Non-Proximity Resonant Tunneling in Multi-Core Photonic Band Gap Fibers: A Revolutionary Technology for All-Fiber Integrated Assemblies

Kunimasa Saitoh[1], Nikolaos J. Florous[1], Tadashi Murao[1], Masanori Koshiba[1], and Maksim Skorobogatiy[2]
[1]Division of Media & Network Technologies, Hokkaido University, Sapporo 060-0814, Japan
[2]École Polytechnique de Montréal, Génie Physique, Canada
Phone: +81-11-706-6542, Facsimile: +81-11-706-7892, E-mail: ksaitoh@ist.hokudai.ac.jp

Abstract *We demonstrate the operation of a novel class of narrow-band pass filters based on the revolutionary technology of non-proximity resonant tunneling in multi-core photonic band gap fibers.*

Introduction

One of the major trends in the development of all-fiber devices is the increasing number of functionalities in a single fiber. The ultimate goal is to be able to fabricate in a single draw a complete all-fiber component provisioned on a preform level. These challenges can be in a certain degree met by using a novel class of multi-core microstructured optical fiber that was recently introduced in Ref. [1], which operates by resonant rather than proximity coupling, where energy transfer is realized via transverse resonators or lightguides integrated into the fiber's cross-section. Such a design allows unlimited spatial separation between interacting fibers which in turn, eliminates inter-core crosstalk via proximity coupling. The main advantage of this coupling mechanism is its inherent scalability as additional fiber cores could be integrated into the existing fiber cross-section simply by placing them far enough from the existing circuitry to avoid proximity crosstalk.

To this end we devote the present work to describe a novel class of all-fiber filters based on multi-core photonic band gap (PBG) fibers with integrated resonators in their profile. Through efficient modal analysis [2] and beam propagation method (BPM) [3], based on the finite element method (FEM), we theoretically investigate the possibility of synthesizing efficient ultra narrow-band wavelength splitters, suitable for all-fiber filtering and resonant sensor applications.

Design guidelines for multi-core PBG fiber splitter

Firstly, we consider a dual-core PBG fiber structure shown in Fig. 1. The hollow core is formed in a silica based microstructured optical fiber with a cladding refractive index n = 1.45 by removing two rows of tubes and smoothing the resulting core edges. The pitch is Λ = 2 μm, while the air-hole size is d/Λ=0.9 with a total of six hole layers in the cladding. Fundamental band gap where the core guided modes are found, extends between 1.29 μm < λ < 1.40 μm [4]. To form a splitter, operating around a single wavelength, we place two hollow cores of N=5 periods apart from each other as shown in Fig. 1. One transverse resonator with d_r/Λ is then introduced by slightly reducing (high index defect) the diameters of the holes in the middle of the line, joining the cores.

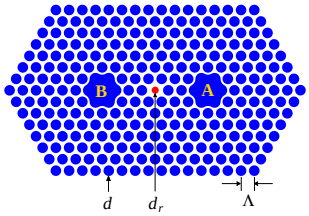

Fig. 1. Dual-core PBG fiber splitter with an embedded resonator in its profile.

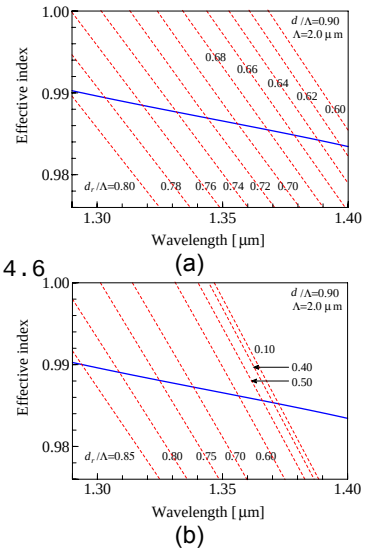

Fig. 2. Effective indexes of the fundamental mode (solid line) and the excited resonant modes (dashed lines) of the multi-core PBG fiber splitter for (a) x-polarization and (b) y-polarization.

By an accurate modal analysis performed using a FEM solver [2], in Figs. 2(a) and (b) we evaluate the effective indexes of the fundamental mode (solid curve) as well as the excited resonant modes (dashed curves) for x-polarized (horizontally polarized) and y-polarized (vertically polarized) states, respectively, as a function of the operating wavelength and for several incremental values of the resonator's normalized diameter d_r/Λ. We can clearly see that the effective index of the fundamental mode is being crossed at certain wavelengths by the excited resonant modes. The physical interpretation of this crossing is that the excited modes at wavelengths of λ_1, λ_2, λ_3, … , λ_n, corresponding to different normalized resonator's diameters d_r/Λ can be effectively transferred via

resonant coupling through the dissimilar resonators, from the input core-A into the output core-B. We can also observe that as soon as the resonator's diameter decreases the resonant wavelength increases. Due to the fact that the resonant wavelength must lie within the PBG region, the possible values of the resonator's diameters are in the range: $0.62 < d_r/\Lambda < 0.8$, for the *x*-polarized state. In the case of *y*-polarized state, we can observe a significant difference in the behaviour of the evolution of the resonance wavelengths. From Fig. 2(b) it is evident that the range of allowable values of the normalized resonator's diameters for the *y*-polarized mode which will result in resonant wavelengths within the PBG of the structure is significantly larger: $0 < d_r/\Lambda < 0.86$. In addition a very interesting phenomenon occurs. This phenomenon is the insensitivity of the resonance wavelength for the following range of the normalized resonator's diameters $0.1 < d_r/\Lambda < 0.4$, since at this range the resonant wavelength appears almost constant at a value of $\lambda_{res} = 1.372$ μm.

Numerical results and device performance

Next, we introduce an additional hollow core and consider three-core PBG fiber splitter shown in Fig. 3, where two dissimilar transverse resonators with d_1/Λ and d_2/Λ are also introduced by reducing the diameters of the air-holes in the middle of the line joining the cores. Assuming the following geometrical parameters of the PBG fiber for the *y*-polarized state: $\Lambda = 2$ μm, $d/\Lambda=0.9$, $d_1/\Lambda=0.7$ and $d_2/\Lambda=0.6$, from the results in Fig. 2(b) we can clearly see that the excited resonant modes cross the effective index curve of the fundamental mode at two distinct wavelengths of $\lambda_1 = 1.339$ μm and $\lambda_2 = 1.357$ μm. In Fig. 4 we plot the calculated coupling lengths as a function of the normalized resonator's diameter d_r/Λ for *y*-polarization. From the results in Fig. 4 we can observe the asymptotic behavior of the coupling length as the resonator's diameter approaches lower values. The coupling lengths at $\lambda_1 = 1.339$ μm and $\lambda_2 = 1.357$ μm are $L_c = 2.9$ mm and $L_c = 2.6$ mm, respectively. In Fig. 5 we plot the obtained spectral characteristics of this PBG fiber splitter with total fiber length of 2.7 mm for the *y*-polarized state through the BPM algorithm [3], where the input port is core-A and output ports are cores-B and C. From these results we can observe a dual band-pass transmission response centered at the prescribed wavelengths of $\lambda_1 = 1.339$ μm and $\lambda_2 = 1.357$ μm. The highly selectivity in the filter's response we could obtain in this case indicates the potential capability of the non-proximity resonator's states to synthesize highly selective resonant coupling characteristics. The full width at half maximum (FWHM) bandwidths of this filter are 1.2 nm and 1.1 nm at wavelengths of $\lambda_1 = 1.339$ μm and $\lambda_2 = 1.357$ μm, respectively. In this case a transmission of about 95 % at the resonant wavelengths of λ_1 and λ_2 could be achieved. The power decrement of 5 % is associated with the slightly difference between the coupling lengths corresponding to the two different operating wavelengths.

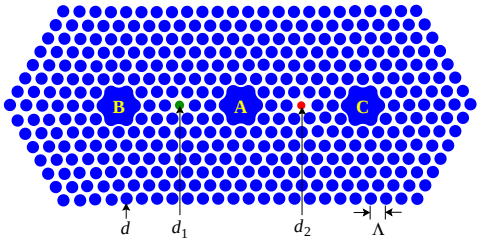

Fig. 3. Topology of a three-core PBG fiber wavelength splitter utilizing a non-proximity add-drop wavelength coupling mechanism.

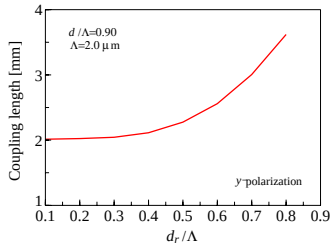

Fig. 4. Coupling length (mm) as a function of the normalized resonator's diameter d_r/Λ for y-polarization.

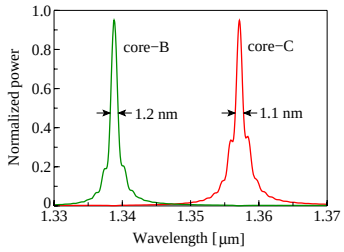

Fig. 5. Dual band-pass filtering characteristics for y-polarization of the three-core PBG fiber splitter.

Conclusions

We have proposed and numerically investigated the propagation properties of a novel bandpass filter based on the resonant tunneling mechanism in multi-core PBG fibers. Results of a full vectorial FEM 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 as well as the ultra-narrowband response and the short coupling length are the main advantages of the proposed PBG fiber architecture.

References

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