Low-Loss 25.3km Few-Mode Ring-Core Fibre for Mode-Division Multiplexed Transmission

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Abstract *We report the design, fabrication and characterisation of a few-mode ring-core fibre supporting 4 mode groups. The low loss (~0.3dB/km) and length (25.3km) are both records for a ring-core fibre.*

Introduction

Mode division multiplexing (MDM) has attracted considerable attention in the fibre-optic community as a promising approach to increase per-fibre capacity by employing multiple distinguishable spatial information channels[1]. Several different types of few-mode fibre (FMF) have been proposed and investigated to date. In the vast majority of FMF transmission systems[2], multiple-input, multiple-output (MIMO) digital signal processing (DSP) is an essential requirement in order to compensate for the linear cross-talk between optical modes that ordinarily occurs due to mode coupling. As the number of modes (information channels) increases, the complexity of the MIMO processing required increases rapidly for conventional step-index or graded-index FMFs. However, if mode coupling can be reduced the use of MIMO processing might be considerably simplified (or possibly even avoided), thereby increasing the viability and scalability of the MDM approach.

In this aspect, few-mode ring-core fibres (FM-RCFs) that support single-radial-order modes (i.e. LP_{1m} modes where m is an integer) have been reported both theoretically[3] and experimentally[4,5] to show great potential for improving the transmission capacity of MDM system with low DSP complexity. In FM-RCFs, the effective index difference between adjacent neighbouring azimuthal modes significantly increases with increasing azimuthal mode number, which can result in relatively weak mode coupling between higher-order azimuthal modes. Therefore, the DSP complexity can be reduced by using MIMO processing only to recover signals carried on those lower-order azimuthal modes which experience strong mode coupling and/or between modes within the same mode group[4,5]. In addition, ring-core fibre amplifiers can, in theory, provide nearly identical gain for all the guided signal modes, owing to the fact that similar overlap factors can be achieved between the erbium doped core and all the signal spatial modes[6]. RCF amplifiers are thus very attractive as MDM amplifiers in terms of having low mode dependent gain. However, despite the aforementioned merits of FM-RCFs the development of long lengths of suitably low loss RCF has proved a challenge. For example, the 7 mode-group RCF reported early in 2015 suffered from a substantial fibre attenuation of a few hundred dB/km[4] and even the most recent results describing development of a 5 mode-group RCF reported fibre attenuation of a few dB/km[5]. It is therefore clear that fibre loss must be driven down in order to make FM-RCFs a feasible approach for high-capacity long-distance MDM transmission.

In this work, we have designed and successfully fabricated a 25.3km length of low loss FM-RCF supporting 4 mode groups (i.e. 7 spatial modes including spatial degeneracies). The fibre attenuation for all guided modes was around 0.3 dB/ km, which is the lowest fibre loss that ever reported in the FM-RCF family.

Fibre Design and Fabrication

A step-index RCF consists of two structural design parameters, i.e. r1 and r2, as shown in Fig. 1(a), which define the two boundaries of the ring core. In this paper, we propose a 4 mode-group RCF (4MG-RCF) design, whose fibre refractive index profile (FRIP) is given by the black line in Fig. 1(a). The key design objective for this 4MG-RCF was to ensure strong guidance of the LP_{01}, LP_{11}, LP_{21}, and LP_{31} mode groups in the C-band, whilst the next higher order mode, i.e. LP_{41}, is completely cut-off at λ=1500nm. Generally, fibre attenuation is strongly related to the macro-bending and/or micro-bending loss of the guided modes and a relatively large effective index difference (Δn_{eff}) between the guided modes and cladding modes is essential to reduce the intrinsic fibre loss by suppressing mode coupling from the guided LP_{31} mode to leaky cladding modes. The simulated power fraction in the core for the LP_{01}, LP_{11}, LP_{21} and LP_{31} mode groups at 1550 nm are 91%, 92%, 91% and 88%,

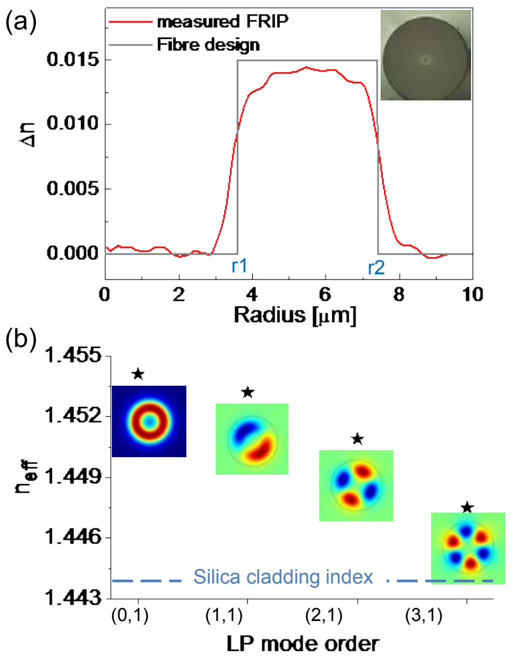

Fig. 1: (a) Fibre design (in black line) and measured FRIP (in red line) of the fabricated 4 mode-group RCF (4MG-RCF). (b) The electric field distribution and effective refractive indices of the guided modes of the RCF at λ=1550nm.

respectively, which indicates that the four mode groups are reasonably well confined in the ring core area. The corresponding modal effective indices are depicted in the Fig. 1(b). The normalized propagation constant $b = \frac{n_{eff}^2 - n_2^2}{n_1^2 - n_2^2}$ of the LP_{31} mode group at 1550nm in the designed 4MG-RCF is 0.23, which also proves good guidance of the modes. Using a conventional plasma chemical vapour deposition (PCVD) process, we have successfully fabricated the 4MG-RCF and the measured FRIP is shown as the red line in Fig. 1(a). The FRIP of the fabricated RCF is reasonably well matched to the fibre design.

Modal characterization of the FM-RCF

First of all, the mode-averaged fibre attenuation was measured by a cut-back method using a white light source and an optical spectrum analyzer. Conventional 50μm step-index multimode fibre pigtails were spliced at both input/output ends of RCF to provide over-filled light launching condition into the RCF, which provides us with an averaged fiber loss over all spatial modes. As shown in Fig. 2(a), the fabricated RCF exhibits an averaged fibre attenuation of 0.32dB/km at 1550nm (i.e. 8.2dB span loss over 25.3km), which is the lowest loss value ever reported for a ring-core fibre. Water

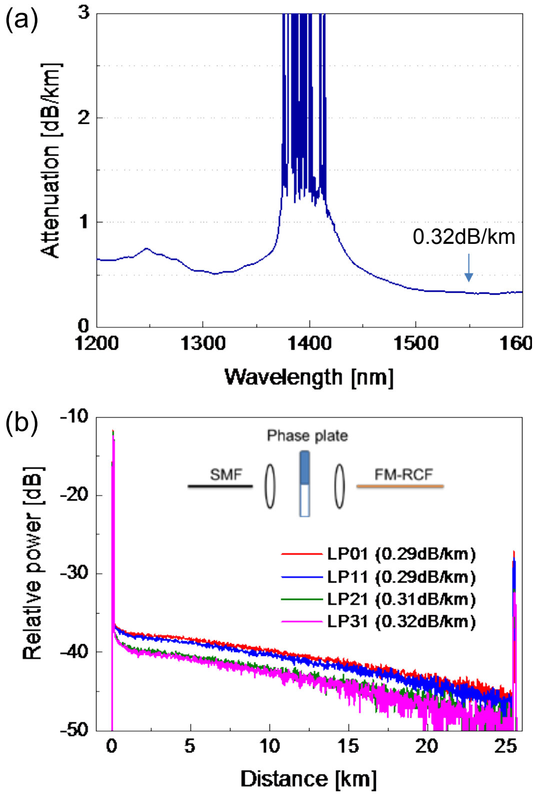

Fig. 2: (a) Averaged fibre loss (using cut-back method) and (b) mode dependent fibre loss (using mode selective OTDR) of the RCF.

absorption peaks appeared at ~1240nm and ~1380nm due to the presence of OH ion impurities but these can be reduced by adopting a "dry fibre" fabrication process in the future. To examine the modal dependency of the fiber attenuation an optical time domain reflectometer (OTDR) was used in conjunction with a selective mode excitation scheme using phase plates. As shown in the inset of the Fig. 2(b), a suitable phase plate is used to selectively launch a specific mode of the RCF and the reflected Rayleigh back-scattered light was analyzed using the same phase plate, which enabled us detect backscatter from the same spatial mode. Therefore, using this selective mode excitation/detection scheme, we can analyze the mode dependent loss of the fibre using a standard single-mode fibre OTDR. Fig. 2(b) shows the OTDR traces for four guided mode groups of the fibre (i.e. LP_{01}, LP_{11}, LP_{21}, and LP_{31}) which are excited selectively one-by-one using the corresponding phase plates. All spatial modes show similar propagation losses (~0.3dB/km). The OTDR measurements coincide with and are quite well matched to measurements made previously using the cutback method. Slightly higher loss was observed for higher-order

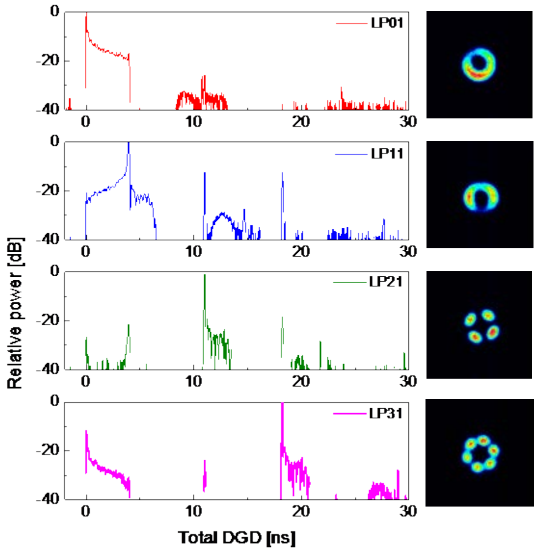

Fig. 3: Time-of-flight measurement of the 4MG-RCF under selective mode excitation.

modes (HOMs) but the differences are very modest.

We performed time-of-flight (ToF) measurements on the 4MG-RCF under selective mode excitation to characterize the multimode fibre impulse response, in particular the differential group delay (DGD) of the different spatial modes. The DGD over the full 25.3km length of 4MG-RCF was too large to be measured using the available equipment and hence a 1km length of fibre was taken to accurately measure the DGDs of the fibre. The traces in Fig. 3 show the four main distinct and discernible mode peaks at their relative DGD locations (3.9ps/m for LP_{11}, 11.0ps/m for LP_{21}, and 18.2ps/m for LP_{31}). To find out the modal identity of the individual peaks in the ToF measurement the output beam intensity from the RCF was examined using a CCD camera to identify the dominant spatial guided mode under the selective mode excitation. The LP_{01}, LP_{11}, LP_{21} and LP_{31} spatial modes are clearly identified after 1km of fibre as shown on the right side in Fig. 3. More importantly, we have observed relatively strong mode coupling between the LP_{01} and LP_{11} mode groups, which is evidenced by a flat plateau between these two mode groups for delays between 0 and 3.9ns. Under LP_{01} mode excitation, for example, a discrete peak was observed at 0 ns but a smooth sloped plateau was noticed towards the LP_{01} peak due to the strong distributed mode coupling occurring along the entire length of fibre. Under LP_{11} mode excitation, however, this plateau is now sloped toward the LP_{11} peak but an almost identical magnitude of gradient due to the symmetric mode coupling. ~50% of the optical power resides in the distributed plateau after 1km fibre propagation corresponding to a modal coupling efficiency of 0.5 km^{-1}. However, there is no noticeable plateau between other higher-order mode groups in the RCF. This interesting mode coupling feature can be easily understood from the modal effective index calculation of the RCF in Fig. 1(b). The Δn_{eff} between the LP_{01} and LP_{11} group is relatively small and it can induce strong mode coupling. However, the large Δn_{eff} between other HOMs in RCFs prevents distributed mode coupling between neighboring modes. We also tested the ToF traces using a 25.3km length of 4MG-RCF and there was no discernable distributed mode coupling between HOMs (less than -30dB MPI). We plan to carry out an MDM transmission experiment using this 25.3km 4MG-RCF to validate the transmission performance and the level of MIMO DSP complexity reduction in the near future.

Conclusions

We have designed and fabricated a low-loss few-mode ring-core fibre supporting 4 mode groups. All spatial modes show a similar fibre attenuation of ~ 0.3dB/km, which is the lowest loss value ever reported for a ring-core fibre. Due to the large effective index separation between the neighboring higher-order modes, the distributed intermodal coupling can be minimized and this should be very beneficial in terms of reducing the MIMO DSP complexity required for MDM transmission.

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