

Aircore microstructure fibers with suppressed higher-order modes

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Abstract: A strategy for suppressing higher-order modes in aircore bandgap fibers is proposed. Simulations confirm that significant suppression of unwanted modes is achieved by including index-matched air-guiding structures in the cladding. Suppressing higher-order modes offers to improve the fundamental loss limit in aircore fibers, addressing key obstacles to the development of this technology.

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Aircore and other bandgap fibers offer interesting functions not achievable in standard fibers. The possibility of achieving low-loss aircore transmission fiber with essentially zero nonlinearity is particularly compelling, since it would dramatically change cost and performance tradeoffs[1]. Recently, it was proposed that the rapidly improving losses of aircore fibers are approaching fundamental limits[2]. The loss limit frames the ongoing discussion of whether aircore fibers can ever outperform standard fiber for data transmission. The estimated limits are in the ballpark of the best standard fiber losses, leaving the final answer on this very important question unknown.

The low-loss limit described in [2] is fundamental in that it describes scattering from unavoidable fiber irregularities of thermodynamic origin. However, the limit does not take a fixed numerical value. In fact the loss limit can be made lower, for example, simply by using a fiber with a larger core, so that core-guided light interacts less with the unavoidable surface irregularities. Realizable losses are then limited ultimately by practical issues constraining core size, and in particular impairments due to higher-order modes (HOMs). Sufficient HOM suppression could remove a key obstacle in the current development of aircore fibers. In this paper, we extend the principles of mode suppression through index-matched mode coupling [3] to the case of bandgap fibers. Preliminary numerical results demonstrate that significant HOM suppression is possible in the regime typical of low-loss aircore fibers.

Resonant suppression of modes

In aircore fiber design, as in other fibers, one would like to break the usual tradeoff between area and HOMs. In this paper, we propose achieving this with a special cladding, resonant with the unwanted HOMs [4]. This is shown conceptually in Fig. 1: the fundamental mode (left) is not resonant with the cladding features and so has ordinary confinement by the cladding. The unwanted mode (right) uses the resonant structure of the cladding as a stepping-stone while tunneling to the outer cladding. Such a fiber would have an enhanced suppression (loss) of HOMs, with no corresponding increase in the fundamental-mode loss. This generally type of approach has been used [3,5,6,7] for non-bandgap fibers for various applications.

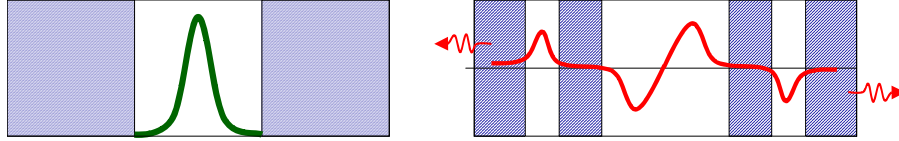


Fig. 1. Selective mode suppression can be accomplished with a resonant-cladding structure. Desirable modes are off-resonance and well-confined (left), while resonant unwanted modes have enhanced leakage.

Figure 2 shows the proposed strategy for achieving selective mode suppression: the cladding includes guiding features that are index-matched to the unwanted modes (but not to the fundamental). Hatched regions indicate portions of the fiber where the bandgap excludes light. When modes guided in the cladding features have effective index sufficiently close to the unwanted modes, energy couples efficiently between them, and can subsequently leak out of the fiber by tunneling to the outer cladding.

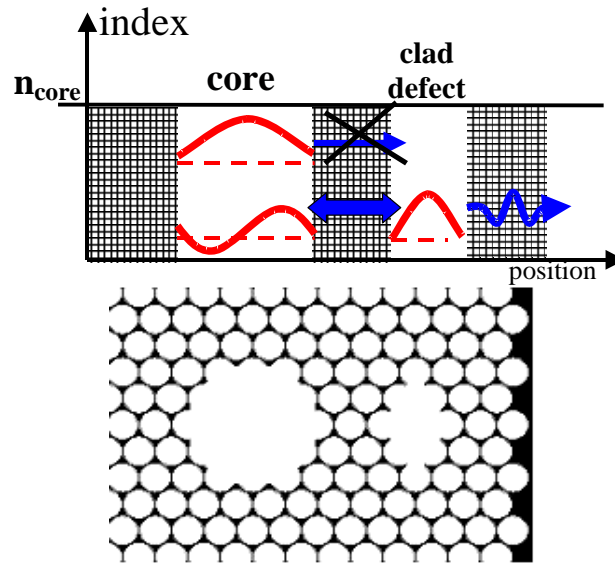


Fig. 2. Resonant suppression of higher-order core modes is accomplished by introducing index-matched cladding defect waveguides. Defect modes are index-matched with HOMs but not the fundamental core mode.

Defect Design for Mode Suppression

Simulations of several different aircore fibers were used to understand higher-order modes and demonstrate the mode-suppression strategy. Simulations were done with the finite difference mode solver [8], and used cladding parameters typical of recent theoretical and experimental work on low-loss aircore fibers. The lattice has circular holes with spacing $\Lambda=2.7$ microns and diameter $d=.94\Lambda$. For simplicity, we consider the central core shape that results when all glass is removed in a circular region of radius R_{core} . Simulation results of Fig. 3 review a well-known result, that higher-order modes become more problematic as the core size R_{core} increases. In the effective index versus wavelength plots, black dots indicate cladding modes, and blue and red curves are core modes guided in the bandgap region. For the small core (left, $R_{\text{core}} = 2.7$ microns), the core is not much bigger than a cladding period, and so the fundamental is the only well-confined core mode. In contrast, the larger core fiber (center, $R_{\text{core}} = 4.59$ microns) has several unwanted higher-order core modes guided in the

bandgap region. Calculated losses for the two fibers (right) similarly show that in moving from small (dashed) to large (solid) core, the losses of the higher-order modes (red) become much lower relative to the fundamental (blue). Low HOM losses mean that energy coupled to these unwanted modes will linger there longer, leading to greater impairments. These simulations highlight the point that HOMs are intimately connected with any strategy of reducing losses by increasing core size.

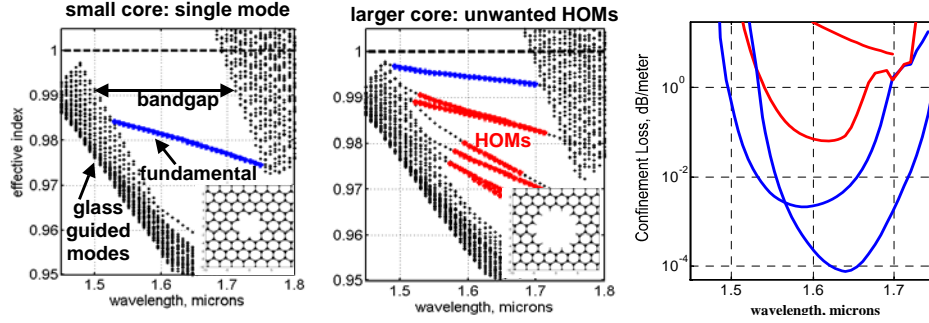


Fig. 3. Calculated modes of two aircore fibers with standard cladding design. Effective index is plotted versus wavelength for small (left) and large (center) core fibers. Losses for the two fibers (right) show the emergence of well-guided HOMs as the core size is increased.

Design of cladding defects for HOM suppression is shown schematically in Fig. 4. To achieve the index-matching as prescribed in Fig. 2, the size W of the cladding defect is adjusted so that the effective index coincides with that of the unwanted modes. In this example, several HOMs are present, but the most problematic are in the group nearest the fundamental, and so these are targeted for suppression. Simulations and approximate waveguiding equations highlight a nice feature of HOM suppression design: If the cladding defect guides light in air, then index-matching at a single wavelength automatically produces fairly broadband index-matching. To argue this, we can start with the simple approximate theory, that a mode is determined by a fixed number of oscillations M across the waveguide width W :

$$\frac{2\pi W}{\lambda} \sqrt{n_{\text{air}}^2 - n_{\text{eff}}^2} \sim \pi M$$

This simple approximation implies that the condition for index-matching is the same for all wavelengths: a mode of the cladding waveguide (width W_{clad} , M_{clad} oscillations) is index-matched to a mode of the core (width D_{core} , M_{core} oscillations) when

$$\sqrt{n_{\text{air}}^2 - n_{\text{clad}}^2} \sim \frac{\lambda M_{\text{clad}}}{2W_{\text{clad}}} \approx \frac{\lambda M_{\text{core}}}{2D_{\text{core}}} \sim \sqrt{n_{\text{air}}^2 - n_{\text{core}}^2}$$

More simply, the two modes are index matched when they have essentially the same ratio M/W , regardless of wavelength. A useful rule of thumb is that, if the core mode is in the first HOM group and the cladding mode is a fundamental, $M_{\text{core}} \sim 2M_{\text{clad}}$, and so $D_{\text{core}} \sim 2W_{\text{clad}}$.

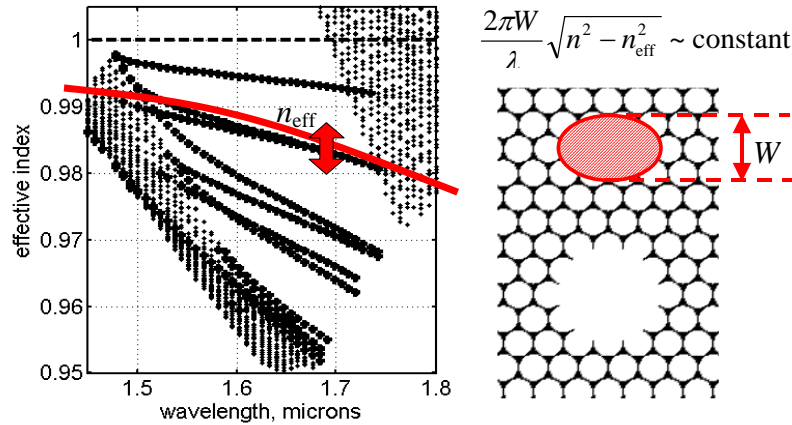


Fig. 4. An air-guiding cladding waveguide region can be designed to achieve broadband index-matching with unwanted core modes by tuning the waveguide size.

Simulated Suppression of Higher-Order Modes

Two structures were designed to test the HOM suppression strategy. Figures 5 and 6 show simulations of the two fibers, with $R_{\text{core}} = 4.59$ and $R_{\text{core}} = 5.26$ microns, respectively. In order to index-match the HOMs of the two different core sizes, two different cladding defects were designed. In both cases, loss plots show that the HOM loss (solid, red) is substantially increased by the defects, compared to identical fibers with uninterrupted periodic claddings (dashed). In the two examples, the fundamental loss is unchanged (Fig. 6) or is actually reduced (Fig. 5), further improving the relative suppression of the HOMs. Fig. 6 also highlights the impact of HOMs on usable bandwidth. Two rectangles have been drawn into the loss plot representing the wavelength range over which the fibers meet requirements of low fundamental loss (10dB/km, for example) and high HOM suppression (200dB/km, for example). In the “standard” fiber with periodic cladding, these requirements are met over a narrow 25nm wavelength range, while the HOM suppressed design achieves a much larger 91nm usable bandwidth. This is simply another way of looking at the increased HOM losses, but highlights that suppression of higher order modes is broadband, extending across much of the bandgap.

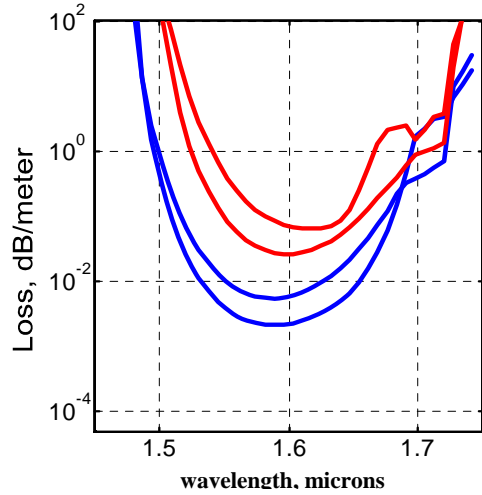
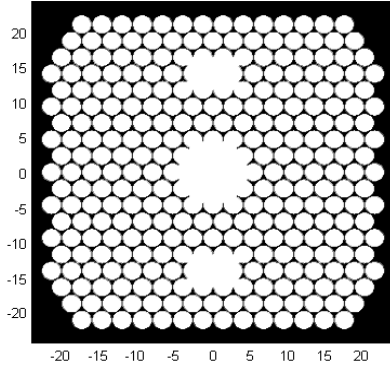


Fig. 5. A fiber design (left) with two air-guiding cladding defects and $R_{\text{core}}=4.59\mu\text{m}$ selectively suppresses the dominant HOMs. Calculated losses (right) show that HOM losses (solid red) are higher than the comparable standard fiber (dashed red, assuming no cladding defects). The fundamental instead shows reduced loss (solid blue) relative to the standard fiber (dashed blue).

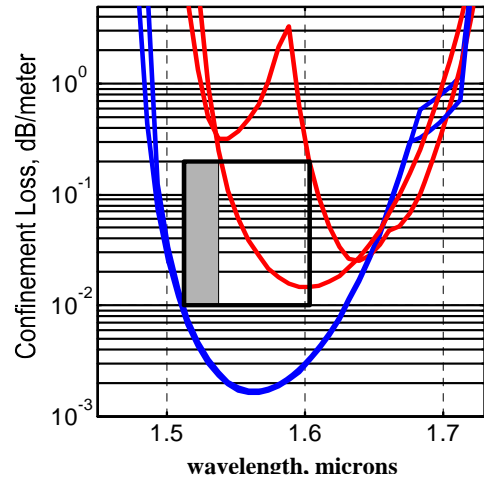
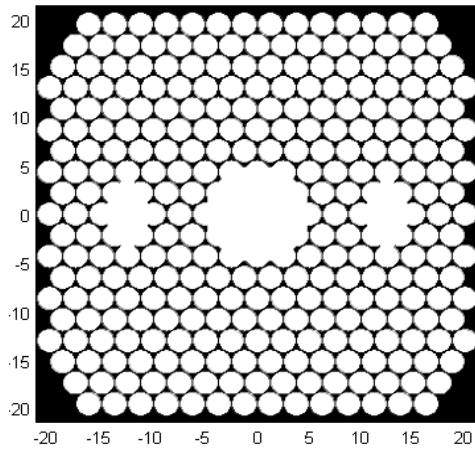


Fig. 6. A second design (left) has cladding defects re-designed to index-match a different core radius, $R_{\text{core}}=5.26\mu\text{m}$. Calculated losses (right) for this structure show almost identical fundamental confinement (solid and dashed blue) for the fibers with and without cladding defects, but substantial suppression of the HOMs by the defects (solid red) compared to the structure without defects (dashed red).

To achieve useful designs, the detailed shape of both the core and cladding defects were chosen to avoid surface modes (in addition to providing index-matching). Surface modes are modes localized in the glass immediately around an air-guiding structure, and can lead to severe losses and other impairments [9]. Methods have been proposed for designing an air-core shape to avoid surface modes [10,11]. In general, any such strategy can be generalized to

the cladding defects by thinking of each defect as an independent air core in a multi-core structure. For these examples, we extended the surface-mode-free strategy of [10]: thick glass “vertex” regions can be removed completely, but should not be cut or partially removed. Each cladding defect consists of a number of glass vertices (10 for Fig 5 and 8 for Fig 6) removed, as illustrated in Fig 7.

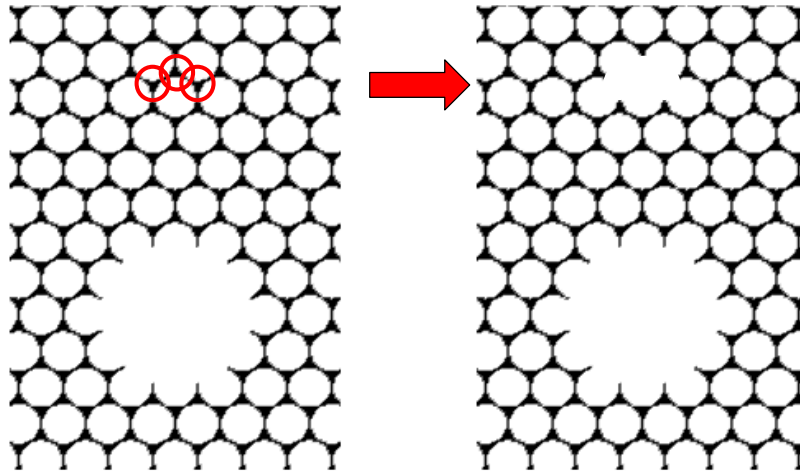


Fig. 7. Problematic surface modes can be avoided if the core and cladding defects have appropriate shapes. Generalizing the design rules of [10], we form defects by removing thick glass vertices, not cutting through them.

A closer look at the calculated mode solutions confirms that the mechanism of HOM suppression is coupling of light between the unwanted core modes and the cladding defects. Figure 8 shows the intensity (log10-scale) of the standard and HOM-suppressed version of the fiber. Both displayed modes are HOMs (with a central null somewhat obscured by the large intensity range). A small intensity peak at the cladding defect is visible in the log10-scale intensity images. This leads to much greater penetration of light into the outer cladding (right), and so increases leakage through the microstructure.

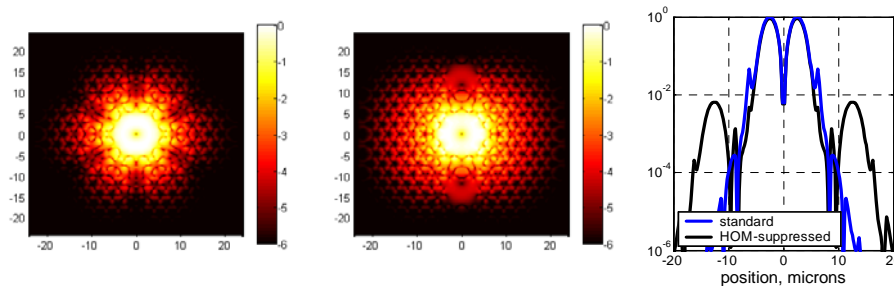


Fig. 8. Intensity profiles of the standard (left) and HOM-suppressed (center) designs highlight the coupling to a defect-guided mode. Intensity plotted vs. radius (right) shows corresponding enhanced penetration through the cladding, leading to increased tunneling losses.

Conclusion

We have shown that design of a cladding with resonant guiding structures can provide selective suppression of unwanted modes in an aircore fiber. If sufficient suppression of unwanted modes is achieved, the fiber can be considered effectively single-mode and critical transmission impairments can be avoided. More interestingly, suppressing higher-order

modes can actually reduce the fundamental loss limit by relaxing a practical constraint on the core size, and thus the interaction of transmitted light with surface irregularities. HOM-suppressed designs are then one strategy for improving the fundamental loss limit, which is a key obstacle to using aircore fibers for transmission.

Simulations presented here show that significant suppression of higher-order modes is possible for fibers similar to those used in the lowest-loss aircore simulations and experiments. Future work will explore several questions raised by these results: What is the maximum suppression achievable with improved HOM-suppressed designs? What level of HOM-suppression is needed to achieve effectively single-mode performance? How are these strategies extended to more manufacturable designs, and what tolerances are required?

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