Fibers design with a bend-compensated cladding for distributed wavelength filtering

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Abstract: Fiber designs are proposed that allow distributed wavelength filtering far more selective than conventional designs, and which is consistent with conventional fiber fabrication. By including a gradient that pre-compensates the bend perturbation in the cladding, the proposed designs overcome the usual tradeoff between mode area and wavelength selectivity. Simulations shows that the resulting fiber performance enables delivery of multi-kW signals over long distances with modest net Raman gain, using bend-resistant fibers of convenient core size.

Fiber lasers have become increasingly utilized for their efficiency, reliability, and beam quality in many high-power applications, displacing other sources. Exciting research in fiber design has achieved impressively large mode areas [1,2], and in some cases reasonably single-moded operation. Large mode area is one approach to overcoming a nonlinear limit on power scaling: when nonlinearities limit the intensity, we can reach higher power by spreading this intensity over a larger area. However, specific nonlinearities can often be mitigated more easily: for example, a large reduction in stimulated Brillouin scattering (SBS) can be achieved in a moderately large mode area through acoustic engineering of the fiber [3], or by modulation techniques. In systems limited by stimulated Raman scattering (SRS), wavelength filtering [4] can be effective in overcoming the nonlinear limit. In this paper, we propose a novel class of fibers for distributed filtering. We present numerical simulations showing that conventional filter-fiber designs are limited by a tradeoff between effective area and selectivity of suppression, and show that this tradeoff severely limits the length of fiber that can be used in practice. Our proposed filter fibers with bend compensated cladding overcome this tradeoff: this allows them to achieve low net Raman gain over long lengths, for example enabling use of a delivery fiber over 20 meters long in a 2-kW system. Remarkably, this fiber strategy thus meets the high-performance requirements of relevant applications without requiring the complex fabrication needed for solid-bandgap, resonantly coupled, or other microstructure fibers.

Bend compensation and selectivity of wavelength filtering

Bend compensation is a powerful design principle that stems from the observation that bend perturbations are responsible for essential limitations in many conventional fibers design problems. Previously, we have applied this principle to achieving improved single-modedness free of the usual tradeoff with effective area [5,6]. Here we show that the principle is more general, and that in the seemingly different problem of wavelength filtering, a bend-compensated cladding can again allow us to greatly exceed the performance of conventional designs.

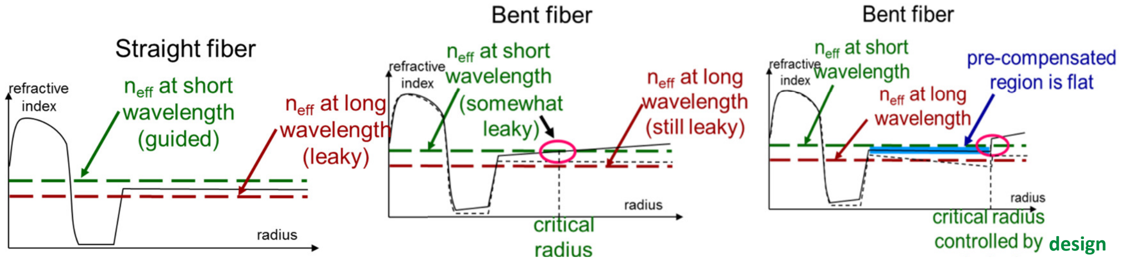

Fig. 1 Wavelength selectivity schematically illustrated for a conventional fiber (left and center) and bend-compensated fiber (right).

As with single-modedness, bends impose the dominant tradeoff on fiber design: in a conventional "w-fiber" design with no bends, simply by fabricating a very flat cladding, one can in principle achieve extremely high selectivity (Fig. 1, left). The cladding sits entirely below the mode index of the signal wavelength, and so tunneling losses are zero. At the same time, the mode index at the noise wavelength sits below the cladding, and so the loss at this wavelength can be engineered to be very high. For any application where the fiber cannot be held straight, the standard bend perturbation model [7] destroys precisely the flatness of the cladding that is essential to selectivity. The tighter the bend (and the larger the mode area), the more the two wavelengths tend to see a tunneling barrier of similar width (Fig. 1 center); that is, selectivity of tunneling is ruined by the bend perturbation. Once we recognize that flatness of the cladding is the essential requirement for selectivity of filtering, the elegant "transformation optics" solution of a bend-compensated cladding [5,6] presents a solution: We fabricate the fiber with a tilted cladding, so that when bent the flatness is restored (Fig. 1 right).

Raman suppression: effective area and loss selectivity

The performance tradeoff between mode area and filter selectivity is shown in Fig. 2 (top). Simulated results are shown for optimized designs of the conventional w-fiber type (black dashed) for the illustrative case where signal loss is constrained to <0.02dB/m. Selectivity of filtering is defined by the ratio of dB/m losses for the signal wavelength 1060nm and noise wavelength 1135nm, and the plot confirms the strict tradeoff depicted schematically in Fig. 1 (b). By comparison, bend compensated designs (blue circles) can greatly exceed the performance tradeoff, simultaneously achieving highly selective suppression, large mode area, and compatibility with conventional fabrication.

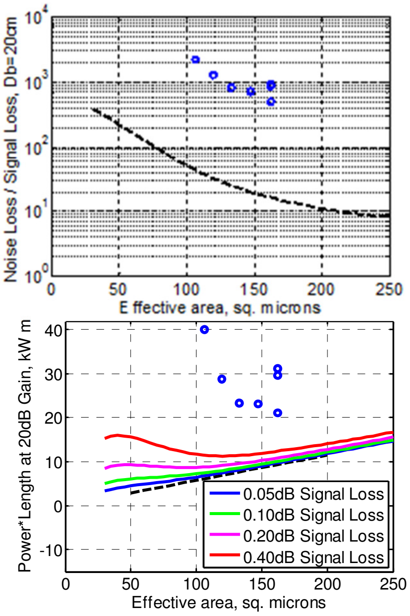

Fig. 2 Calculated selectivity vs Area of conventional and proposed fibers (top); Power-length product limit for moderate net Raman gain.

A simple model of the improved system performance this would enable is plotted in Fig. 2b. This plots the power-length product at which the net Raman gain reaches 20dB, according to the simple equation:

$\exp(g_R\, P\, L / A_{eff}) = \exp([(\ln 10/10)\,(20 + \text{suppression})]$

Here, the SRS suppression is taken to be simply the (Noise Loss/Signal loss) factor from the fiber simulations times the acceptable signal loss (which is a system level design parameter). For simplicity, we assume that relative selectivity ratio is nearly independent of the specific 0.02dB/m signal loss assumed in the simulations. The conventional design performance is plotted (solid lines) assuming several different values of acceptable signal-wavelength loss, from 0.05dB to 0.4dB, and shows that the conventional fiber limitation prevents highly desirable regime of kW power propagating with low loss over distances significantly greater than 10m. In contrast, the bend-compensated fibers (circles) enable dramatically improved performance: suggesting that even for very small 0.05dB signal loss, and moderate core size, one could approach 2kW power delivered over 20m with a reasonable bending requirement that the local fiber radius of curvature be maintained at 10cm (although imperfections and un-modeled effects may reduce actual performance somewhat). Such a bend requirement can be met by proper cabling of the fiber.

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