Modal Loss Characterisation of Thick Ring Core Fiber Using Perfect Vortex Beams

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Abstract: Using a programmable demultiplexer to validate launch conditions, we develop a mode-dependent loss (MDL) measurement method for fiber orbital angular momentum modes. We uncover spread in MDL and confirm low crosstalk in our fiber design. © 2022 The Author(s)

1. Introduction

Orbital angular momentum (OAM) modes are interesting for mode-division-multiplexing (MDM) systems as they require no multiple-input multiple-output (MIMO) digital signal processing (DSP) [1]. In [2], MIMO-free data transmission was demonstrated using thick ring-core fiber (RCF) over three OAM mode groups. Designing fiber with low mode-dependent loss (MDL) is crucial for maximizing MDM systems capacity. Many techniques are used to measure the modal loss including optical time-domain reflectometry (OTDR) [3] and the conventional cutback technique. For specialty multi-mode fibers (MMFs), we have access to a limited fiber length, and therefore performing cutback measurement on different fiber samples for each mode is not practical. Furthermore, variation of the core parameters along fiber length can have an impact on the loss measurement value. Therefore the loss of all modes must be measured in the same fiber length. The OTDR measurements following [3] to uncover MDL require long fiber lengths (e.g., 50 km [4]) and are impractical for design cycle optimization.

In this paper, we examine a thick-RCF supporting first radial OAM modes up to order 13. We characterise fiber modal loss using a ”modified cutback” technique. We use four different lengths of fiber for measurement rather than cutting a long fiber. In this way, we are able to validate similar launch conditions (high extinction ratio) for all mode orders at each fiber length. Our method shows a significant difference in the modal loss for lower-order modes compared to higher-order modes. We demonstrate 1.3 km of stable propagation for OAM modes up to order 10 with negligible inter-modal crosstalk and modal loss of a few dB/km. These measurements confirm the suitability of this fiber for data transmission without complex MIMO-DSP for up to a few kilometers.

2. Thick-Ring Core Fiber Fabrication and Characterisation

We designed [5] a thick-RCF supporting 4 OAM mode groups with an index contrast of 4×10^{-2} between the ring-core and the cladding. We fabricated this fiber with a ring core of silica doped with germanium dioxide, a cladding of pure silica, and an inner core of silica doped with fluorine. The refractive index of the fabricated fiber is shown in Fig. 1(a). Following measurement of the refractive index along the fiber preform, we adjusted drawing parameters to avoid the accidental degeneracy between target modes and higher radial modes. Simulations of the fabricated fiber show 118 eigenmodes guided at 1550 nm; the fiber supports first radial OAM modes up to order 13 and other higher-order radial modes. Mode orders 7 to 10 are most promising for data transmission per the analysis in [5] in terms of polarization purity and minimum index separation between HE and EH modes, Δn_{eff}. For orders 7 to 10, Δn_{eff} is ranging from 0.5×10^{-4} to 1.3×10^{-4}. Mode orders 11 to 13 (Δn_{eff} ranging from 1.6×10^{-4} to 2.4×10^{-4}) are not targeted at this time due to their fast divergence in free space.

2.1. Setup for Launching Perfect Vortex Beams

We used the technique proposed in [6] to generate a perfect vortex (PV) beam in free-space and couple it into the fiber to launch one OAM mode. We used PV beam due to its flexibility to control the beam diameter by programming a spatial light modulator (SLM). Figure 1(b) shows the setup used to launch one spatial OAM mode with one circular polarization in the fiber (see the dashed box labeled PV). We program the SLM with a combination of a spiral phase of order l and an axicon lens; the Fourier lens transforms the output Bessel-Gauss beam into a PV beam. The linearly polarized beam from the SLM is transformed into the desired circular polarization using a quarter-wave plate (QWP). As discussed in [6], the PV beam diameter differs from lower-order to higher-order modes and can be adjusted via the axicon parameter on the SLM. The width of the PV beam

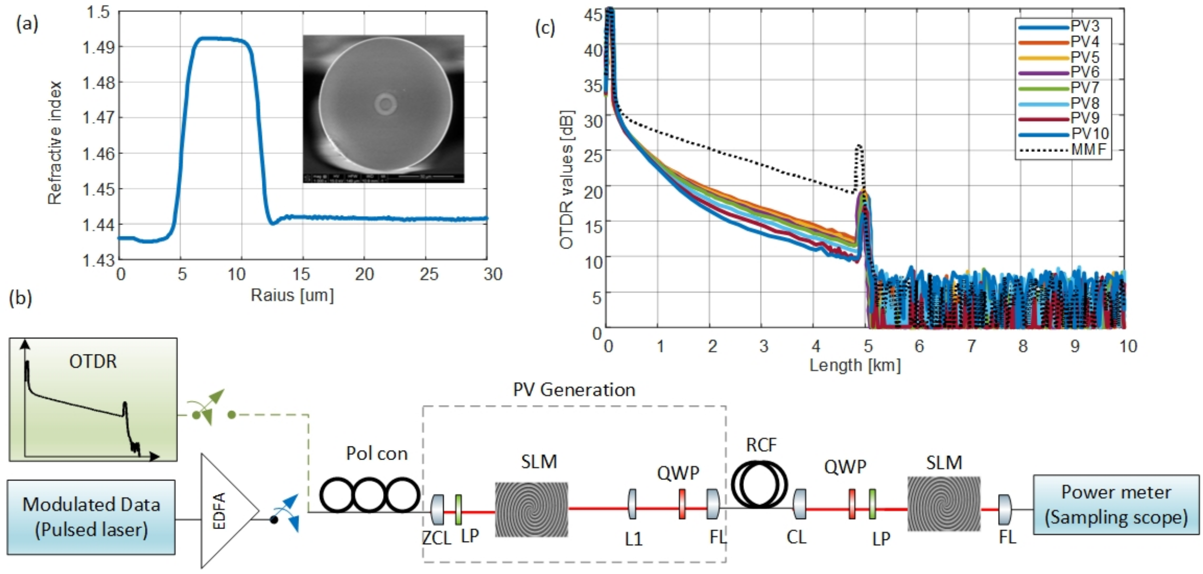

Fig. 1: (a) Index profile and facet image (inset) of the fabricated fiber, (b) Setup for launching and detecting OAM mode with any order, modulated data (or pulsed laser) used for power measurement and EXFO FTB-7400B for OTDR measurements. Pol. con.: polarization controller, ZCL: Thorlabs zoom-collimator, LP: linear polarizer, L1: 50cm Fourier lens, FL: focusing lens, CL: collimating lens, EDFA: erbium-doped fiber amplifier and (c) OTDR traces for mode orders 3 to 10

is set by the waist of the collimated Gaussian beam illuminating the SLM, 1 mm in our experiment. The PV beam is coupled into the thick-RCF using a focusing lens with a 6.24 mm focal length and 0.4 numerical aperture.

2.2. OTDR Measurements

With selective excitation of modes from Fig. 1, we attempted the OTDR technique to measure MDL for our 5 km length of thick-RCF. We launch light from an OTDR (Exfo FTB-7400B) through the ZCL lens at the input to PV. The PV beam is launched into 5 km of thick-RCF. In Fig. 1(c) we present OTDR measurements for modes $l = 3$ to 10. The OTDR has a dynamic range of 35dB and the output power is -7dBm at 1550nm. An OTDR measurement without selective mode launching (OTDR directly connected to thick-RCF) is also plotted in a dashed line for reference; the MMF label indicates an MMF pigtail connected the OTDR to the thick RCF.

We observe more than a 7 dB drop in power using mode selective launching instead of MMF, indicating large insertion loss. There are only minor variations across modes in the measured loss; the average loss is 2.5 dB/km. Our PV guarantees the correct size beam is presented to the OAM fiber, but we cannot assess the purity of the excitation. We suspect that multiple modes were being excited, leading to an averaging effect that yielded all measurements having similar loss. The traces for each mode roll-off slowly, indicating high reflectance in the setup. We conclude the fiber length is insufficient to recover the backscatter slope for an accurate estimate of the MDL. Fiber lengths of 50 km have been tested in [4], but this length is impractical in our systems targeting short-reach applications.

3. Modified Cut-back Technique

In the standard cutback technique for single mode fiber (SMF), light is coupled into a sufficiently long fiber and the power measured; the fiber is cut and the power measured again and this is iterated for several cuts. For MMFs, we need to verify that only one mode is truly excited in a round-robin approach. At each cut, this round-robin excitation could lead to highly variable excitation from one cut to another. To overcome these challenges we cut first and excite each length separately, but with validation of the purity of mode excitation. We examined fiber of length 10 m, 200 m, 600 m, and 1.3 km drawn from the same preform. Launching conditions are adjusted for each spatial mode independently until sufficient purity is attained; only then is the power measured.

We built the programmable demultiplexer in Fig. 1(b) to quantify launch purity. We measure the extinction ratio between the targeted OAM mode and each of the nearest neighbor modes. The beam output from the fiber passes through a QWP to change circular polarization into linear before illuminating an SLM. We program this SLM to selectively convert a given order into the fundamental mode; if multiple modes were excited they will be identified when programming the SLM to each mode. We couple the SLM output to SMF to strip off all but the fundamental mode as in [7].

We use one of two sources, modulated QPSK data or short pulses from a mode-locked laser (MLL), to characterize the fiber. The MLL facilitates distinguishing between different origins of crosstalk; pulse time delays are used to identify and distinguish excitation of different radial modes through their distinct group delays.

3.1. *Confirming High Purity of Mode Launching*

We launch one mode of the degenerate pair for aligned (A) or anti-aligned (AA) modes of order l. For each launch, we set the demux SLM to step through all modes in the launched group and neighbor groups. We record a matrix of the power received for each launched/detected mode pair; Fig. 2(a, b) shows results for 200 m and 1300 m of RCF. Ideally, we would have all power on the diagonal. Note that the A and AA modes from the same OAM order will exhibit the same loss. Therefore, power on the anti-diagonal would not impede MDL assessment. After 200 m propagation the matrix is nearly diagonal, confirming launching with high purity. The power in the nearest neighbors does not exceed 15 dB down from the power in the desired mode. The same procedure is repeated for all fiber lengths. For the 1.3 km propagation in Fig. 2(b) we see that the anti-diagonal components have increased, especially for lower-order modes. This is to be expected as they have small Δn_{eff} compared to higher-order modes. The power from the nearest neighbors remains 15 dB down from the main diagonal, indicating low inter-group crosstalk due to large index separation between mode groups ($> 2 \times 10^{-3}$).

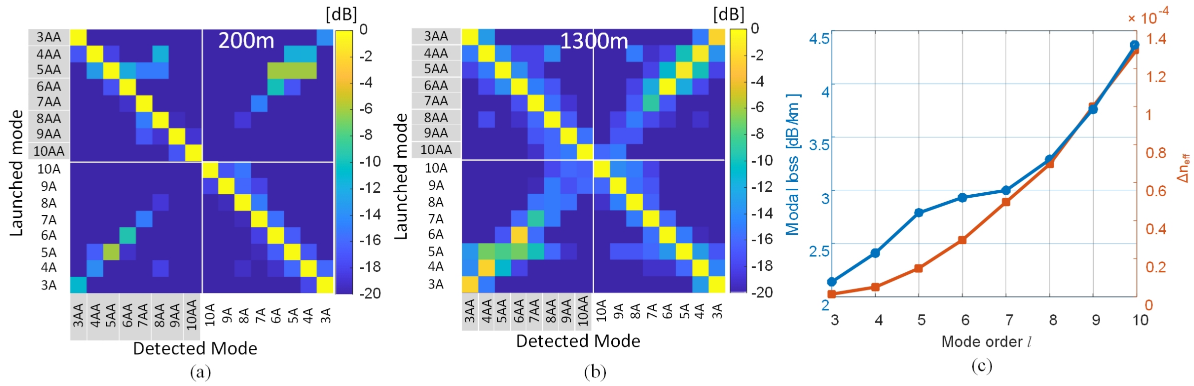

Fig. 2: Mode projection after propagation through (a) 200m, (b) 1300m of thick-RCF and (c) Loss measurements and Δn_{eff} for orders 3 to 10

3.2. *Modal Loss Measurement*

After confirming pure mode excitation, we calculate the modal loss for a given mode order from power measurements (in both A and AA modes) for orders 3 to 10. In Fig. 2(c) we plot the modal loss versus mode order in a blue line with circle markers. The lower order modes have a lower loss, at about 2 dB/km. To support many mode orders, the fiber has large index contrast, hence higher loss than SMF. As mode order grows, the effective index of the modes decreases making modes more vulnerable to microbending and coupling to the cladding [8].

We also plot in Fig. 2(c) the index separation Δn_{eff} within an OAM mode group. Increasing separation allows higher-order modes to be exploited MIMO-free (much better at $l = 10$ than at $l = 3$) [9], but we can see that it correlates also with the loss.

4. Conclusion

We characterized a thick-RCF that supports the propagation of many OAM modes (l>10). We introduced a modified cutback technique to measure the modal loss at different fiber lengths while allowing adjustment of launch conditions separately per mode. We confirmed a high extinction ratio at mode excitation, and stable propagation to 1.3 km. Higher-order modes saw a loss of a few dB/km due to the high doping concentration. Optimization of index contrast for thick-RCF is necessary to balance modal loss and crosstalk for low MIMO-DSP.

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