Highly sensitive temperature sensing based on all-solid cladding dual-core photonic crystal fiber filled with the toluene and ethanol

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Abstract An all-solid cladding dual-core photonic crystal fiber (DC-PCF) filled with toluene and ethanol is proposed for the temperature sensing. The all-solid cladding is formed by using the fluorine-doped silica glass instead of the air holes in the cladding region. By selectively filling the toluene and ethanol into the three air holes near the core region, the characteristic of the temperature sensing is numerically investigated. The simulation results show that the average sensitivity of the temperature sensing can achieve -11.64 and -7.41 nm/℃ in the temperature ranges from 0 to 70 ℃ and -80 to 0 ℃, respectively, when the length of the DC-PCF is as short as 1.6 mm. The maximum sensitivity in the considered temperature ranges can be up to -15 and - 9 nm/℃, respectively. Moreover, the proposed temperature sensor is insensitive to the hydrostatic pressure.

Keywords: Photonic crystal fiber; Temperature sensor; All-solid cladding; Finite element method;

1. Introduction

Photonic crystal fiber (PCF) has important application in the development of novel optical devices due to its designable structure and unique optical characteristics, including adjustable dispersion, large mode field area, high birefringence, etc. In recent years, the sensing based on the PCFs has become a research hotspot [1-4]. At present, different kinds of PCF-based sensing have been reported, such as temperature sensing [1], refractive index sensing [2], magnetic sensing [3], pressure sensing [4], and so on. Among them, the temperature sensing has been attracting great research interests since it plays essential roles in the fields of medical testing, aerospace exploration, and food industry.

The PCF-based temperature sensing can be achieved by utilizing the liquid filling. As the PCF fabrication and multi-step infiltration technologies are developed [5], different sensing liquids, including toluene [6], ethanol [7], and liquid crystal [8], have been successfully filled into the PCFs. In 2016, Dong \textit{et al} reported an ethanol-filled band-gap PCF for the temperature sensing [9]. In 2017, Ma \textit{et al} demonstrated a toluene-filled PCF for the temperature sensing, where the average sensitivity can achieve -6.02 nm/℃ [10]. In 2019, Geng \textit{et al} proposed a compact oil-filled PCF for the temperature sensing based on the four-wave mixing effect, where the average sensitivity is 0.61 nm/℃ in the detection range...
of 30 to 150 °C [11]. In 2019, Mirza et al investigated a water-filled dual-core PCF (DC-PCF) for the temperature sensing, where the maximum sensitivity is 818 pm/℃ in the detection range of 30 to 70 °C [12]. In addition, the PCFs based on the surface plasmon resonance (SPR) effect can also be applied to the temperature sensing. In 2012, Peng et al reported a PCF-based temperature sensor, which was realized by selectively coating the gold film in the six air holes of the PCF [13]. In 2016, Liu et al achieved a PCF-based temperature-sensitive sensor by filling the liquid into the gold-coated air holes, where the average temperature sensitivity was $-3.08 \text{ nm/}^\circ\text{C}$ in the temperature range of 0 to 100 °C [14]. In 2017, Weng et al proposed a D-shaped liquid-filled PCF based on the SPR effect for the temperature sensing, where the average temperature sensitivity was $-3.635 \text{ nm/}^\circ\text{C}$ in the temperature range of 20 to 50 °C [15].

Recently, some investigations are concentrated on the all-solid cladding PCFs. Compared with the traditional air-silica PCFs, the all-solid cladding PCFs could avoid the deformation during drawing because other materials are used to take the place of the air holes in the cladding region. At present, different kinds of soft glasses are usually used as alternative materials in the design of the all-solid cladding PCFs [16, 17]. However, because of the large refractive index difference between the silica and soft glasses, their physical characteristics, including the transition temperature, viscosity coefficient, thermal expansion coefficient, have obvious difference. Thus, it is a great challenge to fabricate the soft glasses-based all-solid cladding PCFs in practice.

In this paper, we proposed an all-solid cladding DC-PCF filled with the toluene and ethanol for the temperature sensing. The all-solid cladding is formed by the fluorine-doped silica glass, and the refractive index difference between the fluorine-doped silica glass and silica is as low as -0.008. The temperature sensing performance of the proposed all-solid cladding DC-PCF is numerically investigated by the finite element method (FEM). The simulation results show that the average sensitivity can achieve $-11.64 \text{ nm/}^\circ\text{C}$ in the temperature range of 0 to 70 °C and $-7.41 \text{ nm/}^\circ\text{C}$ in the temperature range of -80 to 0 °C, respectively. It is also demonstrated that the proposed temperature sensor based on the all-solid cladding DC-PCF is insensitive to the hydrostatic pressure.

2. Design of the all-solid cladding DC-PCF and theory

Fig. 1. The cross-sectional structure of the designed PCF.

Fig. 1 shows the cross-sectional structure of the designed all-solid cladding DC-PCF. The refractive index and radius of the fluorine-doped silica glass in the cladding region are set as $n_f$ and $r_f$ respectively. The cores A and B are formed by the two toluene-filled air holes, and the corresponding refractive index and radius are $n_t$ and $r_t$, respectively. The central air hole is filled with the ethanol, and the refractive index and radius of the ethanol-filled air hole are set as $n_e$ and $r_e$, respectively. The triangular lattice
constant is $\Lambda$, and the background material is the silica, whose refractive index is $n_{\text{silica}}$. It is worth indicating that $n_{\text{silica}} - 0.008$ is chosen. Compared with the conventional solid core PCF, the proposed all-solid cladding DC-PCF filled with the toluene and ethanol could achieve the better temperature sensing performances. The main reasons are considered as follows. First, the structure parameters of the all-solid cladding DC-PCF could be adjusted more flexible. Second, the thermal optical coefficient (3.94 $\times 10^{-4}/^\circ C$) of the toluene and ethanol is the two orders of magnitude higher than that of the silica (8.6 $\times 10^{-6}/^\circ C$), which can significantly improve the temperature sensitivity. Third, the all-solid cladding is pressure resistant, and the liquids can be filled conveniently.

The FEM is used to calculate the propagation and temperature sensing characteristics of the proposed DC-PCF. In the simulation, the perfectly matched layer (PML) is added to the outermost layer of the PCF, and its thickness and refractive index are set as 15 $\mu$m and $n_{\text{silica}} + 0.03$, respectively. In addition, the grid sizes of the silica, fluorine-doped silica, and PML are set as $\lambda/4$, and the grid size of the air holes filled with the toluene and ethanol is set as $\lambda/6$.

According to the coupled mode theory (CMT), the guiding modes of the DC-PCFs are called as the supermodes, which are formed by coupling the individual core mode in the same polarization direction. Figs. 2(a) and 2(b) show the mode field distributions of the even and odd supermodes in the $x$-polarized direction, respectively. Figs. 2(c) and 2(d) show the corresponding mode field distributions of the even and odd supermodes in the $y$-polarized direction, respectively.

![Fig. 2. The mode field distributions of the (a) $x$-polarized even supermode, (b) $x$-polarized odd supermode, (c) $y$-polarized even supermode, and (d) $y$-polarized odd supermode.](image)

The refractive index of the silica $n_{\text{silica}}$ can be obtained from Ref. [18]

\begin{equation}
\begin{aligned}
n_{\text{silica}}^2(\lambda, T) &= (1.31522 + 6.90754 \times 10^{-4} T) + \frac{(0.788404 + 23.5835 \times 10^{-4} T)\lambda^2}{\lambda^2 - (0.0110199 + 0.584758 \times 10^{-4} T)} \lambda^2 - 100
\end{aligned}
\end{equation}

where $T$ is the temperature in Celsius and $\lambda$ is the free-space wavelength.

The refractive index of the toluene $n_t$ can be calculated by the following equation [10]

\begin{equation}
\begin{aligned}
n_t(\lambda) &= 1.474775 + \frac{0.00690031}{\lambda^2} + \frac{2.1776 \times 10^{-4}}{\lambda^4} - \alpha(T - 20.15).
\end{aligned}
\end{equation}

The refractive index of the ethanol $n_e$ can be described as [19, 20]

\begin{equation}
\begin{aligned}
n_e(\lambda) &= \sqrt{1 + \frac{0.0165^2}{\lambda^2 - 9.08} - \frac{0.8268^2}{\lambda^2 - 0.01039} - \alpha(T - 20)}.
\end{aligned}
\end{equation}

In Eqs. (2) and (3), the thermos optic coefficient $\alpha$ of the toluene and ethanol is chosen as $\alpha=3.94 \times 10^{-4}/^\circ C$, which is the two orders of magnitude higher than that of the silica (8.6 $\times 10^{-6}/^\circ C$) [21].
For the DC-PCFs, the coupling length $L_c$ as an important parameter indicates that the maximum power transfers from the core A to B and can be described as [22, 23]

$$L_c' = \frac{\lambda}{2(n_{\text{even}}^i - n_{\text{odd}}^i)}, \quad i=x, y$$

(4)

where $n_{\text{even}}^i$ and $n_{\text{odd}}^i$ represent the real parts of the effective refractive indices of the $i$-polarized even and odd supermodes, respectively.

If the input light is launched into the core A, the power transfers from the core A to B along the propagation direction can be described as [24, 25]

$$P_a = \cos^2\left(\frac{\pi}{2} \cdot \frac{L}{L_c}\right),$$

$$P_a = \sin^2\left(\frac{\pi}{2} \cdot \frac{L}{L_c}\right).$$

(5)

(6)

The temperature sensitivity is defined as [26, 27]

$$S(\text{nm/}^\circ \text{C}) = \frac{d\lambda_{\text{peak}}}{dT},$$

(7)

where $d\lambda_{\text{peak}}$ is the difference between the two peak wavelengths of the transmission curves and $dT$ is the temperature change. By choosing the peak wavelength as the detection signal, it is possible to obtain the high signal to noise ratio [28].

3. Influences of the fiber structure parameters on the temperature sensing

In order to investigate the influences of the fiber structure parameters on the temperature sensing, the initial structure parameters are chosen as $r_t=1.2$ μm, $A=3.5$ μm, $r_c=0.50$ μm, and $r_f=0.65$ μm. The fiber length is set as $L=1.5$ mm. Moreover, the melting points of the toluene and ethanol are -94.9 and -114 °C, and the corresponding boiling points are 110.6 and 78°C, respectively. Therefore, considering the practical application and material characteristic, we set 0 °C as the boundary temperature, and then investigated the two temperature ranges of 0 to 70 °C and -80 to 0 °C, respectively.

According to Eq.(4), the two supermodes with the different polarization directions are orthogonal, and there is no coupling between them. Therefore, only the two supermodes in the same polarization direction can be used for the temperature sensing. For the proposed DC-PCF, the materials are isotropic, and the structure is regular hexagonal lattice, so the even and odd supermodes in the two polarization directions are degenerate, respectively. Thus, for the $x$-polarized and $y$-polarized supermodes, there is no difference between the temperature sensing results. In the following, only the $x$-polarized supermodes are chosen to investigate the temperature sensing.
Fig. 3. The transmission spectra of the $x$-polarized light when the temperature changes from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively. The variation in the peak wavelengths and the linear fitting results when the temperature changes from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

Fig. 3(a) shows the transmission spectra of the $x$-polarized light in the temperature range of 0 to 70 °C. According to Eq. (2), $n_t$ decreases with the increase of the temperature. At this time, the evanescent field of the two cores becomes stronger, and the corresponding coupling effect is enhanced. Thus, as the temperature increases, the peak wavelengths occur to blue-shift. Fig. 3(b) shows the transmission spectra of the $x$-polarized light in the temperature range of -80 to 0 °C. As the temperature decreases, the peak wavelength occurs to red-shift. Compared with the results shown in Fig. 3(a), the red-shift of the peak wavelengths becomes weak. The main reason is considered that $n_t$ increases with the decrease of the temperature. Figs. 3(c) and 3(d) show the variations in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C, respectively. From Fig. 3(c), the linear fitting result is $y=-0.0094x+1.95917$, $R^2$ is 0.996, the average sensitivity is -9.4 nm/°C, and the maximum sensitivity is 11.1 nm/°C in the temperature range of 60 to 70 °C. According to Eqs. (2) and (3), $\alpha$ of the toluene and ethanol are the same, which means that the changes of $n_t$ and $n_e$ are the same when the temperature changes. Thus, the good linearity can be obtained for the temperature sensing. From Fig. 3(d), the linear fitting result is $y=-0.00612x+1.95089$, $R^2$ is 0.998, the average sensitivity is -6.12 nm/°C, and the maximum sensitivity is -7 nm/°C in the temperature range of -20 to 0 °C. Compared with Fig. 3(c), for the temperature range of -80 to 0 °C, the average and maximum sensitivities are reduced, and $R^2$ remains basically the same due to the weakening evanescent field.
The transmission spectra of the $x$-polarized light for the different temperature ranges from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively, when $r_t=1.4 \mu$m. The variations in the peak wavelengths and linear fitting results when the temperature changes from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

In the following, we will investigate the influences of the fiber structure parameters on the temperature sensing by changing $r_t$, $\Lambda$, $r_e$, and $L$, respectively. Fig. 4(a) shows the transmission spectra of the $x$-polarized light in the temperature range of 0 to 70 °C when $r_t=1.4 \mu$m. From Fig. 4(a), as the temperature increases, the peak wavelength occurs to blue-shift. Compared with the results of $r_t=1.2 \mu$m, the peak wavelengths at the same temperature occur to red-shift when $r_t$ increases to 1.4 \mu m. The reason is considered that the increase of $r_t$ weakens the evanescent field between the two cores. Fig. 4(b) shows the transmission spectra of the $x$-polarized light in the temperature range of -80 to 0 °C when $r_t=1.4 \mu$m. From Fig. 4(b), as the temperature decreases, the peak wavelengths occur to red-shift. Similar to the results shown in Fig. 4(a), the peak wavelengths at the same temperature also occur to red-shift. Figs. 4(c) and 4(d) show the variations in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C, respectively. From Fig. 4(c), the linear fitting result is $y=-0.01024x+2.09242$, $R^2$ is 0.990, the average sensitivity is -10.24 nm/°C, and the maximum sensitivity can achieve -12.9 nm/°C in the temperature range of 60 to 70 °C. From Fig. 4(d), the linear fitting result is $y=-0.00665x+2.074$, $R^2$ is 0.997, the average sensitivity is -6.65 nm/°C, and the maximum sensitivity can achieve -8.3 nm/°C in the temperature range of 0 to -10 °C. It is found that the temperature sensitivity can be improved by increasing $r_t$. 
Fig. 5. The transmission spectra of the x-polarized light at different temperature ranges from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively, when \( \Lambda = 3.7 \) μm. The variation in the peak wavelengths and linear fitting results when the temperature change from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

Fig. 5(a) shows the transmission spectra of the x-polarized light in the temperature range of 0 to 70 °C when \( \Lambda = 3.7 \) μm. From Fig. 5(a), as the temperature increases, the peak wavelengths occur to blue-shift since the distance between the two cores increases as \( \Lambda \) increases. Compared with the results of \( \Lambda = 3.5 \) μm, the peak wavelengths at the same temperature occur to red-shift when \( \Lambda \) increases to 3.7 μm. Fig. 5(b) shows the transmission spectra of the x-polarized light in the temperature range of -80 to 0 °C when \( \Lambda = 3.7 \) μm. From Fig. 5(b), as the temperature decreases, the peak wavelengths occur to red-shift. Similar to the results shown in Fig. 5(a), when \( \Lambda \) increases from 3.5 to 3.7 μm, the peak wavelengths at the same temperature also occur to red-shift. Fig. 5(c) and 5(d) show the variation in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C, respectively. From Fig. 5(c), the linear fitting result is \( y = -0.0098x + 2.05667 \), \( R^2 \) is 0.996, the average sensitivity is -9.8 nm/°C, and the maximum sensitivity can achieve -12.0 nm/°C in the temperature range of 60 to 70 °C. From Fig. 5(d), the linear fitting result is \( y = -0.0065x + 2.04889 \), \( R^2 \) is 0.998, the average sensitivity is -6.5 nm/°C, and the maximum sensitivity can achieve -7.1 nm/°C in the temperature range of 0 to -30 °C. Obviously, when \( \Lambda \) increases from 3.5 to 3.7 μm, the average sensitivity increases from -9.4 to -9.8 nm/°C in the temperature range of 0 to 70 °C and -6.12 to -6.5 nm/°C in the temperature range of -80 to 0 °C, respectively.
Fig. 6. The transmission spectra of the \( x \)-polarized light at different temperature ranges from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively, when \( r_e = 0.7 \) μm; The variation in the peak wavelengths and linear fitting results when the temperature changes from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

Since the ethanol-filled air hole is located at the center of the coupling bridges between the two cores, \( r_e \) has also an important influence on the sensitivity. Except for \( r_t \) and \( \Lambda \), the coupling effect can also be adjusted by the coupling bridge. Fig. 6(a) shows the transmission spectra of the \( x \)-polarized light in the temperature range of 0 to 70 °C when \( r_e = 0.7 \) μm. From Fig. 6(a), as the temperature increases, the peak wavelengths occur to blue-shift. Because \( n_e \) is lower than \( n_{\text{silica}} \), it can reduce the effective refractive index of the coupling bridge. Thus, compared with the results shown in Fig. 3(a), when \( r_e \) increases from 0.5 to 0.7 μm, the peak wavelengths at the same temperature occur to blue-shift. Fig. 6(b) shows the transmission spectra of the \( x \)-polarized light in the temperature range of -80 to 0 °C when \( r_e = 0.7 \) μm. From Fig. 6(b), because the ethanol-filled air hole reduces the effective refractive index of the coupling bridge and \( n_t \) increases with the decrease of the temperature, the peak wavelengths at the same temperature also occur to red-shift. Figs. 6(c) and 6(d) show the variation in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C, respectively. From Fig. 6(c), the linear fitting result is \( y = -0.00865x + 2.03667 \), \( R^2 \) is 0.997, the average sensitivity is -8.65 nm/℃, and the maximum sensitivity can achieve -9.8 nm/℃ in the temperature range of 60 to 70 °C. From Fig. 6(d), the linear fitting result is \( y = -0.00573x + 2.02844 \), \( R^2 \) is 0.998, the average sensitivity is -5.73 nm/℃, and the maximum sensitivity can achieve -7.0 nm/℃ in the temperature range of 0 to -20 °C. When \( r_e \) is increased from 0.5 to 0.7 μm, the average and maximum sensitivities are reduced. Thus, \( r_e \) can be appropriately reduced to improve the sensitivity.
Fig. 7. The transmission spectra of the x-polarized light at different temperature ranges from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively, when L=1.7 mm. The variation in the peak wavelengths and linear fitting results when the temperature changes from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

Fig. 7(a) shows the transmission spectra of the x-polarized light in the temperature range of 0 to 70 °C when L=1.7 mm. From Fig. 7(a), when L increases from 1.5 to 1.7 mm, the peak wavelengths at the same temperature occur to blue-shift. Fig. 7(b) shows the transmission spectra of the x-polarized light in the temperature range of -80 to 0 °C when L=1.7 mm. From Fig. 7(b), when L increases from 1.5 to 1.7 mm, the peak wavelengths at the same temperature also occur to blue-shift. It can be known from Eq. (4) that compared to other structure parameters, the effective refractive indices of the supermodes cannot be changed by L. Thus, Lc will not be changed when L increases. However, according to Eq. (6), Pb transfers from the core A to B, and L shows the quadratic relationship of the sine function. Thus, when L increases, the peak wavelengths at the same temperature occur to blue-shift. Figs. 7(c) and 7(d) show the variation in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C, respectively. From Fig. 7(c), the linear fitting result is \( y = -0.00936x + 1.91 \), \( R^2 = 0.995 \), the average temperature sensitivity is -9.36 nm/°C, and the maximum sensitivity can achieve -13.0 nm/°C in the temperature range of 60 to 70 °C. From Fig. 7(d), the linear fitting result is \( y = -0.00607x + 1.90244 \), \( R^2 = 0.999 \), the average temperature sensitivity is -6.07 nm/°C, and the maximum sensitivity can achieve -6.0 nm/°C in the temperature range of 0 to -20 °C. It is found that even if L is increased by 0.2 mm, the temperature sensitivity is changed slightly.

4. Discussion

Based on the above analyses, we optimize the fiber structure parameters as \( r_t = 1.41 \) μm, \( A = 3.72 \) μm, \( r_c = 0.30 \) μm, and \( r_f = 0.65 \) μm. \( n_r - n_{silica} = -0.008 \), and \( L = 1.6 \) mm. At this time, the transmission spectra of the x-polarized light in the temperature ranges of 0 to 70 °C and -80 to 0 °C are shown in Figs. 8(a) and 8(b).

It can be seen from Figs. 8(a) and 8(b) the peak wavelengths occur to blue-shift with the increase of the temperature. Figs. 8(c) and 8(d) show the variation in the peak wavelengths and linear fitting results when the temperature changes from 0 to 70 °C and -80 to 0 °C. From Fig. 8(c), the linear fitting result is \( y = -0.01164x + 2.1425 \), the average temperature sensitivity is -11.64 nm/°C, and the maximum sensitivity can achieve -15.0 nm/°C in the temperature range of 60 to 70 °C. From Fig. 8(d), the linear fitting result is \( y = -0.00741x + 2.12644 \), the average temperature sensitivity is -7.41 nm/°C, and the maximum sensitivity can achieve -9.0 nm/°C in the temperature range of -10 to 0 °C. In addition, the high \( R^2 \) values indicate that the good linearity are obtained for the temperature sensing sensitivity.
Fig. 8. The transmission spectra of the x-polarized light with different temperature ranges from (a) 0 to 70 °C and (b) -80 to 0 °C, respectively, when the fiber structure parameters are optimized. The variation in the peak wavelengths and linear fitting results when the temperature changes from (c) 0 to 70 °C and (d) -80 to 0 °C, respectively.

The influence of the hydrostatic pressure on the temperature sensing is also investigated. According to the photoelastic effect, $n_{\text{silica}}$, which is modulated by the hydrostatic pressure, can be described as [29]:

$$n_x = n_{\text{silica}} - C_1 \sigma_x - C_2 (\sigma_y + \sigma_z),$$
$$n_y = n_{\text{silica}} - C_1 \sigma_y - C_2 (\sigma_x + \sigma_z),$$
$$n_z = n_{\text{silica}} - C_1 \sigma_z - C_2 (\sigma_x + \sigma_y),$$

(8)

where $\sigma_x$, $\sigma_y$, and $\sigma_z$ are the pressure components. In this work, the Yong’s modulus $E_{\text{silica}}=73.1$ Gpa, and Poisson’s ratio $\nu_{\text{silica}}$ is set as 0.17. $C_1=6.5 \times 10^{-13}$ m$^2$/N, and $C_2=4.2 \times 10^{-12}$ m$^2$/N [30, 31]. Because of the all-solid cladding structure, the proposed DC-PCF is pressure resistant.

Fig. 9. (a) The variation in the peak wavelengths, and (b) the linear fitting results when the hydrostatic pressure changes from 0 to 40 Mpa.

Figs. 9(a) and 9(b) show the variation in the peak wavelengths and linear fitting results when the
hydrostatic pressure changes from 0 to 40 Mpa at the temperature of 20 °C. From Fig. 9(a), as the hydrostatic pressure increases, the peak wavelengths slightly occur to red-shift. The all-solid cladding makes the proposed DC-PCF stronger and less sensitive to the hydrostatic pressure compared to the air-silica PCFs. Compared with the peak wavelengths shift induced by the temperature, the effect of the hydrostatic pressure is almost negligible. From Fig. 9(b), the linear fitting result is $y=-0.099x+1923.08$, and the average hydrostatic pressure sensitivity is only 0.099 nm/MPa. Thus, the proposed temperature sensor is insensitive to the hydrostatic pressure. The comparisons between the proposed all-solid cladding DC-PCF temperature sensing and other reports are shown in Table 1. It can be clearly seen from the Table 1 that the proposed temperature sensor has high temperature sensitivity and wide detection range. In addition, for the proposed all-solid cladding DC-PCF, only the three air holes need to be filled with the liquids, so the cladding deformation can be avoided, and the good performance of the temperature sensing can be achieved.

Table 1. Comparison between the proposed all-solid cladding DC-PCF temperature sensing with other reports.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Structures</th>
<th>Temperature detection range (°C)</th>
<th>Sensitivity (nm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Ethanol-Filled photonic bandgap fibers.</td>
<td>25-50</td>
<td>0.292</td>
</tr>
<tr>
<td>[10]</td>
<td>Toluene filled PCF.</td>
<td>-80-90</td>
<td>6.02</td>
</tr>
<tr>
<td>[11]</td>
<td>Oil-filled PCF.</td>
<td>30-150</td>
<td>0.61</td>
</tr>
<tr>
<td>[12]</td>
<td>Water-filled dual-core PCF.</td>
<td>30-70</td>
<td>0.818</td>
</tr>
<tr>
<td>[13]</td>
<td>Selectively gold-coated PCF.</td>
<td>0-50</td>
<td>0.72</td>
</tr>
<tr>
<td>[14]</td>
<td>SPR-based liquid-filled PCF.</td>
<td>0-100</td>
<td>3.08</td>
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<tr>
<td>This work</td>
<td>Dual-core toluene and ethanol filled PCF</td>
<td>0-70</td>
<td>11.64</td>
</tr>
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</table>

5. Fabrication and filling processes of the all-solid cladding DC-PCF

Fig. 10 shows the schematic diagram of the all-solid cladding DC-PCF fabrication with the stack and draw method. From Fig. 10, the capillary rods are first stacked in a regular hexagonal arrangement to obtain the desired structure, where the three hollow silica rods are placed in the center and the solid fluorine-doped silica rods are arranged in the cladding region. Then, the DC-PCF preform is formed by putting the arranged structure into a silica glass tube. After that, the DC-PCF cane is obtained by drawing the preform under the optimized parameters of the drawing tower. Finally, the jacket tube is added to the surface of the DC-PCF to obtain the desired DC-PCF.
Selectively filling the toluene and ethanol into the air holes can be achieved by the multi-step filling technique [32-34]. Fig. 11 shows the schematic diagram of the all-solid cladding DC-PCF filling with the multi-step filling technique. First, a section of all-solid cladding DC-PCF with the length of ~10 cm is taken, and then the UV glue carried by the mental tip can be aligned with the air holes of the target DC-PCF through adjusting the relative positions of the end face of the DC-PCF and the UV glue droplets. Second, a UV lamp is used to irradiate the end face of the DC-PCF until the UV glue is completely cured. Third, the end face of the DC-PCF is inserted into the toluene, and a gas pump is used to pump the toluene into the two air holes. Fourth, the length of the central air hole sealed by UV glue is cut off, and then the first and second steps are reused to seal the two air holes filled with the toluene. After that, the same method can be used to fill the central air hole with the ethanol. Finally, the desired fiber length can be obtained by cutting off the all-solid cladding DC-PCF filled with the toluene and ethanol.

6. Conclusion

In summary, an all-solid cladding DC-PCF filled with the toluene and ethanol is proposed for the temperature sensing. The two cores of the DC-PCF are filled with the toluene, and the central air hole is filled with the ethanol. By optimizing the fiber structure parameters, the average temperature sensitivity can achieve -11.64 and -7.41 nm/℃ in the temperature ranges of 0 to 70 ℃ and -80 to 0 ℃, respectively. The maximum temperature sensitivity in the two temperature ranges can achieve -15 and -9 nm/℃, respectively. Moreover, the average hydrostatic pressure sensitivity is only -0.099 nm/MPa, so the proposed temperature sensor based on the all-solid cladding DC-PCF is insensitive to the hydrostatic pressure.
pressure.

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