Highly Negative Dispersion in honeycomb Photonic Crystal Fiber of Borosilicate Material with Circular Air Holes

Arjun Singh Dhakar, Yogendra Kumar Katiyar

Abstract—In this paper we proposed a new design of Borosilicate Honeycomb photonic crystal fiber for highly Negative chromatic dispersion. Finite Difference Time Domain (FDTD) method and transparent boundary condition (TBC) is used to analyze the dispersion property in a high-index core PCF. This method produced highly negative dispersion in result at wavelength range 0.5 µm to 1.8µm. in this proposed HPCF diameter of air holes is 0.66 µm & this PCF is made by using borosilicate glass material.

Index Terms—Effective Refractive Index (neff), Photonic Crystal Fiber (PCF), Finite Difference Time Domain (FDTD) method, Transparent Boundary Condition (TBC).

I. INTRODUCTION

Optical fiber is widely used in wavelength division multiplexing (WDM) network for optical data transmission. In WDM communication systems, it is essential to maintain a uniform response in the different wavelength channels, which requires that the transmission line approach the ideal state of ultra-flattened dispersion and ultra-low loss [1]. But flexible dispersion or losses in optical fiber have become a major problem in high bit rate wavelength division multiplexing optical communication systems.

The dispersion is a phenomenon that causes to broaden optical pulses, when they spread in the optical fibers [1]. So when a pulse come to receiver, it is not possible to differentiate whether it high or low. The intersymbol interference (ISI) can occur between the bits in communication channel, by linearly accumulated chromatic dispersion along the transmission channel, which can affects the communication process & communication quality. Because of this, zero and flat dispersion slope with low losses are needed in high speed optical communication.

Thus, a new technology of manufacturing photonic crystals has led to a new generation of optical fibers, namely Photonic Crystal Fibers. The PCF has some features such as controllable dispersion, very low confinement loss and flexible design. The photonic crystal fibers (PCFs) are also called microstructures fibers or holey fibers. The photonic crystal fiber structure is formed by a core and a cladding. The cladding is two dimensional photonic crystal types consisting of air holes that run along the fiber length show unique properties.

Light guidance in PCFs are depending on the core and cladding photonic crystal materials. The refractive index difference between the core and cladding is always positive in index-guiding PCF. It can be possible by choosing a core material with a higher refractive index than the cladding refractive index. The photonic crystal fiber is also known as solid core photonic crystal fiber. These fibers guide light through a form of total internal reflection (TIR).

The refractive index of the cladding is higher than refractive index of the core in the fibers with air core. However, in fibers with air core, TIR is not possible. So light guidance in these fibers attained by coherent Bragg scattering, where light at wavelengths within well-defined stop bands is prohibited from propagating in the photonic crystal cladding and is confined to a central defect [2].Only some wavelength bands are confined and guided down the fiber. Each band corresponds to the presence of a full two-dimensional PBG in the photonic crystal cladding. For this reason, these fibers are called photonic band gap fibers (PBGFs) or hollow core fibers in which light is guided in a low-index core by the PBG effect [1,2].

Reducing dispersion & confinement loss are main aim to designing PCF’s. To designing PCF’s, multiple parameters can change such as diameter & shape of the holes, the number of air hole ring and the spacing between these holes. Many designs of PCF’s have been proposed for the nearly zero ultra-flattened chromatic dispersion and low confinement loss.

II. THEORY OF DISPERSION

The chromatic dispersion (D) of a PCF is easily calculated from the second derivative of the mode index, neff = β / k0, with respect to wavelength. Once the mode index is solved, the chromatic dispersion parameter can be obtained.

\[ D_{nf} = \frac{-\lambda^2}{c^2} \frac{d^2}{d\lambda^2} \lambda \Delta_{nf} \] \hspace{1cm} (1)

Where, Re[neff ] is real part of (neff ).And the total dispersion, D = DM + DW. Where \( \lambda \) is the operating
wavelength and $c$ is the velocity of light. DM is the material dispersion, DW is the waveguide dispersion.

The chromatic dispersion profile can be easily controlled by varying the hole diameter and the hole pitch. By using the sellemier formula we can calculate the value of refractive index of Borosilicate glass.

$$\lambda^2 - 1 = \sum \left( \frac{1}{n_i^2} \right) \quad \text{………… (2)}$$

where $\lambda$ is operating wavelength in $\mu$m

III. DESIGN AND SIMULATION

The proposed Borosilicate honeycomb PCF is an array of air holes running along its length. Now here we will analyze the dispersion properties of photonic crystal fiber. The designed PCF consists of a solid core with a regular array of air holes running along the length of the fiber acting as the cladding. For the entire configurations analyzed the mean cladding refractive index is lower than the core index.

The core material is borosilicate glass which refractive index is 1.5186 and the refractive index of cladding air holes is 1. The pitch difference ($\Lambda=2.0\mu$m) which is center to center spacing between two nearest air holes for entire configuration. The dispersion property is numerically simulated by scalar effective index method. The finite difference time domain method and the TBC boundary condition is used for the simulation. The software is used for various layouts designed and investigated is OPTIWAVE SYSTEM-FDTD mode solver tool.

Our proposed HPCF design is made up of seven layer having air holes diameter$(d)=0.66\mu$m, pitch difference($\Lambda=2.0\mu$m) which is shown in figure 2. 3-D layout of proposed HPCF is shown in figure 2. This type of structure is made up of small small hexagonal where core is missing in whole structure.

Figure1: Basic layout structure of Photonic Crystal fiber with 5 layer and pitch difference is 2.0$\mu$m.

Figure2: Proposed HPCF
RESULT

Designed PCF structure provides negative dispersion shown in figure 3. Calculated dispersion value is highly negative. In this paper of the proposed honeycomb photonic crystal fiber with seven rings of circular air holes is designed for investigation of highly negative dispersion. The mode field pattern of the designed HPCF of highly negative dispersion is shown in Figure 4. Generally silica material is used in the different application of the optical fiber, but recently Borosilicate material is the replacement of the silica material with its different properties. Material dispersion is always unchanged for any structure. First we find waveguide dispersion between effective refractive index and wavelength than after material dispersion of borosilicate and silica at last we calculate total dispersion between Dispersion(ps/km.nm) and wavelength (micrometer).

A. Simulation result of waveguide dispersion.
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B. Simulation result of Total dispersion

In this paper HPCF gives better result using scalar method. It gives highly negative dispersion. Here we have calculated the dispersion for various wavelengths from 0.5 μm to 1.8 μm and it gives negative dispersion in wavelength range 0.5 μm to 1.8 μm shown in Table 1.

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Waveguide Dispersion</th>
<th>Material Dispersion</th>
<th>Total Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>27.15003</td>
<td>-354.00000</td>
<td>-326.84997</td>
</tr>
<tr>
<td>0.6</td>
<td>22.91836</td>
<td>-331.00000</td>
<td>-308.08164</td>
</tr>
<tr>
<td>0.7</td>
<td>11.37003</td>
<td>-250.00000</td>
<td>-238.62997</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.20948</td>
<td>-150.00000</td>
<td>-150.20948</td>
</tr>
<tr>
<td>0.9</td>
<td>-3.46815</td>
<td>-92.80000</td>
<td>-96.26815</td>
</tr>
<tr>
<td>1</td>
<td>-8.13896</td>
<td>-57.50000</td>
<td>-65.63896</td>
</tr>
<tr>
<td>1.1</td>
<td>-10.70491</td>
<td>-33.60000</td>
<td>-44.30491</td>
</tr>
<tr>
<td>1.2</td>
<td>-8.99322</td>
<td>-16.40000</td>
<td>-25.39322</td>
</tr>
<tr>
<td>1.3</td>
<td>-10.28253</td>
<td>-3.79000</td>
<td>-14.07253</td>
</tr>
<tr>
<td>1.4</td>
<td>-14.86195</td>
<td>6.30000</td>
<td>-8.56195</td>
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<td>1.5</td>
<td>-22.14782</td>
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<tr>
<td>1.6</td>
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<td>1.7</td>
<td>-115.14420</td>
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<td>-86.24420</td>
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<td>1.8</td>
<td>-179.33510</td>
<td>35.00000</td>
<td>-144.33510</td>
</tr>
</tbody>
</table>

Table 1: Material dispersion, Waveguide dispersion & Total dispersion on different Wavelength

VI. FUTURE WORK

In future we can calculate flattened dispersion or near to zero dispersion by varying the size of air holes and by varying pitch size. Here we also shows how borosilicate is better than silica through table 2 & table 3.

Table 2: Comparison of silica with BK7

<table>
<thead>
<tr>
<th>Properties</th>
<th>Silica glass</th>
<th>BK7(borosilicate)glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.2</td>
<td>2.51</td>
</tr>
<tr>
<td>Refractive Index (micrometer)</td>
<td>1.458</td>
<td>1.516</td>
</tr>
<tr>
<td>Light transmission wavelength (micrometer)</td>
<td>0.18to2.5</td>
<td>0.35to2.5</td>
</tr>
<tr>
<td>Max. Temperature (degree C)</td>
<td>1120</td>
<td>860</td>
</tr>
<tr>
<td>Material dispersion at 1.55μm</td>
<td>18.01246ps/km.nm</td>
<td>15.01038(ps/km.nm)</td>
</tr>
</tbody>
</table>
Table 2: Comparision between Borosilicate and Silica.

C. Simulation result of Material dispersion
Graph between silica and BK7.

Table 3: Material dispersion between Silica and Borosilicate

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Silica dispersion (ps/km nm)</th>
<th>Borosilicate dispersion (ps/km nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>-769.00</td>
<td>-354.29</td>
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<td>0.7</td>
<td>-204.00</td>
<td>-250.01</td>
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<td>0.8</td>
<td>-121.00</td>
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<tr>
<td>0.9</td>
<td>-74.20</td>
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<td>1</td>
<td>-44.40</td>
<td>-57.46</td>
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<tr>
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<td>-33.57</td>
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<td>1.2</td>
<td>-9.61</td>
<td>-15.41</td>
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<tr>
<td>1.3</td>
<td>1.52</td>
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<tr>
<td>1.4</td>
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<td>36.63</td>
<td>34.97</td>
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<tr>
<td>1.9</td>
<td>41.51</td>
<td>39.77</td>
</tr>
<tr>
<td>2</td>
<td>45.70</td>
<td>43.58</td>
</tr>
</tbody>
</table>

Figure 7: Material dispersion between silica and Borosilicate (BK7) glass.

REFERENCES
11. Huizhen Xu, Jian Wu, Yitang Dai, Cong Xu, and Jintong Lin ; Design procedure for photonic crystal fibers with ultra flattened chromatic dispersion


