Scaling to 100 modes by exploiting topological confinement

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Abstract: By conducting a systematic study of the phenomenon of topological confinement for light transport, we demonstrate a record of 100 unmixed modes over ~22m of fiber with average nearest-neighbor crosstalk of -36 dB. © 2024 The Author(s)

1. Introduction:

The scalability of uncoupled modes in multimode fibers is an important consideration for the type of space-division multiplexing [1] – with multiple-input and multiple-output (MIMO) or MIMO-free, with multimode or multicore fibers – that becomes deployed, not only for transmission, but also for devices such as EDFAs. The recent discovery of topological confinement [2] reveals a regime beyond total internal reflection (TIR) cutoff, where the coupling between modes is naturally suppressed, yielding a record of 50 uncoupled modal channels over a km of fiber. Here we investigate the scalability of topologically confined modes (TCM) for propagation lengths of interest in devices – 10s to 100s of meters – and demonstrate a record mode count of 100 in an appropriately sized ring-core fiber (RCF).

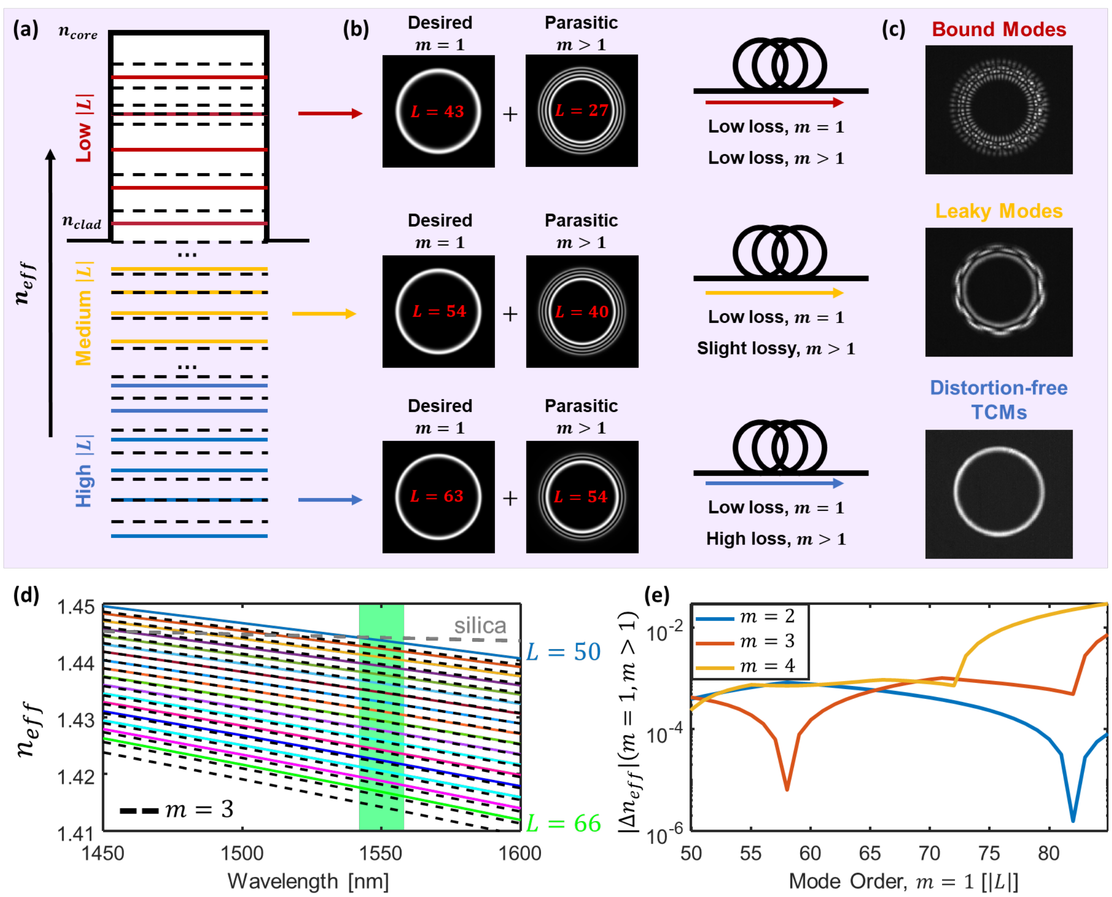

Fig. 1: (a) Low loss TIR bound $|L|, m = 1$ modes and high-m modes mix together during propagation when their respective n_{eff} cross, creating a speckled image at the fiber's output. This mixing continues for even some TCMs, but some of the $m > 1$ mode is stripped away from having a slightly larger differential loss. Whereas, sufficiently high $|L|$ TCMs can be naturally resistant to mode mixing with $m > 1$ modes having very high differential losses, which are completely stripped away (regime of distortion-free TCMs). (b) Simulated images of modes at crossing points, and (c) experimental images of the fiber's output. (d) Simulated $n_{eff}(\lambda)$-curves for $m = 1$ modes from a ~83µm RCF (solid lines) and $m = 3$ modes (black dashed lines). (e) The difference in effective index $|\Delta n_{eff}|$ between $|L|, m = 1$ modes and their nearest neighbor $m > 1$ modes (simulated at 1550nm), where dips indicate strong mode crossing points.

2. Concept: Mode mixing mitigation due to topological confinement; Experimental setup:

Figure 1a illustrates the concept of topological confinement and the resultant suppression of mode-coupling. The schematic displays a step index fiber with index contrast Δn. The effective index (n_{eff}) of modes are also displayed. Each colored line represents an $|L|; m = 1$ mode, where L represents the angular order of a mode carrying orbital angular momentum (OAM) (or the first index of an $\mathrm{LP}_{L,m}$ mode – the concept of topological confinement is valid for all fiber mode eigenbases), and m represents the radial order. The black dashed lines depict higher order $m > 1$ modes (of various Ls). It is well known that mode crossings lead to mode mixing, depicted with simulated images of 3 pairs of modes (Fig. 1b) – one pair in the conventional bound regime where TIR is valid, and two past cutoff – for which we expect strong mode mixing between a desired $m = 1$ and parasitic $m > 1$ mode due to their proximity in n_{eff}. The key finding of topological confinement is depicted with experimentally measured output images (at 1550nm; Fig. 1c) for the three desired modes (in an exemplary fiber, described later). Whereas degenerate or near-degenerate modes of any radial order m have similarly low losses in the conventional bound regime, and hence strongly couple, topological confinement yielding low losses even past cutoff is operative only for modes of sufficiently high $|L|$ and low m. Hence, just past cutoff, the differential losses between the desired $m = 1$ and parasitic $m > 1$ modes are non-negligible, leading to some mode cleanup (less speckle for intermediate $|L|$ in Fig. 1c). Sufficiently past cutoff, differential losses are so high that the output mode is clearly mode-coupling-free, even when the desired and parasitic modes are completely degenerate.

To maximize this uncoupled mode count, we conduct a systematic study that first defines a wavelength band of interest over which to find all the mode crossings past cutoff (Fig. 1d) and then by plotting the n_{eff} difference between the desired and closest undesired modes ($|\Delta n_{eff}|$; Fig. 1e) for each $|L|$. Dips in the curve depict mode crossings, and the design criterion is to reduce the number of such dips and/or increase differential modal losses at these dips. The simulations depicted in Fig. 1d,e were conducted at $\lambda = 1550$nm for an idealized ring-core fiber (RCF) with outer diameter of ~83μm and ring thickness that is 16% of that value, with NA~0.34. Scaled versions of this simulated fiber were available for testing, as shown in Fig. 2a. To test the performance of fibers with ring-core outer diameters greater than 77μm (largest fiber we had available), we test the fiber at shorter wavelengths, 1445nm and 1310nm, effectively emulating a fiber with 83μm and 92μm for operation at $\lambda = 1550$nm, respectively. This scaling is valid because of the well-known invariant of the $\lambda/(\text{waveguide dimension})$ ratio for waveguides. Figure 2b depicts the typical experimental setup, which comprises a source and mode sculpting via a spatial light modulator (SLM), followed by power and image characterization. For tests at 1445nm and 1550nm, we use narrowband external cavity lasers (ECL), which allows quantitative mode purity measurements via spatial interferometry [3]. Tests at 1310nm were limited to qualitative assessments of the output images, given the availability of only broadband (LED) sources.

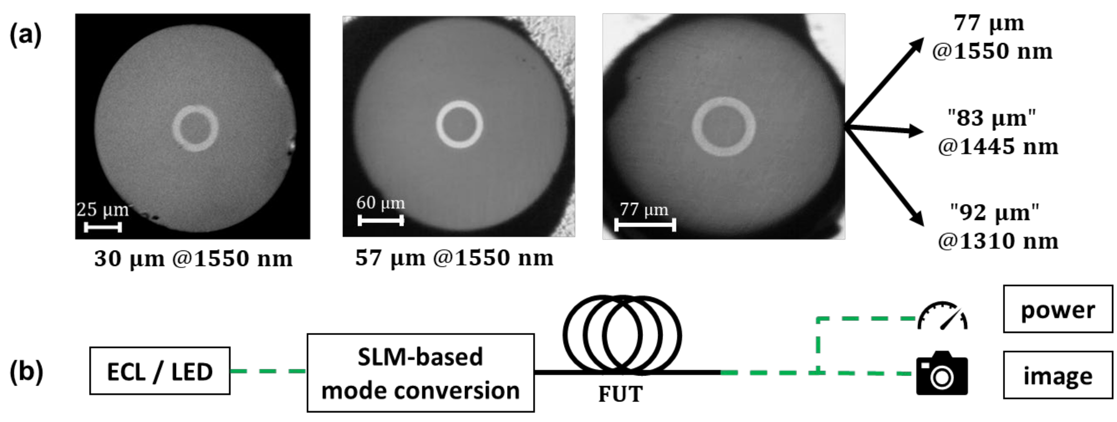

Fig. 2: (a) RCFs with ring diameters of 30μm, 57μm, and 77μm are real fibers, while those with diameters of 83μm and 92μm are λ-emulated. All these RCFs have NA~0.34 and a ring thickness of ~16%. (b) Experimental setup to measure mode purity and power.

3. Results – 100 Uncoupled Modes:

Figures 3a and 3b show the transfer matrices at $\lambda = 1445$nm for both left and right circular polarizations (LCP and RCP) of modes with $m = 1$ ranging from $|L| = 43 - 72$. The white strike-through line represents distorted modes that exhibit coupling and hence are discarded. These results show that we have obtained 100 modes (red squares) counting modes between $|L| = 43 - 70$ ($|L| = 71$ and 72 are too lossy, > 0.1 dB/m), with average nearest neighbor crosstalk (relative power in the anti-diagonals) of -31 dB for bound modes and -42 dB for TCMs, and an average propagation loss of 0.03 dB/m. The non-negligible power in the off-diagonals (< -18 dB for $\Delta L = \pm 1, 2, 3$) results from imperfect mode excitation, which is not a fundamental property of the fiber. In Fig. 3c, a comparison of the 1445nm (mode count 100) and 1550nm (mode count 72) modes reveals why "83µm" is the optimal size for this RCF design, since we have: (i) more non-mixing bound modes, (ii) a smaller intermediate TCM range (depicted as "leaky" modes in Fig. 1 and 3), and (iii) therefore more distortion-free TCMs. Figure 3d shows the mode count for the Fig. 2a RCFs (see blue Xs), which largely matches the trend found from simulations when predicting total mode count from various RCFs (see red-dotted line). Furthermore, we see that experimental measurements match better with simulations when more TCMs than bound modes make up the total count (see cyan and pink lines).

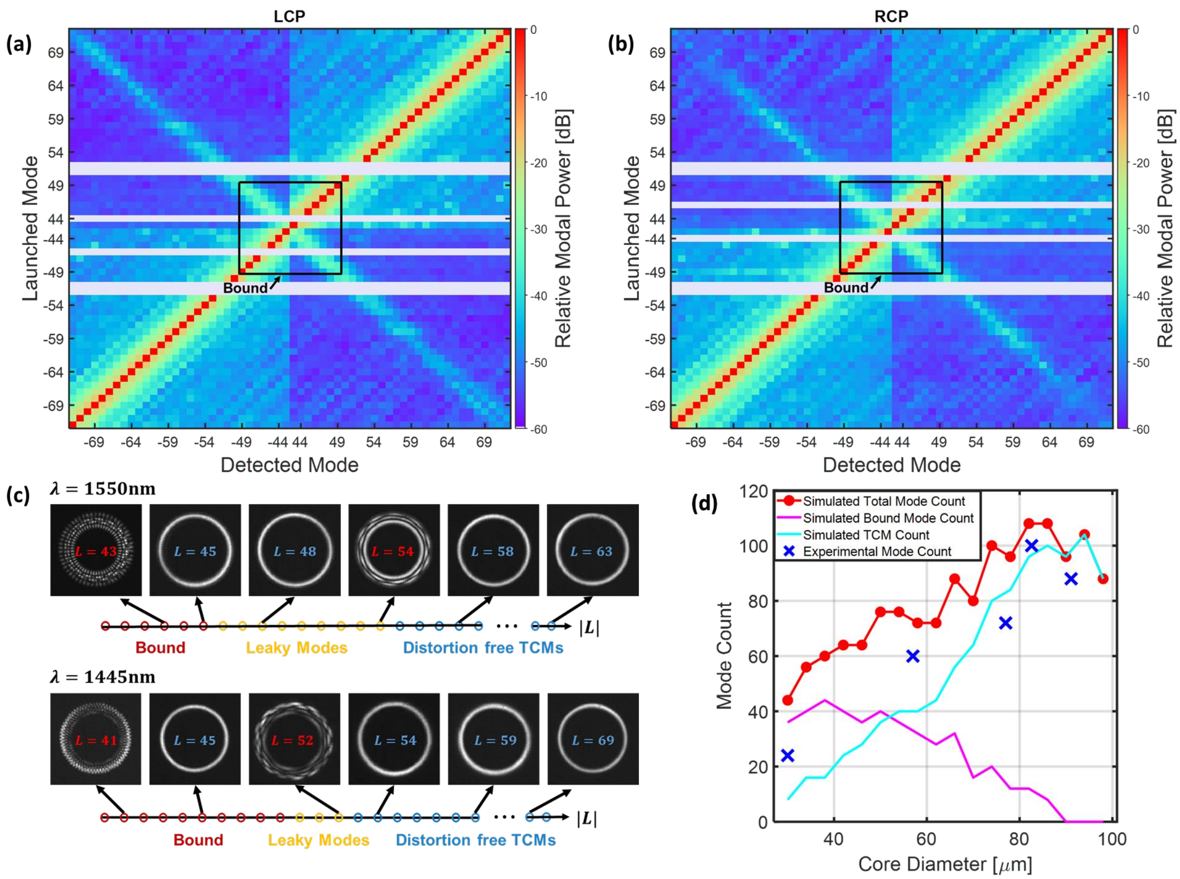

Fig. 3: Transfer matrix for the "83µm" fiber (a) LCP and (b) RCP modes at 1445nm. All OAM modes (bound to TCM) have excitation impurities < -18 dB, and antidiagonal crosstalk as low as -50 dB. The white strike-through lines fill in for modes which are distorted and clearly mixing. (c) Comparison between the 1445nm and 1550nm modes, showing that the "83µm" fiber has more distortion-free TCMs and is a more optimal design. (d) Mode count simulations and experimental mode counts for the RCF designs.

4. Summary and Conclusions:

In summary, we demonstrate mode-mixing free (average nearest neighbor crosstalk ~ -36 dB) transmission of the largest number of modes (100) in any flexible fiber of any length, to date. The tests were conducted at 1445nm to emulate (at 1550nm) a 0.34 NA ring-core fiber of ring diameter ~83µm and ring thickness ~13µm, over a length of ~22m. Measured average propagation losses are ~0.03 dB/m primarily due to interfacial scattering losses. Given average theoretical confinement losses ~ 6×10^{-5} dB/m, there is much scope to improve the losses via manufacturing optimizations, enabling km-length transmission, though the currently obtained losses are already sufficiently low for applications such as high channel count EDFAs [4]. This scalability study was limited to fibers with 0.34 NA, but preliminary simulations indicate optimal size *and* mode count increase with NA, and so high-NA fibers such as microstructured air-clad fibers may enable pushing achievable mode counts well above 100.

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