Refractive Index Grading Optimization for Rectangular Core Fiber

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Abstract: We optimize the refractive index grading for rectangular core fibers in support of mode division multiplexing. Designs maximizing the effective index separations for MIMO-less support and others minimizing the differential group delays are identified. ©2020 Lior Rechtman and Dan M. Marom

1. Introduction

Mode-division multiplexing (MDM) in few-mode fibers (FMF) offers the ability to transmit additional information encoded on spatial channels [1, 2], potentially addressing the looming capacity crunch in single-mode fiber (SMF) based optical communication systems [3]. However, there are challenges to be addressed for MDM-based communications. Depending on the FMF properties, modes may experience mixing (which may become prominent when modes' phase velocities are close), necessitating the use of multiple-input, multiple-output (MIMO) digital signal processing (DSP) at the receiver to unravel the mixed spatial channels. The MIMO-DSP complexity scales with the temporal spread of the launched signals (or differential group delay-DGD), resulting from modal dispersion in FMF. Hence, ideally, we desire FMF with no—or strongly suppressed—mode mixing, for which we can omit MIMO processing [4], and if this cannot be obtained and mode mixing is present and significant, then to minimize its DGD.

Previously, we suggested a new type of FMF for MDM, where the core has a rectangular shape designed to support spatial modes along one transverse direction and be single-moded in the orthogonal direction [5]. The rectangular core fiber (RCF) has several key advantages: mode groups of size two (polarization degenerate only, designated TE_{1x}/TM_{1x}, with x being the mode number: 1, 2, 3…), regularly placed mode groups for suppression of mode mixing, and facilitated and direct planar device integration capability. We further investigated the option of a graded-index of quadratic profile (Fig. 1) and favorably found that the quadratic grading has more regularly spaced mode groups (almost equal effective index differences), and more closely packed group indices that upon closer inspection are in reverse order to those of the step index fiber. In this paper we investigate whether the quadratic grading is optimal for

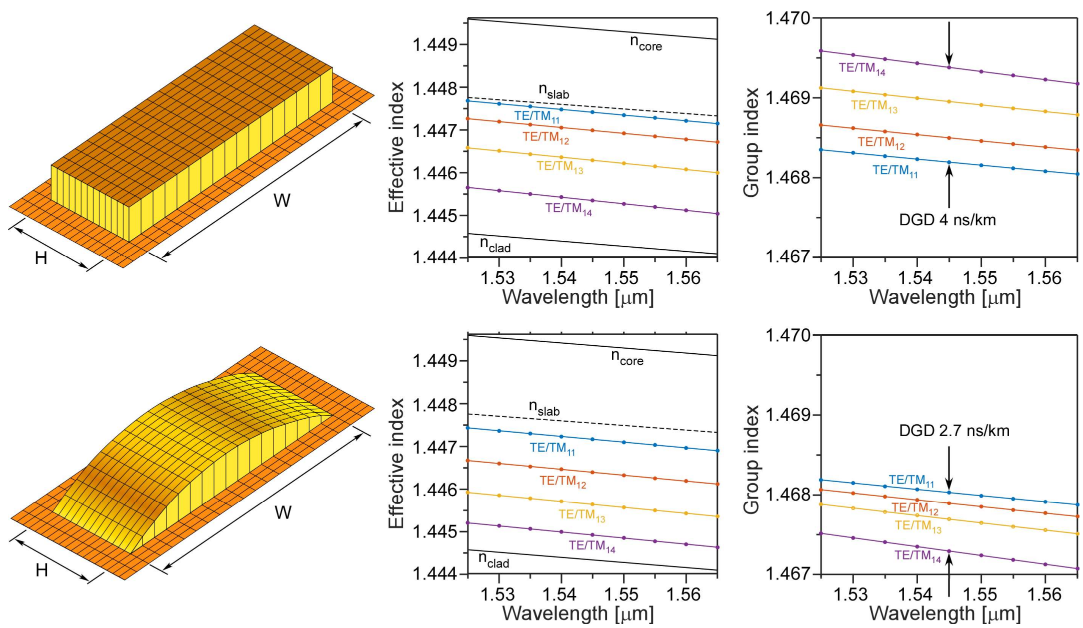

Figure 1 – Rectangular core fiber designs and their modal propagation characteristics as a function of wavelength.
Top row: Step index. Bottom row: Quadratic index. Left: Refractive Index profile. Center: Effective index. Right: Group index.

the RCF geometry, using power-law (alpha profile) graded index optimization and find design alternatives for widest spread of modes' effective index, least DGD, and a fiber combination for modal dispersion compensation.

2. Modeling and mode-solving rectangular core fiber designs

The rectangular core fiber with variable grading is modeled as follows: We assume the fiber cladding is composed of silica and the core region is germanium doped to achieve the desired refractive index profile. All index grading is performed in the multimode direction, the rectangle's width, W (see Fig. 1). The highest refractive index contrast corresponds to $\Delta = (n_{core}^2 - n_{clad}^2)/2n_{core}^2 = 0.00344$, providing a low contrast as appearing in the design of conventional SMF and multimode operation is achieved by scaling the width parameter. (The findings of this work will apply to higher refractive index contrasts too; However, higher refractive indices may exhibit higher scattering losses.) The core index grading follows the α profile, as performed for multi-mode fiber in [6] and defined by:

$$n(x) = n_{core}\sqrt{1 - 2\Delta\left(\frac{|x|}{W/2}\right)^{\alpha}} \quad \text{for } |x| \leq \frac{W}{2}$$

With α=2 corresponding to a quadratic profile and α=∞ to a step index profile (see Fig. 2). For each $\alpha \in (1, \infty)$, we optimize the width such that the fifth mode is nearly excited. This ensures that we well-guide the first four spatial modes (we seek for the highest supported mode, the fourth, to be as far from the excitation point as it is most dispersive at that region). The core width increases as the grading across the core becomes less uniform ($\alpha \to 1$), and saturates as $\alpha \to \infty$ (step index) to a width of 33 microns (see Fig. 2-left), similar to our reported fiber sample [7]. The rectangle's height, H, is kept constant at 6.3 μm for maintaining single mode support.

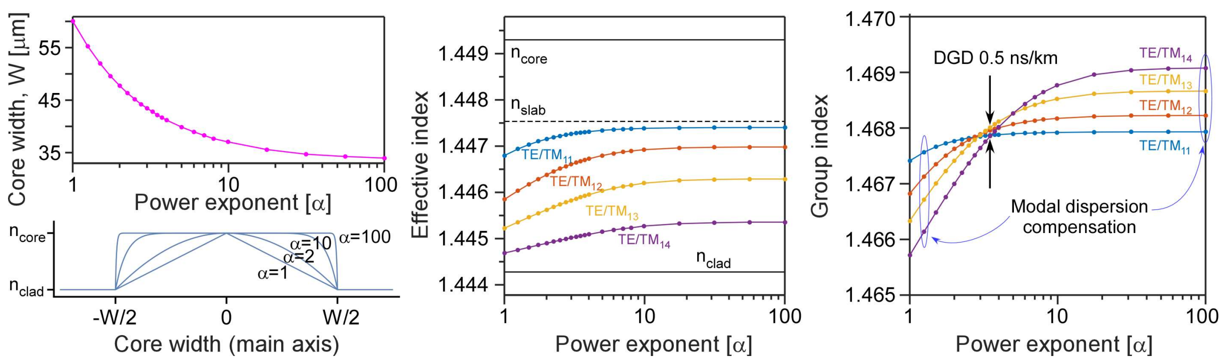

Figure 2 – RCF refractive index grading designs. Left-bottom: Refractive index profiles for select α values. Left-top: Rectangular core width adjustment for different α values, to well-support four spatial modes in all cases. Mode effective indices (center) and mode group indices (right) for different α values.

For each fiber design (α value), we solve for the supported fiber modes using Comsol© finite element analysis E&M software package, for wavelengths across the C-band. The group indices are derived from the effective index local slopes. Typical results for α=2 and α=∞ are shown in Fig. 1. To compare different designs, we chart the effective and group indices at λ_0=1.545μm for different power exponent values, α (see Fig. 2-center, right). Some characteristics are immediately evident: (i) The effective mode indices never span the entire range between n_{core} and n_{clad} in RCF, due to the separable projection of the propagation constant, k, onto the x-direction (κ_x) and the y-direction (κ_y). Hence the spatial modes are bound between n_{slab} and n_{clad}, where n_{slab} is the effective index of the fundamental mode of the slab waveguide (see dashed lines in all effective index graphs). (ii) The effective indices bunch towards n_{slab} as $\alpha \to \infty$ (step index) hence well-guided, whereas the effective indices bunch towards n_{clad} as $\alpha \to 1$ (triangular profile) becoming less-guided. (iii) Close to α=2 the effective indices appear equally spaced. The precise value is obtained in the next section. (iv) The effective indices bunching towards n_{slab} and n_{clad} at $\alpha \to \infty$ and $\alpha \to 1$, respectively, result in a flipping of the group indices ordering. At some fiber design α value, their span will be minimized.

3. Optimal refractive index grading designs for RCF

When designing FMF to suppress mode-group mixing, we wish to separate the mode group's momentum, or effective indices. For RCF, the mode groups contain only the two polarization degenerate modes (TE/TM), hence if no mode group mixing occurs then MIMO-less operation can be adopted and standard receivers (coherent or incoherent) can be used. We plot the effective index differences for different RCF grading designs (Fig. 3-left), and observe that the modes achieve optimum spacing (the min spacing is maximized, and the max spacing is minimized) at α=2.25. While the achieved mode separation is small, ~7.5×10^{-4} (i.e., less than the quoted target difference of 10^{-3} for MIMO-less operation [6]), this is a direct consequence of our choice of low index contrast fiber (n_{core}-n_{clad}=5×10^{-3}). Scaling the index contrast would immediately translate to greater separation of the effective index differences.

For a fiber design with minimum DGD, we choose α=3.5 where the least separation exists between the group indices (see Fig. 2-right), leading to a low modal dispersion value of 0.5 ns/km. However, since we observe fibers with reversed ordering of the group indices, we can identify fiber design pairs, of unequal lengths, that jointly can achieve modal dispersion compensation. To identify the optimal fiber pairing for modal dispersion compensation, we calculate for each fiber design with α<3.5 the best compensating fiber having α>3.5, and then seek the global optimum (see Fig. 3-right). We find the optimal fiber pair of nearly equal lengths (1:1.17) of RCF with α=1.5 and α=100, respectively, reducing the total link DGD to 0.14 ns/km. Note that concatenating different RCF designs may result in modal crosstalk, and require specialized connectors for maintaining modal purity across the fiber design transition.

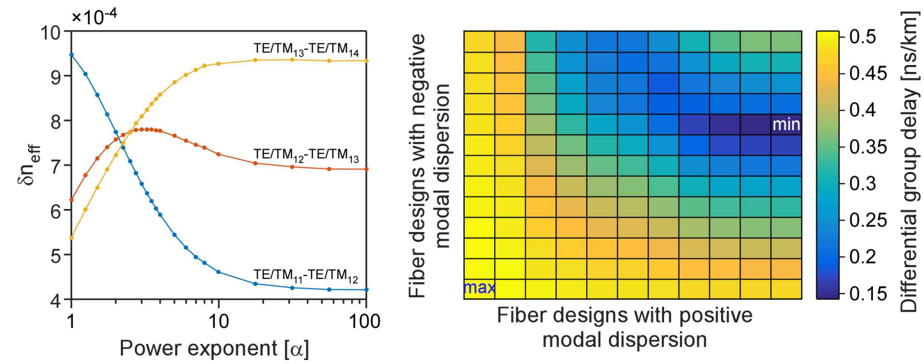

Figure 3 – Optimized design points for RCF. Left: Effective index differences for different design choices. Right: Optimization of fiber design pairs for modal dispersion compensation, for finding minimum DGD.

4. Conclusions

We analyzed the modal properties of RCF under various refractive index gradient profiles, identifying designs that will suppress mode mixing by maximizing the effective index differences between propagating modes, and ones for minimizing DGD for relieving the computational MIMO-DSP load. Such RCF fiber designs can potentially support communication distances for distances ranging from 1-100 km.

Acknowledgment

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5. References

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