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Design of narrow band-pass filters based on the resonant-tunneling phenomenon in multi-core photonic crystal fibers

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Abstract: The objective of the present paper is to introduce and numerically demonstrate the operation of a novel band-pass filter based on the phenomenon of resonant tunneling in multi-core photonic crystal fibers (PCFs). The proposed PCF consists of two identical cores separated by a third one which acts as a resonator. With a fine adjustment of the design parameters associated with the resonant-core, phase matching at a single wavelength can be achieved, thus enabling very narrow-band resonant directional coupling between the input and the output cores. The validation of the design is ensured with an accurate PCF analysis based on finite element and beam propagation algorithms. The proposed narrow band-pass filter can be employed in various applications such as all fiber bandpass/bandstop filtering.

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1. Introduction

Recently, photonic crystal fibers (PCFs) [1], also known as microstructured optical fibers or holey fibers have attracted a great attention because they can provide unprecedented degrees of freedom in tailoring their modal properties. Although PCFs are usually formed by a central defect region surrounded by multiple air holes with the same diameter in a regular triangular lattice, the manufacturing technology of PCF such as multiple-capillary drawing method [2] can readily realize multi-core PCFs [3], [4], as well.

Wavelength-selective fiber devices such as fiber filters have become important elements in optical fiber communications and optical fiber measurements. A number of fabrication techniques have been used in realizing such devices [5]-[7]. Operation of fiber filters typically involves energy transfer over a coupling length between two distinct fiber cores coupled by proximity interaction. Modes in closely separated individual cores are phase matched over a certain frequency region which ultimately defines filter bandwidth. When the two fiber cores are the same, such filters are known as symmetric directional couplers. As modes in identical fiber cores are degenerate, symmetric directional couplers exhibit large operational bandwidth. When the two cores are not identical, and their modal dispersion relations are matched at a single frequency, such filters are called asymmetric directional couplers. Thus

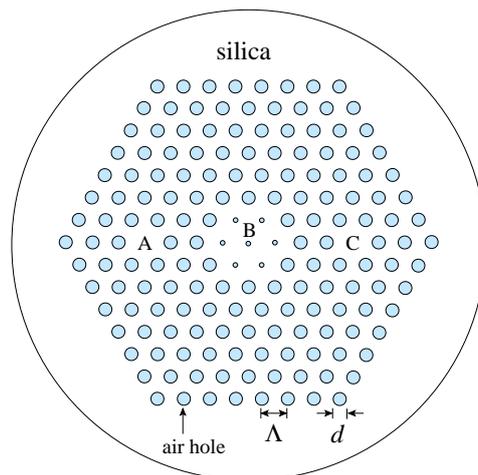


Fig.1. Schematic cross-section of the proposed bandpass filter in three-core PCF.

designed asymmetric directional couplers exhibit narrow-band filtering characteristics [8]. When designing a narrow-band fiber filter a challenge is to achieve a given filtering profile at a target wavelength. Devices based solely on proximity coupling are thus limited as there are few degrees of freedom in the design space. In this respect a promising alternative strategy for realizing narrow band-pass filters is the phenomenon of resonant tunneling [9], [10]. According to this approach, instead of bringing two fiber cores to interact directly via proximity coupling one separates them instead, so that proximity effects become negligible. To induce interaction between the cores one places a resonator in-between identical fiber cores. The resonator is designed in such a way as to be phase matched at a single frequency with the two cores. Narrow bandwidth energy transfer between identical cores is thus achieved via excitation of a resonator state, while a required filtering profile can be obtained via the resonator specifications.

In this paper, a novel design approach for realizing resonant bandpass filters in a three-core PCF is proposed. The three-core PCF consists of two identical cores separated by a dissimilar core (resonator). By adjusting sizes of air holes in the resonator region phase matching at a single wavelength can be achieved with the other cores, enabling narrowband resonant directional coupling. Although other mature technologies such as fiber Bragg grating (FBG) with circulator have been successfully used to realize narrow-band filters, perhaps one of the appealing properties of PCFs is the exhibition of temperature and strain insensitivity in comparison to FBGs. We perform numerical simulations using a full vectorial beam propagation method (BPM) [11], [12] to confirm our findings.

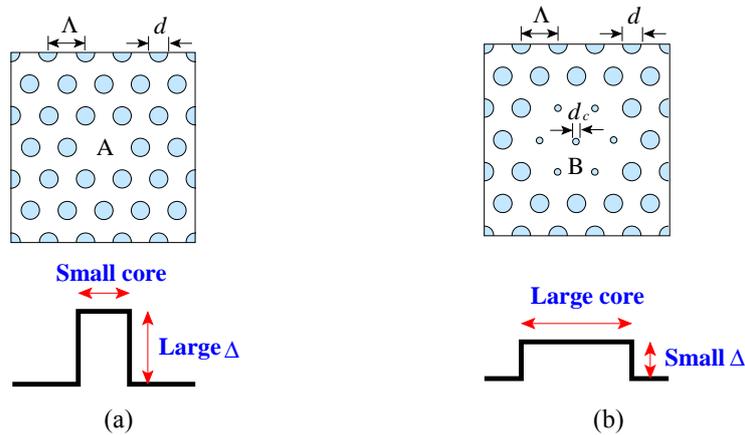


Fig. 2. Magnified areas around (a) the input core-A and (b) the resonator core-B of the structure in Fig. 1. Bottom figures represent their effective refractive index profiles.

2. Principle of operation

In Fig. 1 the cross-section of a three-core resonant PCF filter is presented. Centers of all air holes are positioned in a regular triangular lattice with lattice constant- Λ and hole diameters- d . The filter consists of two identical cores A (input core) and C (output core), separated by a resonator core B. Cores A and C are formed by removing a single air hole, as in usual index-guiding PCFs. Core B has a much larger effective area (~ 7 unit cells) and is formed by seven small air holes of diameter $d_c < d$. In Fig. 2 we present close-ups around the cores A and B and a sketch of their effective index profiles.

The operation of this filter is based on the resonant tunneling phenomenon. In general, dispersion relations of the fundamental modes in the dissimilar isolated cores A and B are different from each other. Effective area of core A is smaller than that of core B, while refractive index contrast between core and cladding in region A is larger than that in region B

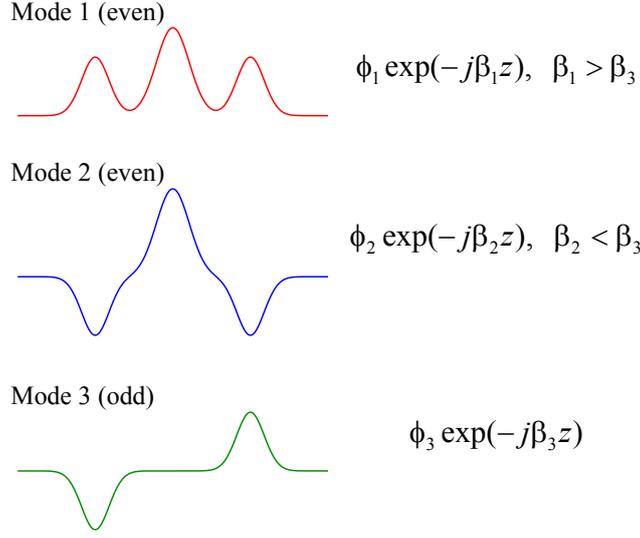


Fig. 3. Schematic of 3 supermodes of a 3 core PCF filter.

because of the presence of small air holes in the resonator structure. This leads to a stronger wavelength dependence of the propagation constant of the fundamental mode in core A, compared to that in core B. The small air-hole diameters- d_c in the resonator core-B can be chosen to impose phase matching between cores A and B at a particular wavelength, λ_0 , at which propagation constants in cores A and B become equal, and bandpass filtering can be achieved.

Alternatively the operational principle of this bandpass filter can also be explained in terms of the supermodes of the three-core directional coupler. If the individual cores of the coupler are single-moded, the coupler structure supports three supermodes, two symmetric and one anti-symmetric with corresponding fields defined as ϕ_1 , ϕ_2 , ϕ_3 (see Fig. 3). Let $n_{eff,1}$, $n_{eff,2}$, and $n_{eff,3}$ represent the effective refractive indices of the two symmetric and one anti-symmetric supermodes, respectively, for each of the polarization states. Assuming that initially all the energy is in a core A, this will correspond to the excitation of a supermode combination:

$$(\phi_1 + \phi_2)/2 + \phi_3. \quad (1)$$

After propagation over a distance- z , this excitation pattern will evolve into:

$$(\phi_1 \exp(-j\beta_1 z) + \phi_2 \exp(-j\beta_2 z))/2 + \phi_3 \exp(-j\beta_3 z) \quad (2)$$

where $\beta_i = 2\pi n_{eff,i}/\lambda_0$ ($i = 1, 2, 3$) and λ_0 is operating wavelength. If we design the PCF filter so that the effective refractive indexes of its supermodes satisfy the condition:

$$n_{eff,1} - n_{eff,3} = n_{eff,3} - n_{eff,2} \quad (3)$$

or equivalently,

$$2n_{eff,3} - n_{eff,1} - n_{eff,2} = 0 \quad (4)$$

complete power transfer from core A to core C can be achieved at the resonant wavelength λ_0 [13] by choosing mode propagation length $z=L_c$ where

$$L_c = \frac{\lambda_0}{2(n_{eff,1} - n_{eff,3})}. \quad (5)$$

By choosing the PCF filter's length to be L_c this will result in the super-mode excitation pattern at the end of the fiber $\sim (\phi_3 - (\phi_1 + \phi_2)/2)$, which will transfer all the power in core-C.

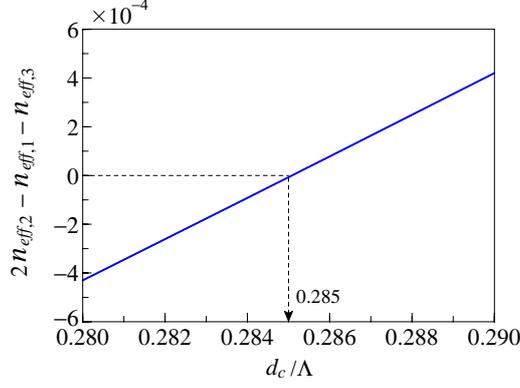


Fig. 4. Variation of the value of $2n_{eff,3} - n_{eff,1} - n_{eff,2}$ as a function of d_c/Λ at $1.55 \mu\text{m}$.

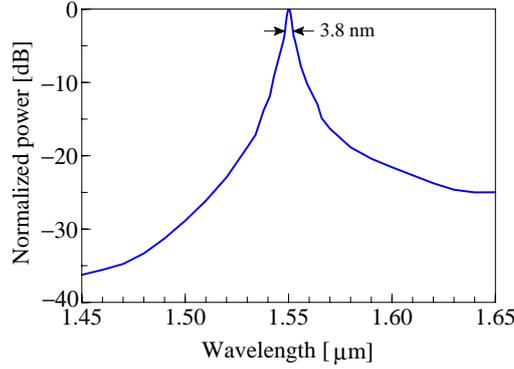


Fig. 5. Bandpass filtering characteristics of three-core PCF filter.

3. Numerical results and devise performance

In our numerical analysis we consider a three-core PCF structure as in Fig. 1, where the hole pitch is $\Lambda = 2.4 \mu\text{m}$, the normalized diameters of the air holes in the cladding are $d/\Lambda = 0.5$, and the background material is silica with refractive index 1.45. The selection of the lattice constant- Λ determines the shape of the filter's response and the fiber's coupling length. If we increase the lattice constant- Λ , the coupling length of the fiber increases while the bandwidth of the filter's response decreases. On the other hand if we decrease the lattice constant- Λ , the coupling length decreases while the bandwidth increases. In order to have narrow-band response as well as short coupling length, the above value of the lattice constant is highly appropriate. First we choose the air-hole diameter d_c so that the fundamental mode in core B is phase matched with the fundamental mode of the outer cores A and C at a wavelength of $1.55 \mu\text{m}$. As we mentioned in the previous section, the necessary condition for obtaining a high power-transfer efficiency between the outer cores is $2n_{eff,3} - n_{eff,1} - n_{eff,2} = 0$, i.e., the effective refractive indices of the supermodes of the coupler must be equally spaced. In Fig. 4 we plot

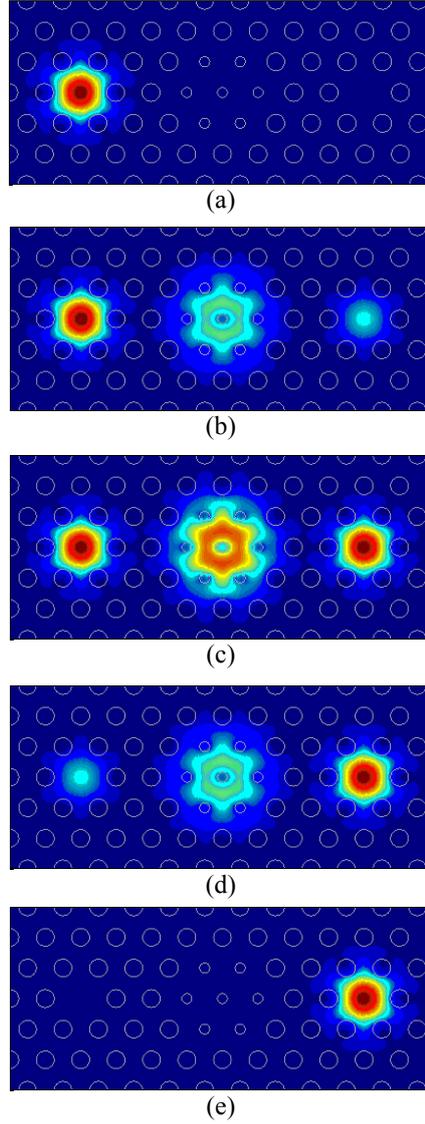


Fig. 6. Snapshots of electric field distribution at (a) $z=0$, (b) $z=L_c/3$ (c) $z=L_c/2$, (d) $z=2L_c/3$, and (e) $z=L_c$.

the value of $2n_{eff,3}-n_{eff,1}-n_{eff,2}$ for the horizontal-polarization state as a function of d_c/Λ , at a fixed operating wavelength of $1.55 \mu\text{m}$. To obtain the effective refractive indices of the supermodes of the three-core structure, a full vectorial modal solver based on finite element method [14] was used. We find that the value of $2n_{eff,3}-n_{eff,1}-n_{eff,2}$ becomes zero at $d_c/\Lambda = 0.285$. Using a full vectorial BPM based on finite element method [11], we confirm that the designed three-core PCF operates as a bandpass filter. Initial condition for the BPM simulation is assumed to be a fundamental mode in the core A. The fiber length is chosen to be one coupling length for complete power transfer from core A to C, and is given by Eq. (3) $L_c=75.8 \text{ mm}$ at $\lambda_0=1.55 \mu\text{m}$. Figure 5 shows bandpass filtering characteristics in the three-core PCF filter. A full width at half maximum (FWHM) bandwidth of this filter is 3.8 nm and

transmission of 100% at the center wavelength of 1.55 μm can be achieved. In addition we can clearly see that side-lobes outside the transmission band have been completely suppressed. The suppression of side-lobes in this narrow-band filter configuration can be explained by the fact that the cascaded nature of the filter reduces the level of the side-lobes as a result of the addition of each of the individual responses of the cascaded sections [15]. This mechanism significantly improves the band-pass characteristics in comparison to other technologies used so far for realizing bandpass fiber filters, such as the filtering mechanism realized in conventional mismatched twin-core fiber filters. The asymmetric response in Fig. 5 can be explained by the fact that at longer wavelengths the coupling between the input/output cores and the resonator becomes stronger resulting in weak isolation between the input and the output cores. Increasing the hole pitch Λ or hole diameter d , the coupling between the modes of individual cores becomes weaker and the width of FWHM can be reduced, at the cost of increasing the fiber's length. Finally, in Fig. 6 we present snapshots of electric field distribution from BPM simulation at propagation lengths of $z=(0, L_c/3, L_c/2, 2L_c/3, L_c)$ at $\lambda_0=1.55 \mu\text{m}$. At $z=0$, we see input field in a core A, at $z=L_c/2$, resonator B is clearly excited enabling power transferring between cores A and C, and at $z=L_c$, all the power is transferred from core A to core C. The power transfer from core A to core C is very smooth.

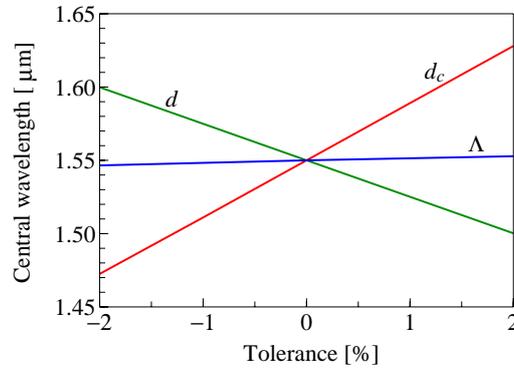


Fig. 7. Impact of the design parameters on the central wavelength of the filter. The variance of the central resonance wavelength- λ_0 is plotted as a function of the fabrication tolerance for various design parameters, that is d (green line), d_c (red line), and Λ (blue line). It is evident that the filter's response is insensitive to variations of the lattice constant- Λ due to the non-proximity feature of the coupling mechanism between the input and the output cores.

4. Sensitivity analysis and robustness of the proposed PCF filter

A crucial question concerning the performance of the proposed filter in terms of massive production is apparently the sensitivity of the filter's characteristics to the various design parameters. In other words the robustness of the design has to be clarified in terms of accurate sensitivity analysis which can identify possible flaws during the manufacturing of a large number of such filters. In this respect we have performed sensitivity analysis of the filter's performance on various design parameters in order to identify possible tolerance-limitations associated with the current fabrication technologies.

Firstly we consider the impact of the tolerances of the design parameters d , d_c , and Λ on the central wavelength λ_0 of the filter's response. We consider here that the design parameters change independently with a uniform tolerance of $\pm 2\%$ around their nominal values. In Fig. 7 we can see the results of the sensitivity analysis. Specifically we plot the central wavelength as a function of the tolerance (%) for the following design parameters: d (green line), d_c (red line), and Λ (blue line). Concerning the variation of the design parameter- d we see that the continues increment results in the continues down-shift of the central wavelength of the filter,

and typically a $\pm 2\%$ variance of d will result in a wavelength shift of $\mp 3.2\%$. For the variation of the design parameter- d_c we observe that the continues increment of it's value will result in the continues up-shift of the central wavelength, and our computations show that a $\pm 2\%$ variance of d_c will result in a wavelength shift of $\pm 5\%$. On the other hand the variation of the lattice constant- Λ seems to have no practical influence on the central wavelength of the filter's response, because from Fig. 7 we can see almost no variation when the design parameter- Λ changes. This is an interesting phenomenon and the physical explanation behind this result is associated with the high-quality tunneling effect that is being incorporated in the design. In other words we do not expect to see drastical variations of the central wavelength on the lattice constant, because the mechanism of resonance is primarily determined by the resonator in core-B. To achieve the resonance wavelength appropriately, the geometrical parameters of the resonant cavity (core-B) have been selected elaborately, thus the crucial parameter on the wavelength selectivity can not be the lattice constant- Λ but the cavity's design parameter- d_c . Indeed from Fig. 7 it is evident that the parameter- d_c influences more the variance of the central wavelength- λ_0 than any other parameters. These results are reported for the first time and they are associated with the non-proximity feature of the coupling mechanism between the input and the output cores. As a conclusion we can fairly say that if the fabrication tolerances can be kept below $\pm 2\%$ the performance of the design is acceptable for most practical applications.

An important parameter which can have a major impact in the wavelength response of the filter is apparently the bending operation. In practice the proposed fiber-filter can be bent either on purpose or accidentally, thus influencing the overall response of the filter. In order to identify the impact of the bending radius variance to the total coupling length of the device, in Fig. 8 we plot the calculated sensitivity response to the coupling length, as a function of the bending radius- R for the nominal device parameters $d/\Lambda=0.5$, $d_c/\Lambda=0.285$, and $\Lambda=2.4 \mu\text{m}$. For calculating the bending sensitivity, we have employed the tilted index model described recently in Ref. [16], where we have assumed that the fiber was bent in the same direction to that of the input and output cores (horizontal axis). From the results in Fig. 8 we can conclude that when the bending radius is large (larger than three meters), the sensitivity response to the coupling length is negligible. On the other hand when the bending radius becomes smaller (less than one meter), we can observe a drastical change in the coupling length, because when the fiber is highly bended, the resonator's characteristics change drastically, thus influencing the coupling length. In addition in such case the fiber becomes structurally-asymmetric, and as a result the filter's response will be destroyed. As a conclusion, to maintain the performance of the filter, the bending radius should be kept above three meters.

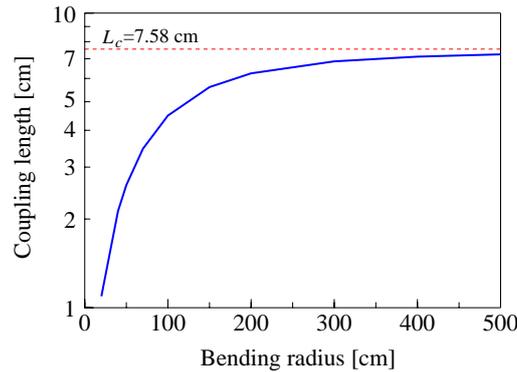


Fig. 8. Total coupling length as a function of the bending radius. The high impact of the small bending radii to the coupling length is evident. As the bending radius tends to large values the convergence to the nominal coupling length of $L_c = 7.58 \text{ cm}$ is clear.

5. Conclusions

To summarize our work, we have proposed and numerically investigated the optical properties of a novel bandpass filter based on the resonant tunneling phenomenon in a three-core PCF. The design strategy of realizing multi-core couplers based on the resonant tunneling effect, according to the best of our knowledge, is reported here for the first time. Results of a full vectorial finite element modal analysis confirmed by BPM simulations have been presented for a variety of quantities related to the fiber's propagation characteristics. The high suppression of the side-lobes in comparison to previous reported filters based on conventional fiber technology [17]-[19], as well as the narrow-band response, are the main advantages of the proposed PCF architecture. Our three-core PCF coupler can be employed in applications such as, compact all-fiber bandpass/bandstop filters. Other types of filters based on the resonant tunneling effect in multi-core PCFs are currently under consideration.