Transverse lightwave circuits in MOFs: waveguides and resonator arrays

M. Skorobogatiy[1], K. Saitoh[2] and M. Koshiba[2]
[1] *Géne Physique, École Polytechnique de Montréal, H3C 3A7, Canada*
[2] *Division of Media and Network Technologies, Hokkaido University, Sapporo 060-0814, Japan*
maksim.skorobogatiy@polymtl.ca

Abstract: Microstructured optical fiber couplers are proposed that operate by resonant rather than proximity energy transfer via transverse waveguides and resonator arrays in a fiber crossection, allowing significant inter-fiber separations, eliminating inter-core crosstalk by proximity coupling.

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1. Introduction

Integration of multiple functionalities in a single fiber is a major trend in current fiber optics. The goal is to be able to fabricate in a single draw a complete all fiber component provisioned on a preform level. Major roadblock to realization of the complex all-fiber devices is an unavoidable complexity of a required transverse refractive index profile resulting in the major challenges for preform fabrication and drawing. Assuming that these technological issues can be resolved there is still a conceptual difficulty in going to the increasingly complex fiber profiles. Particularly, many of the interesting functionalities that fiber devices offer such as modal dispersion profile design, directional power transfer between several fiber cores [1-4], inter-mode conversion, etc. rely on proximity interaction between modes localized in different core regions placed in the immediate proximity of each other. Such arrangement forms an all-interacting system with a complexity of a system design increasing greatly with a number of fiber cores. While it can be beneficial to have individual sub-components designed on a proximity principle, scalable integration of several of them in the same fiber would rather require individual spatially separated "non-interacting" sub-components and a transverse lightwave circuitry enabling connectivity between them. In what follows we use FEM solver [5] to demonstrate design principles of such transverse lightguides enabling long range energy transfer between greatly separated cores by using an analogy with waveguides in planar photonic crystals. Moreover, we demonstrate that resonator array waveguides enable polarization independent long range coupling.

2. Structure and Definitions

In what follows we introduce resonant directional coupler, which unlike a traditional proximity directional coupler, allows efficient inter-fiber energy transfer regardless of an inter-core separation. To demonstrate robustness of our approach we choose the most challenging case - long range coupling between two hollow core fibers guiding in the band gap of a surrounding 2D photonic crystal cladding. Structure and modal properties of the individual hollow waveguides are detailed in [5]. Briefly, hollow core is formed in a silica based MOF with cladding refractive index n=1.45 by removing two rows of tubes and smoothing the resulting core edges. The pitch is Λ=2μm, d/Λ=0.9 with a total of six hole layers in the reflector. Fundamental bandgap is located between 1.29μm −1.40μm.

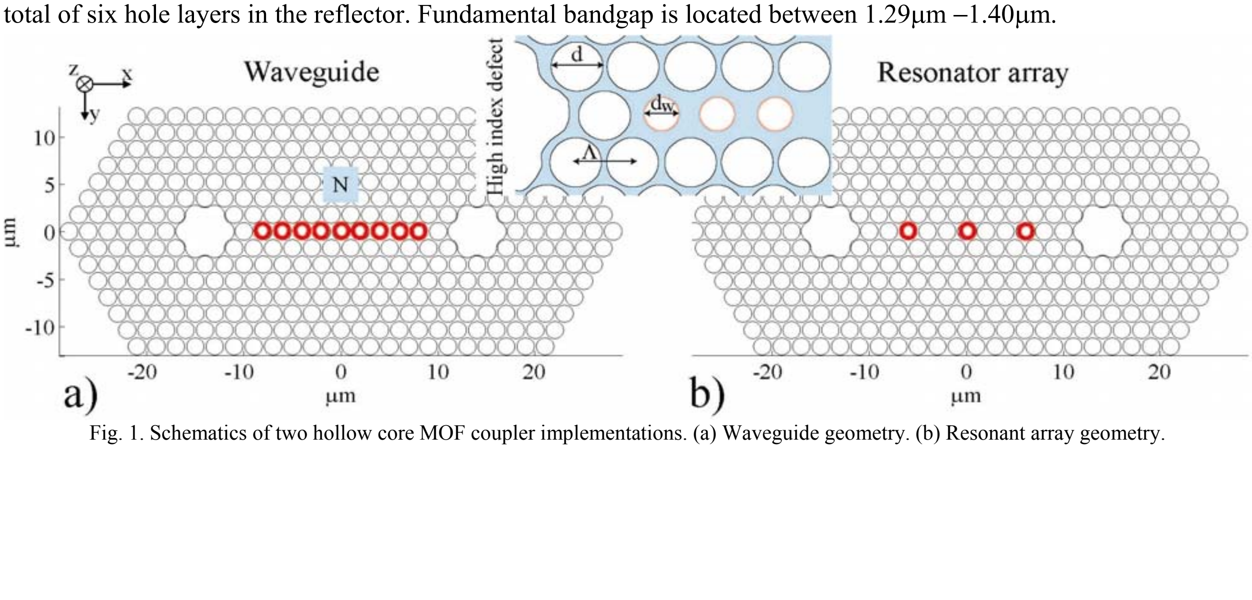

Fig. 1. Schematics of two hollow core MOF coupler implementations. (a) Waveguide geometry. (b) Resonant array geometry.

To form a coupler we place two hollow cores N periods apart from each other as in Fig.1, and then connect them by a transverse lightguide formed by changing diameters of some of the holes along the inter-core line. In a waveguide implementation Fig.1(a) sizes of all but the two closest to the cores holes are reduced. In a resonant array implementation of a coupler, diameter of every other hole is reduced Fig.1(b). In a weakly interacting case for each polarization X and Y there are two fundamental supermodes (even and odd) with effective refractive indexes $n^{x,y+}_{eff}$, $n^{x,y-}_{eff}$ closely spaced around $n0_{eff}$ of a single core fiber mode. Coupling length after which power launched in one core is completely transferred into the other core is then $L^{x,y}_c = l/(2\Delta n^{x,y}_{eff})$. Coupler radiation loss per coupling length is $1-P(L^{x,y}_c)/P(0) = 1-\exp(-L^{x,y}_c / L^{x,y}_d)$ where power decay length is $L^{x,y}_d = \lambda/(4\pi \max(\mathrm{Im}(n^{x,y+}_{eff}), \mathrm{Im}(n^{x,y-}_{eff})))$. In the absence of transverse waveguides proximity coupling between the cores decreases exponentially fast with increased inter-core separation, as fields of the core modes guided by PBG decay exponentially fast into the cladding. Thus, for inter-fiber separation N=4 coupling length is ~10cm, for N=7 it is ~1m, while for N=11 it is ~20m.

3. Long range resonant coupling via transverse waveguides and resonator arrays

Consider a resonator array implementation of a coupler Fig.1(a) with N=11, $d_w/\Lambda=0.7$ (transverse waveguides were considered in [6]). Enhanced coupling between fiber core modes happens at the points of their near degeneracy with guided modes of the individual resonators. Complete power transfer between the fiber cores via excitation of a resonator array is still possible at a resonance when the frequency of a resonator state is exactly in between the frequencies of two supermodes. Outside of the resonance power transfer in not complete and definition of a coupling length is modified to describe interaction between the resonator mode and a closest supermode. In the left plot of Fig.2 coupling length between two hollow core modes across the band gap is presented. At resonances (sharp drops in Lc) coupling length becomes as small as $L^{x,y}_c$=3cm, to be compared with L_c~20m for a proximity coupler in the absence of a transverse lightguide. Important characteristic of a resonant coupler is radiation loss over one coupling length (middle plot of Fig.2) which at resonances is ~10-20%, and increasing rapidly outside of the resonances.

In conclusion, we comment on relatively weak polarization dependence (compared to transverse waveguides [6]) of resonator arrays. Weak polarization sensitivity can be explained by perturbation theory argument. Namely, an individual resonator, and a stand alone hollow core fiber support doubly degenerate (with respect to X and Y polarizations) states. Assuming weak resonator-core and resonator-resonator coupling, resonant energy transfer between fiber cores via an array of identical resonators will be at the frequencies of incidental degeneracy between the hollow core and resonator modes which are similar for X and Y polarizations due to their near degeneracy. In the right plot of Fig.2, distribution of the leading components of electric fields in the supermodes strongly mixed with the transverse guided modes of a resonator array are presented four both polarizations at a second λ~1.312μm resonance. Detailed simulations show that at λ=1.3118μm polarization independent coupling is possible with a coupling length of 10.5cm and 80% coupling efficiency for both polarizations with a coupler bandwidth of ~0.5nm.

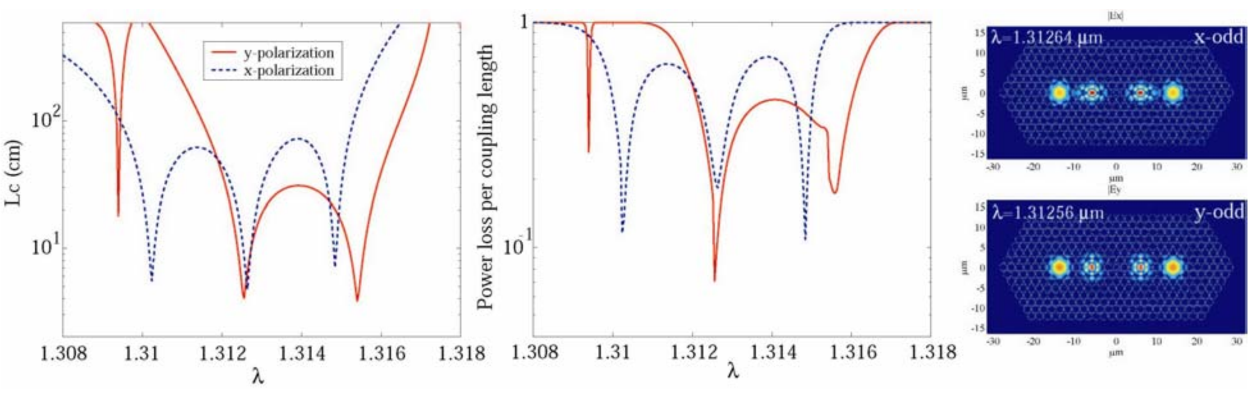

Fig. 2. Resonant coupling between two cores separated by 11 periods for X and Y polarizations (resonant array implementation). Left: coupling length between core modes. Middle: coupler loss per one coupling length. Right: leading components of the electric fields near λ~1.312μm.

3. References

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