Record (60) Uncoupled Modes in A Step-Index Fiber due to A New Light Guidance Mechanism: Topological Confinement

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Abstract *We exploit a recently discovered, so-called, topological confinement effect, to achieve mode-mixing resistant (inter-mode purity > 15 dB) propagation of a record 60 modes over 90 meters of a simple step-index fiber.*

Introduction: mode-count scaling

Scaling channel counts of optical fibers remains a topic of immense interest for applications that exploit light's spatial diversity, such as space-division multiplexing[1],[2], quantum encryption[3], nonlinear signal processing[4], beam-steering/shaping[5] and machine learning[6]. Channels that remain unmixed and independent over desired length scales would be desirable in most applications. Multicore fibers with up to 37 cores have been demonstrated[7], but this scaling comes at the expense of ever-increasing overall fiber sizes, which poses reliability constraints. Multimode fibers are significantly more space-efficient, but require complex (elliptical[8], ring-core[9]) fiber designs, and even so, have been restricted 12 modes over km lengths[10] or 24 modes over meter lengths[11]. This was achieved with fiber designs that minimize the number of higher radial order (m) modes that are guided, hence reducing their chance of mixing with the desired higher azimuthal order L, radial order $m = 1$ modes (also called orbital angular momentum (OAM) modes). Further scaling has stagnated because guiding a greater number of L modes necessarily results in guiding more $m > 1$ modes, and avoiding mode-crossings between all these modes becomes virtually impossible.

Here, we exploit a light-guiding mechanism traditionally considered to be forbidden in optical fibers, to fundamentally solve the mode-mixing problem mentioned above. Instead of modes guided by total-internal reflection (TIR), we show that modes of very high azimuthal order L not only experience negligible leakage loss, but also naturally avoid coupling to proximal parasitic modes $m > 1$ modes. Since this effect is not fiber-design-dependent but arises from a confinement effect based on the topological charge L of light, we are able to demonstrate a record level of 60 unmixed modes over 90 m of a fiber that is merely step-index in profile.

Concept of Topological confinement

Figure 1a illustrates the transverse wavevector k_T, and propagation constant $\beta = 2\pi \cdot n_{eff}/\lambda$ of modes in a waveguide. Light propagation is conventionally possible due to TIR, but when $n_{eff} < n_{clad}$, a mode is "cutoff" and is supposed to be debilitatingly leaky. In the wavevector picture, the cutoff mode is leaky

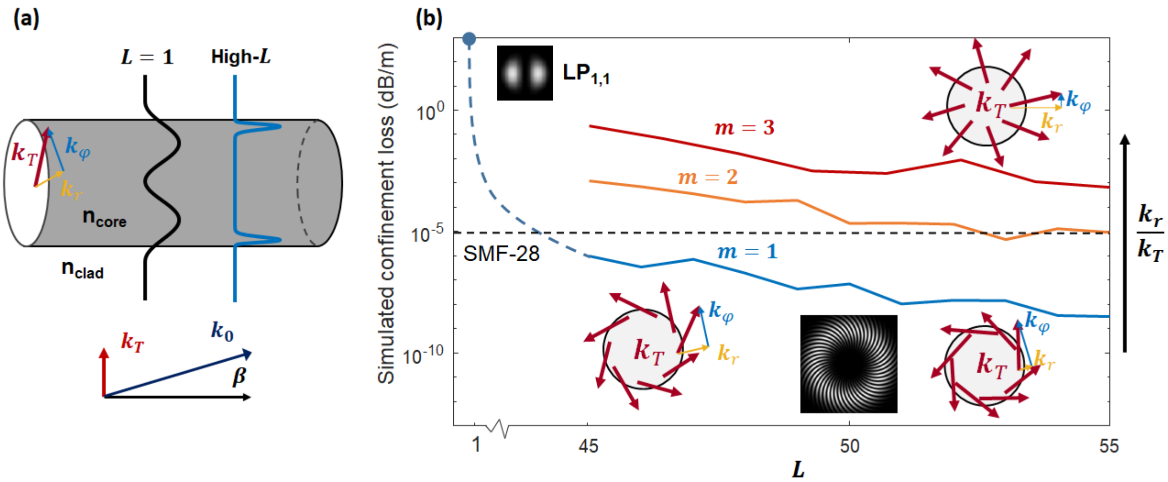

Fig. 1. (a) Guidance of $L = 1$ and high-L mode in a step-index fiber, and the wavevector picture; (b) Simulated confinement loss as a function of L at a wavelength 20% beyond the cutoff wavelength of each L. Inserts are transverse wavevector distribution for three select modes, $LP_{1,1}$ mode image and spiral patterns for $L = 50$ OAM mode. Black dashed line indicates transmission loss for SMF-28

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because k_T is large enough (bounce angle steep enough) that TIR is no longer possible. However, simulated field profiles for a cutoff $L = 1; m = 1$ (e.g. the $LP_{1,1}$) and a cutoff high $L; m = 1$ mode shows that the higher L mode appears significantly more confined to the core. Simulating propagation losses for different $L; m = 1$ modes at a relative wavelength 20% past cutoff using well-known phase-matched layer models[12] clearly shows (Fig. 1b) that loss dramatically decreases for high-L cutoff modes. The relative distribution of the transverse wavevector k_T in the radial (k_r) and azimuthal (k_φ) directions reveals the reason – as OAM order L increases, radially outward "escape" decreases, and the cutoff mode remains effectively confined and quasi-guided[13],[14]. Indeed, a cutoff $LP_{1,1}$ mode, possessing very low L, has loss as high as 1000 dB/m at a relative wavelength ~20% past cutoff, as per conventional wisdom. However, for $m = 1; L > 45$ modes, the confinement loss is, in fact, lower than the overall loss of SMF-28! While high $L; m = 1$ modes behave in this counterintuitive fashion, the loss conventionally increases for $m > 1$ cutoff modes. Modes with substantially different losses seldom mix because the coherent coupling process is "frustrated"[15]. Hence, the results of Fig. 1 indicate that cutoff high $L; m = 1$ modes also naturally avoid coupling to other for $m > 1$ modes. Thus, operating with cutoff high $L; m = 1$ modes, called topologically confined modes (TCM) henceforth, yields a low loss, naturally mode-mixing-free environment.

Setup and Results

Since none of the above phenomena are particular to fiber design, one may expect to exploit the benefits of spatial diversity from the simplest kind of a fiber – a step-index fiber. The 90-meter step-index fiber (Fig. 2b) we used has a large index contrast (Δn ~ 0.04) and core size (~70um). Figure 2a shows the experimental setup: a spatial light modulator (SLM) converts the Gaussian beam from a 1550nm laser source to an OAM beam, and the output from the step-index fiber is separated into two (left/right) circular polarizations (LCP/RCP) by the combination of a quarter-wave plate and a polarization beam displacer (PBD). This eases the analysis of modal output since OAM fiber eigenmodes (of a given n_{eff}) are naturally circularly polarized.

Figure 2c shows the measured cutback loss, using a 1550-nm pulsed ps laser source, of select modes in either circular polarizations. The measured loss remains remarkably low (~0.05 dB/m) up to $L = 60$, even though these mode orders are significantly past cutoff. Anomalous loss behavior is observed for $L = 44$, 46, 50 LCP modes – this is because these modes accidentally couple to high-m modes with much higher loss (see further discussion on mode purity, below). Overlaid in the plot is the simulated confinement loss – this loss is theoretically zero for bound modes with $L \leq 42$, and then starts rising for cutoff modes. Dramatic increases in simulated loss occur for $L > 60$, which matches well with experiment. The theoretically predicted loss is, however, substantially lower than experimental measurements for $L \leq 60$, indicating that a large contribution to the currently measured loss is scattering, pointing the potential for future manufacturing improvements. Picking 0.1 dB/m loss as an arbitrary "cutoff" for useful modes, we analyze the mode purity of all conventionally bound and TCM modes in the range $L = \pm 40$ to ± 63 with LCP and RCP.

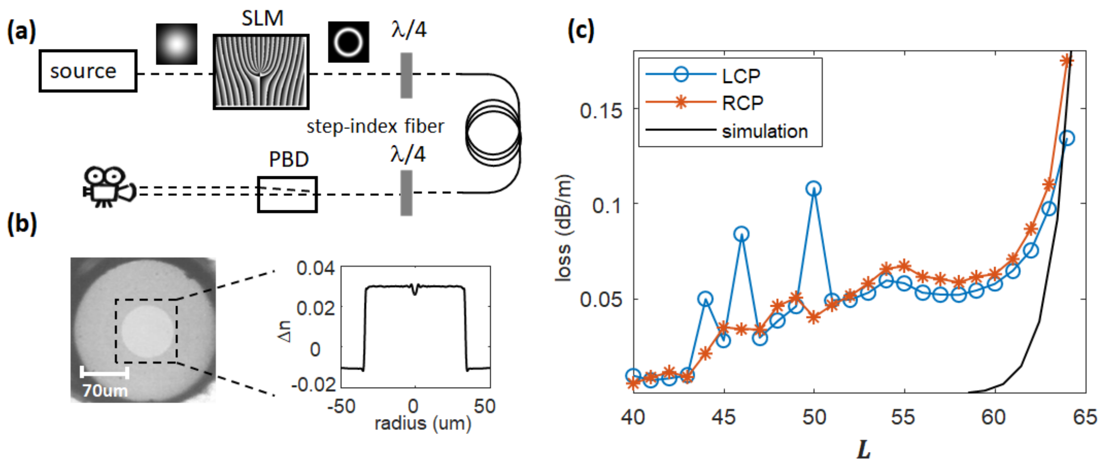

Fig. 2. (a) Experimental setup; (b) End facet and index profile of the step-index fiber; (c) Measured loss for LCP &RCP and simulated confinement loss as a function of L at 1550nm.

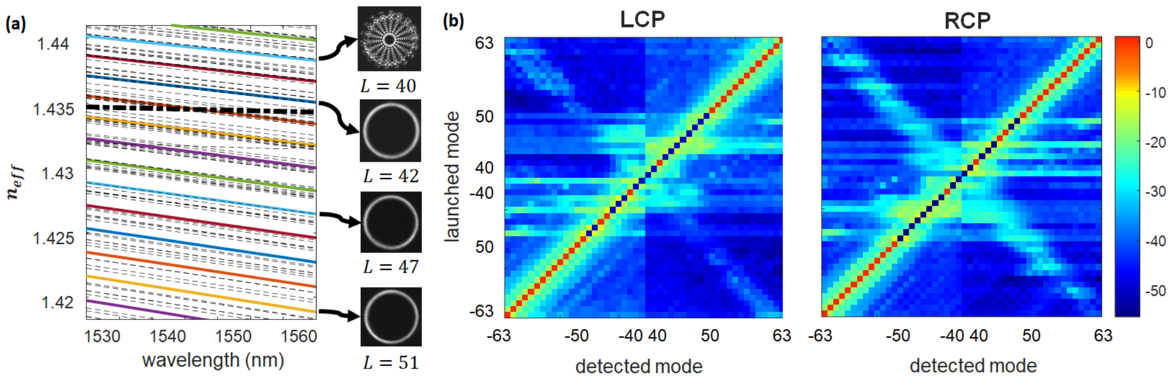

Fig. 3. (a) n_{eff} vs. λ for select modes – bound OAM modes usually mix with undesired modes but high-L TCMs remain stable and clean; (b) Transfer matrix of all the modes $|L| = 40 - 63$ with LCP and RCP.

Figure 3a shows n_{eff} of select modes $L = 40$ to 51 where the bold colored lines are the desired $m = 1$ OAM modes and the thin black dashed lines are the plethora of undesired high-m modes. The horizontal bold dashed line represents the refractive index of the cladding, illustrating that the modes are cutoff for $L > 42$. Also shown are output mode images from the fiber when select modes were excited. As is evident, the conventionally bound $L = 40$ mode dramatically mixes with neighboring high- m modes, while the bound $L = 42$ manages to avoid this fate. This trend, of being able to find only a few clean modes (e.g. $L \sim 47$) because they happen to be far, in n_{eff}, from offending high-*m* modes, continues past cutoff in what we call an "intermediate" region. However, for modes with $L \geq 51$, a clean modal output is obtained *regardless* of whether or not they cross, in n_{eff}, with other high-*m* modes, clearly illustrating the power of TCMs to naturally avoid mode mixing.

Figure 3b shows a quantitative summary of our fiber's modal performance. The purity of all modes with propagation loss < 0.1 dB/m (criterion set earlier) is deduced by using a narrowband tunable external-cavity laser in the 1550-nm range for mode excitation, and then employing spatial[16] and spectral interferometry[17] to quantify modal content. The transfer matrices shown in Fig. 3b illustrate that, for modes denoted with red squares, mode purity exceeds 15 dB, with an average > 18 dB. The polarization extinction ratios (PER) average ~10 dB for all modes, but were substantially better (>16 dB) for more than ½ of the modes. Spectral interferometry indicated that much of the parasitic mode content we measured was discrete in nature, and hence influenced by our excitation technique and not a fundamental property of the fiber – hence optimizing excitation should yield even better mode purities and PERs. Overall, we conclude that this fiber supports a record value of 60 OAM modes with high purity, PER and low loss.

Discussion and Summary

In summary, we demonstrate the highest, to the best of our knowledge, channel count (60) of modes that are resistant to mode mixing over 90 meters of fiber – a length scale governed by fiber available to us, but already of relevance to applications ranging from lasers/amplifiers and data-center connections to nonlinear optics and machine learning. We believe this is the first instance of utilizing a standard, simple step-index multimode fiber for transmitting a large ensemble of uncoupled modes, hence pointing to the possibility of using legacy fiber for mode multiplexing. These interesting attributes were made possible by exploiting light propagation in the recently discovered regime of conventionally cutoff modes that provide guidance due to the topological charge and not total internal reflection. Since topological charge/ azimuthal index/ OAM order L, is an unbounded integer, it is likely that this concept can help scale mode count even further.

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