEEE Photonics Technology Letters* **28**(2), 115–118 (2015).
- 429 27. K. Ahmed, M. Jabin, and B. K. Paul, "Surface plasmon resonance-based gold-coated biosensor for the  
430 detection of fuel adulteration," *Journal of Computational Electronics* **19**(1), 321–332 (2020).
- 431 28. M. A. Jabin, Y. Luo, G. D. Peng, M. J. Rana, K. Ahmed, T. K. Nguyen, and v. Dhasarathan, "Design and  
432 fabrication of amoeba faced photonic crystal fiber for biosensing application," *Sensors and Actuators A:  
433 Physical* **313**, 112204 (2020).
- 434 29. S. A. Mitu, K. Ahmed, M. Hossain, B. K. Paul, T. K. Nguyen, and v. Dhasarathan, "Design of Magnetic  
435 Fluid Sensor Using Elliptically Hole Assisted Photonic Crystal Fiber (PCF)," *Journal of Superconductivity  
436 and Novel Magnetism* **33**(7), 2189–2198 (2020).
- 437 30. Y. E. Monfared, C. Liang, R. Khosravi, B. Kacerovska, and S. Yang, "Selectively toluene-filled photonic  
438 crystal fiber Sagnac interferometer with high sensitivity for temperature sensing applications," *Results in  
439 Physics* **13**, 102297 (2019).
- 440 31. E. Haque, M. A. Hossain, and Y. Namihira, and F. Ahmed, "Microchannel-based plasmonic refractive index  
441 sensor for low refractive index detection," *Appl. Opt.* **58**(6), 1547–1554 (2019).
- 442 32. S. Zhang, W. Chen, H. Liu, Y. Ma, and M. Li, "Analysis of a magnetic field sensor based on photonic crystal  
443 fiber selectively infiltrated with magnetic fluids," *Optical Fiber Technology* **46**, 43–47 (2018).
- 444 33. X. G. Li, X. Zhou, Y. Zhao, and R. Q. Lv, "Multi-modes interferometer for magnetic field and temperature  
445 measurement using photonic crystal fiber filled with magnetic fluid," *Optical Fiber Technology* **41**, 1–6  
446 (2018).
- 447 34. X. Zu, P. Chan, C. C. Lew, W. S. Hu, L. Jin, Y. Liew, H. F. Chen, L. H. Wong, and W. C. Dong,  
448 "Temperature-insensitive magnetic field sensor based on nanoparticle magnetic fluid and photonic crystal  
449 fiber," *IEEE Photonics Journal* **4**(2), 491–498 (2012).
- 450 35. C. Li, T. Ning, X. Wen, J. Li, and C. Zhang, "Magnetic field and temperature sensor based on a no-core fiber  
451 combined with a fiber Bragg grating," *Optics & Laser Technology* **72**, 104–107 (2015).
- 452 36. H. Liu, C. Chen, H. Wang, and W. Zhang, "Simultaneous measurement of magnetic field and temperature  
453 based on surface plasmon resonance in twin-core photonic crystal fiber," *Optik* **203**, 164007 (2020).
- 454 37. A. Mahmood, v. Kavungal, S. S. Ahmed, G. Farrell, and Y. Semenova, "Magnetic-field sensor based on  
455 whispering-gallery modes in a photonic crystal fiber infiltrated with magnetic fluid," *Optics letters* **40**(21),  
456 4983–4986 (2015).
- 457 38. S. A. Mitu, K. Ahmed, F. M. Bui, P. Nithya, F. A. Al-Zahrani, M. A. Mollah, and M. M. Rajan, "Novel  
458 nested anti-resonant fiber based magnetic fluids sensor: Performance and bending effects inspection," *Journal  
459 of Magnetism and Magnetic Materials* **538**, 168230 (2021).
- 460

