A Novel All-Solid Photonic Bandgap Fiber
With Ultra-Low Confinement Loss

Sh. Mohammad-Nejad*, M. Aliramezani*, M. Pourmahyabadi*
*Nanoptronics Research Center, Department of Electrical Engineering,
Iran University of Science and Technology, Tehran, 16846-13114, Iran.
Shahramm@iust.ac.ir, Mohammad_Aliramezani@ee.iust.ac.ir, Pmahyabadi@iust.ac.ir

Abstract: In this paper, a novel design of all-solid photonic bandgap fiber with ultra-low confinement loss is proposed. The confinement loss is reduced remarkably by managing the number of rods rings, up-doping level, pitch value, and rods diameters. Moreover, the designed PCF shows ultra-flattened dispersion in L and U-band. Furthermore, a new design, based on introducing of an extra ring of air holes on the outside of the all-solid bandgap structure, is then proposed and characterized. We demonstrate that it significantly reduces the fiber diameter to achieve negligible confinement loss. The validation of the proposed design is carried out by employing a tow dimensional finite difference frequency domain with perfectly matched layers.

Keywords: Confinement loss, dispersion, finite difference frequency domain, photonic bandgap fiber, up-doping.

1. INTRODUCTION

In the large family of photonic crystal fibers (PCFs) [1-4], photonic bandgap fibers (PBGFs) are probably the most original ones as the light in these structures is confined in a low index core conversely to all the other fibers. PBGF is an optical fiber in which light is confined to the core by a photonic bandgap of the cladding, instead of the usually total-internal reflection [2]. Hollow-core PBG fibers with air holes in a glass background, as a hot investigation field, allow low-loss propagation in an empty or gas-filled core, giving the fibers several interesting properties and applications [5]. However, these fibers suffer from some important drawbacks among which a tricky fabrication and splicing to other fibers. Furthermore, surface modes appear in these structures, limiting significantly the fiber properties. Comparing to hollow–core bandgap fiber, all-solid PBGF is better to realize rare-earth-doped amplifier and laser or to write Bragg gratings which are widely used in photonics. Furthermore, these fibers should be easier to fabricate and splice for its elimination of mechanically unstable holey structure.

In all-solid PBGFs, the core is made from a low index area formed by omitting one or several rods [6-7]. Since the mean core–cladding index contrast is negative, TIR cannot operate, and photonic bandgap effects are the only possible guidance mechanism.

In both solid-core and hollow-core PCFs it is necessary to consider another contribution to the losses, that is the leakage or confinement losses. These are due to the finite number of air-holes which can be made in the fiber cross section. As a consequence, all the PCF guided modes are leaky. For example, in solid-core PCFs light is confined within a core region by the air-holes. Light will move away from the core if the confinement provided by the air-holes is inadequate. This means that it is important to design such aspects of the PCF structure as air hole diameter and hole-to-hole spacing, or pitch, in order to realize low-loss PCFs. In particular, the ratio between the air-hole diameter and the pitch must be designed to be large enough to confine light into the core. On the other hand, a large value of the ratio makes the PCF multi-mode. However, by properly designing the structure, the confinement loss of single-mode PCFs can be reduced to a negligible level [8].

The outline of this paper is the following: in the next section, we describe the numerical method which is used to characterize the fiber structure. In section III, we propose our design to achieve the desirable characteristics. After that numerical results are discussed and finally a design to reduce the number of doped ring is proposed and analyzed.

2. Theoretical Discussion

Tow dimensional finite difference frequency domain (2-D FDFD) is popular and appealing for numerical electromagnetic simulation due to its many merits. The discretization scheme can be derived from the Helmholtz equations [9] or Maxwell’s equations [10] directly. Now we use the direct discretization schemes first described for photonic crystal fibers by Zhu et al [11]. Yee’s two-dimensional mesh is illustrated in Fig. 1: note that the
transverse fields are tangential to the unit cell boundaries, so the continuity conditions are automatically satisfied. After inserting the equivalent non-split-field anisotropic PML [12] in the frequency domain, the curl Maxwell equations are expressed as

\[ jk_0 s \varepsilon_0 E = \nabla \times H \]

\[ jk_0 s \mu_0 H = \nabla \times E \quad (1) \]

\[
\begin{bmatrix}
\frac{s_x}{s_y} & 0 & \frac{s_z}{s_y} \\
0 & 1 & 0 \\
\frac{s_z}{s_x} & 0 & \frac{s_z}{s_x}
\end{bmatrix}
\]

\[ s = \begin{bmatrix} s_x \\ s_y \\ s_z \\ \end{bmatrix} \quad (2) \]

where

\[ s_x = 1 - \frac{\sigma_x}{j\omega \varepsilon_0}, \quad s_y = 1 - \frac{\sigma_y}{j\omega \varepsilon_0} \quad (3) \]

and \( \sigma \) is the conductivity profile.

Assuming that the PCFs are lossless and uniform and the propagation constant along the \( z \) direction is \( \beta \), the propagation direction derivative can be replaced by \( -j\beta \). Using the central difference scheme and zero boundary conditions outside of the anisotropic PML layers, the curl (1) can be rewritten in a matrix form which includes six field components. Then eliminating the longitudinal magnetic and electric fields, the eigenvalue matrix equation in terms of transverse magnetic fields and transverse electric fields can be obtained as

\[
\begin{bmatrix}
Q_{xx} & Q_{xy} & H_x \\
Q_{yx} & Q_{yy} & H_y \\
\end{bmatrix}
\begin{bmatrix} H_x \\ H_y \\ \end{bmatrix}
= \beta^2
\begin{bmatrix} H_x \\ H_y \\ \end{bmatrix}
\quad (4) \]

\[
\begin{bmatrix}
P_{xx} & P_{xy} & E_x \\
P_{yx} & P_{yy} & E_y \\
\end{bmatrix}
\begin{bmatrix} E_x \\ E_y \\ \end{bmatrix}
= \beta^2
\begin{bmatrix} E_x \\ E_y \\ \end{bmatrix}
\quad (5) \]

3. Design

The proposed all-solid PBGF is formed by up-doped rods around a core that is made from omission of seven rods. As a result, the all-solid PBGF structure imposes photonic bandgap guidance as the dominant guidance mechanism. The cross-section of the proposed all-solid PBGF is shown in Fig. 2. As it can be seen, the all-solid PBGF has a triangular lattice of rods in cladding.
The mode field distribution of the proposed all-solid PBGF is depicted in Fig. 3. It is evident that the guided mode is well confined.

4. Numerical Result

In this article, $d_1=d_2=6\mu m$, and $\Lambda=8\mu m$ are chosen as the basic geometrical parameters. One should note that up-doping level (or the index contrast of the two materials) is defined by following equation:

$$\Delta n\% = \frac{\text{rods index} - \text{background index}}{100} \quad (6)$$

Furthermore, the confinement loss and dispersion are respectively calculated by using [13]:

$$L_c=8.686\times\text{Im}[^{k_0}\text{n}_{\text{eff}}] \quad (7)$$

where $k_0=\frac{2\pi}{\lambda}$.

$$D(\lambda) = \frac{\lambda^2}{c} \frac{d^2n}{d\lambda^2} \quad (8)$$

where $c$ is the velocity of light in a vacuum.

Table I shows confinement loss variation with number of rings increment. As we expected, the larger number of rods rings provides the more confined guided mode and result in lower confinement loss. Moreover, Table I shows that 12 rings are large enough to achieve negligible confinement loss. Although the confinement loss can be reduced simply by increasing the number of the rings, this will result in a thicker fiber diameter.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Confinement loss (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>892.61</td>
</tr>
<tr>
<td>10</td>
<td>1.007</td>
</tr>
<tr>
<td>12</td>
<td>2.9923×10^{-9}</td>
</tr>
<tr>
<td>14</td>
<td>8.0090×10^{-10}</td>
</tr>
<tr>
<td>16</td>
<td>3.6378×10^{-10}</td>
</tr>
<tr>
<td>18</td>
<td>-4.8170×10^{-11}</td>
</tr>
</tbody>
</table>

We are also interested in the influence of up-doping level ($\Delta n$) on the confinement loss. Table II demonstrates confinement loss behavior with increment of up-doping level. Surprisingly, the dependence of confinement loss on doping level is found weaker than number of rods rings dependence (see Table I and II). As Table II depicts, confinement loss can be reduced by increasing the up-doping level.

Table III shows how the confinement loss is reduced as $d_1$ increases. It should be pointed that by employing simulation, it is understood that $d_1$ has a major impact on confinement loss in comparison with $d_2$.

![Table III](image)

![Fig. 4](image)
According to Fig.4, dispersion and dispersion variation are decreased with \(d_1\). Thus, it is believed; more flattened dispersion can be attainable by using larger \(\Lambda\) and \(d_1\). But it leads to thicker fiber consequently.

Fig.5 and Fig.6 show dispersion and confinement characteristics of the proposed all-solid PBGF versus wavelength when \(d_1=7.8\mu m\), \(d_2=6\mu m\), \(\Lambda=8\mu m\), \(N_r=14\) and \(\Delta n=2\%\). Based on Fig.6, ultra-flattened dispersion slope of \(\Delta D=0.0074\) (ps/nm²/km) and \(\Delta D=0.0079\) (ps/nm²/km) can be obtained in L-band (1.565 µm to 1.625 µm) and U-band (1.625 µm to 1.675 µm) respectively.

### 5. PBGF with an extra air-hole

In this section we propose an alternative design to reduction of the number of doped rings. It is based on using an extra air-hole ring to help the confinement of the core mode. The cross-section of the designed all-solid PBGF with an extra air-hole ring is shown in Fig.7.

In this design, we introduce another geometric parameter: \(d_a\), which is the air-hole diameter of the seventh ring. As can be seen from Fig.8, ultra-low confinement loss can be achieved by using only 7 rings. It should be noted that confinement loss of 892.61dB/km at a wavelength of 1.55µm is obtained by using Fig. 2 design and 8 rods rings (see Table I).

It is noteworthy that the holey ring will act as a low index layer compared to the high index doped microstructured region. Thus, any cladding modes with effective index higher than \(n_{FSM}\) will also benefit from the confinement offered by the depressed cladding region. In particular, all the cladding modes with effective index lower than \(n_{silica}\) were leaky in our previous design, whereas some of these modes will be allowed to propagate along the fiber with relatively low losses. Because of the loss reduction of these unwanted modes, one has to avoid realizing a depressed cladding with a too low refractive index and with a too large section. This is also why we limit ourselves to only one ring of air-hole.

### 6. Conclusions

In this article, an all-solid PBGF with ultra-low confinement loss and ultra-flattened dispersion is proposed. The all-solid PBGF presents negligible confinement loss of \(-2.1102\times10^{-9}\) (dB/km) at a wavelength of 1.55µm. Moreover, the proposed PCF...
shows ultra-flattened dispersion of $\Delta D = 0.445$ (ps/nm/km) and $\Delta D = 0.399$ (ps/nm/km) in L-band (1.565 µm to 1.625 µm) and U-band (1.625 µm to 1.675 µm) respectively. Furthermore, we proposed a novel design consisting in the addition of a ring of air holes around the all-solid PBGF. The design has the important benefit to reduce significantly the fiber diameter. This paper foreshows the ultra-low confinement loss and ultra-flattened dispersion capability of all-solid PBGF, which may be used in nonlinear application or to raise the radiation efficiency of rare earth element doped fibers.

References