Design of Near Infrared Bandpass Filter using All-Solid Photonic Crystal Fiber with Parasitic Bandgaps Suppression

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Abstract—In this work, an approach of realizing fiber-based near infrared bandpass filter with parasitic bandgaps suppression is proposed. By doping the core of an all-solid photonic bandgap fiber with lower refractive index material, single-mode light is confined in the main bandgap centered at 1.0 µm wavelength region. Light guiding in higher order bandgaps is suppressed due to the coupling of light to the cladding region. The proposed design is suitable for realizing in-fiber single-band broadband light filter with possible applications in lasing, spectroscopy and optical communication.

Keywords—photonic crystal fiber, photonic bandgap, bandpass filter, NIR range

I. INTRODUCTION

Photonic crystal fiber (PCF) is a type of optical fiber which has transverse periodic structure as cladding with a center core defect extending through its entire length. There are two categories of PCFs: index-guiding PCFs and photonic bandgap (PBG) PCFs. For index-guiding PCFs, the core refractive index (RI) is higher than the effective RI of the cladding, light is guided in the core by modified total internal reflection. On the contrary, the core RI of PBG PCFs is lower than the effective RI of the cladding. In the later, the periodic cladding structure gives rise to certain photonic bandgaps in which light could not penetrate through the cladding region, leading to light confinement in the core.

Fiber in-line filter has gained huge interests recently due to the ability to inhibit light propagation in unwanted wavelengths and simple system integration. A number of fiber types and methods have been introduced. A thermo-optic bandwidth variable filter with central wavelength at 1 µm and bandwidth of 25 to 500 nm has been demonstrated theoretically and experimentally in [1]. In addition, broad and narrow bandpass filter using index-guiding holey PCF numerically designed by changing the parameters of the core and air holes [2]. In [3] the fabrication of a tunable bandpass filter at 1.1 µm region is demonstrated by combining the bend loss edge of an all-solid PBGF and a Bragg fiber. The band-pass filter was fabricated by coating polymer material on a tapered standard single mode fiber. In addition, the transmission of light inside the main and higher order bandgaps of an all-solid PBGF has been demonstrated in [4] which guide light at 1.31 µm with bandwidth of 0.7 µm. Other attempts have been done to manipulate the bandgaps of PBG PCFs for various application [5-9]. However, in all previous PBG fiber in-line filters, parasitic bandgaps in unwanted wavelength regions exist and complicate the filtering process.

In this work, we proposed an uncomplicated approach to suppress parasitic higher order bandgaps by doping the core of an all-solid PBG fiber with lower RI materials. Using plane-wave method, the filter design is arbitrarily optimized for light guiding at near infrared (NIR) wavelength region centered at 1.0 µm. The proposed design does not require the addition of any extra component or material to the system setup or to maintain any specific environmental parameter. The proposed fiber and method could be employed in fiber laser [10], spectroscopy [11], optical communication [12], sensing [13] and high quality imaging [14].

II. METHODOLOGY

The photonic bandgaps of PCF cladding are numerically computed using plane-wave method, freely available in MIT Photonic-Bands (MPB) software package [15]. This method finds the solution of plane-waves superposition to calculate the electromagnetic modes of each propagation constant in the periodic structure of the cladding. Then the core, as a defect, is applied to the structure and the guided modes through the bandgaps are calculated using the supercell approximation.

The proposed fiber’s cross section is consisted of a triangular high-index rods with \( n_{\text{rod}} = 1.8 \), embedded inside the background material as pure silica (\( n_{\text{ silica}} = 1.45 \)). These rods could be made by doping silica with high-index materials or alternatively, by using capillaries filled with high-index liquids. The rods radius and the pitch size of the structure are 0.2 µm and 1.0 µm, respectively. These parameters have been optimized for guiding in 1.0 µm region. The small size of the high-index rods simplifies and speeds up the doping process during preform fabrication by modified chemical vapor deposition (MCVD). In the first step, one rod at the center of the structure is missed (the core of the fiber considered pure silica) and its band diagram is calculated. Second, we replaced the core by a fluoride-doped silica rod with RI lower than that of pure silica and its band diagram is compared with the previous one. This proposed method of reducing core RI would inhibit the parasitic bandgaps for guiding in the core. The fiber can be pulled to reach the intended pitch size using standard fiber draw tower by applying thick jacketing tube on the preform cane.
III. RESULTS AND DISCUSSION

Fig. 1 shows the calculated propagation diagram of the proposed PBG fiber when the core is made of pure silica (without any doping). The propagation diagrams are presented as modal RI versus normalized wavelength. The bandgaps in the diagrams are delineated by shaded areas with blue color curves. The black dot-dashed line indicates the effective RI of the cladding. Light propagating within the bandgap areas cannot penetrate through the cladding structure. The guiding mode in the core is located inside all bandgaps and have lower RI than that of core. Such guided modes are illustrated in Fig. 1 by the red dotted lines forming the 1st, 2nd and 3rd transmission bands (TM bands) which are passing through the 1st, 2nd and 3rd bandgaps (I, II, III), respectively. The insets show the modal analysis of light confinement in the core inside each bandgaps using COMSOL Multiphysics software. This guiding mode is single mode and the two cut-off wavelengths are set by the 1st bandgap which are around 1.4 μm and 0.65 μm in the NIR region. However, for shorter wavelengths, light can be guided by the higher order bandgaps which are in the visible and ultraviolet regions. To suppress the other passbands with a single passband in NIR, the propose approach is to reduce the core RI yet does not affect the main bandgap.

In order to suppress the parasitic higher order bandgaps, core radius and RI have been optimized to 0.5 μm and 1.42, respectively (Fig. 2(a)). Practically, this refractive index can be achieved by doping low RI materials such as fluorine into the silica glass. Fig. 2(b) shows the calculated bandgaps (shaded area) and core guided mode (dashed red line inside the 1st bandgap). The core RI is shown with green straight line. As the graphs imply, the guided mode does not propagate in the 2nd and 3rd bandgaps. Therefore, only one passband exists which is in NIR region with cut-off wavelengths at 0.8 μm and 1.3 μm. Modes with RI higher than that of the core within the bandgaps will be guided as surface modes around the core. The size of core $R=0.5 \, \mu m$ in this design was optimized to avoid surface modes guiding in 2nd and 3rd bandgap. Smaller core size shows guiding surface modes. This design offers a good single-band bandpass filter in NIR region with center wavelength at 1.0 μm.

IV. CONCLUSION

An all-solid PBG fiber with passbands in NIR, visible and UV is introduced. Then another all-solid PBG fiber which is single-band NIR bandpass filter with a low RI core is proposed. By reducing the core RI, higher order bandgaps, which are responsible for guiding in visible and ultraviolet regions, cease to exist. Thereby, only the 1st bandgap is used in light guiding from 0.8μm to 1.3μm.

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REFERENCES


