Ultra-Low Inter-Mode-Group Crosstalk Ring-Core Fiber Optimized Using Neural Networks and Genetic Algorithm

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Abstract: We design and fabricate a ring-core fiber whose refractive-index profile is optimized using neural networks and genetic algorithm under fabrication constraints. Experimental results confirm ultra-low inter-mode-group crosstalk of <-55 dB/km.

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1. Introduction

In recent years, ring-core-fiber (RCF) based mode-division multiplexing (MDM) schemes has attracted much interest due to their good potential of decreasing the complexity of the multiple-input multiple-output (MIMO) equalization of inter-mode-crosstalk and differential group delay (DGD) [1,2]. RCF with single radial-mode order can fix the number of modes to 4 in each orbital-angular-momentum (OAM) high-order mode group (MG) (azimuthal order >1) and make them highly degenerate. By carefully designing the refractive index profile (RIP) of RCF, it is possible to achieve low coupling coefficient between higher order MGs so that the MIMO complexity is confined to 4×4 [3].

Nevertheless, RCFs had relatively high attenuation and inter-MG coupling. Several schemes have been proposed to improve RCF performance. In [4], a RCF with a low loss of ~0.3 dB/km was reported, whose inter-MG coupling coefficient (< -25 dB/km) was significantly decreased compared with previously reported RCFs [4]. More recently, we reported a RCF supporting 4 MGs with a modulated refractive index (RI) that suppresses micro-perturbation-induced mode coupling based on a novel principle of RIP-slope cancellation, achieving attenuation of ~0.21 dB/km for all guided modes and crosstalk of <-36 dB/km between adjacent high-order MGs, which were the lowest fiber attenuation and mode crosstalk reported so far in the RCF family [5]. However, despite such progresses, further decrease of the fiber attenuation and modal coupling of RCF will be necessary for long-haul transmission purposes, where optimized designs not only need to be searched more comprehensively but also considering fabrication constraints.

Therefore, in this paper, we design and fabricate a ring-core fiber with ultra-low inter-mode-group crosstalk, whose RIP is optimized using neural networks and genetic algorithm under fiber fabrication constraints. The measured averaged power coupling coefficients between adjacent high-order ($|l| > 0$) MGs of < -55 dB/km confirm the superior performance of the RCF after optimization, while maintaining low fiber attenuation of ~ 0.23 dB/ km for all guided modes.

2. Fiber design strategy and fabrication

The RIP design of the RCF in this work aims at minimizing the power coupling coefficient [2, 6] between adjacent high-order ($|l|>0$) orbital angular momentum (OAM) MGs. According to the analysis in [2, 7], the micro-bending-induced inter-MG coupling efficiency can be decreased by modulating the fiber RIP $n(r)$, so that the contribution of its positive and negative slopes cancel out each other in the overlap integration between the modal fields and the RI gradient when the effective refractive index separations (Δn_{eff}) between MGs become large enough (typically more than 1e-3). Therefore, the overlap integration between OAM MGs $|l| = 1$ and 2 (C_{21}) as well as that between the $|l| =$ 2 and 3 (C_{23}) are selected as the output targets in the fiber design optimization algorithms that attempts to minimize C_{21} and C_{23} under the constraint of Δn_{eff} between adjacent high-order OAM MGs ($|l|>0$) being no less than 1×10^{-3}.

Several fiber structure constraints are also set considering the fiber-fabrication accuracy and simplicity. As shown in Fig. 1(a), the RCF RIP with a four-core-layer structure is proposed for design optimization. The overall core inner and outer radii are fixed at 3.75 μm and 8.25 μm, respectively, to ensure the single-radial-order limitation of the RCF and fix the number of the guide MGs to 4. The maximum core-cladding relative RI difference (Δn) is set to 0.008 to ensure relatively low dopant concentration during the fiber fabrication. The other three radii as well as the core-cladding Δn of each layer within the ring-core area are selected as the input variables. The thickness of each ring-core layer is required to be no less than 0.5 μm and their core-cladding Δn is set between 0.004 and 0.008, taking into consideration of the limited accuracy during the fiber fabrication. There are four steps included in the fiber design optimization process, whose brief flowchart is shown in Fig. 1(b). A five-layer back propagation (BP) neural network (NN) model with 3 hidden layers and 32 neurons in each hidden layer is trained using data sets, which are prepared by calculating the values of C_{21} and C_{23} under different RCF RIP parameters in the commercial software of COMSOL Multiphysics. A genetic algorithm (GA), whose fitness function is defined as $Fit = 1/2 \times (1/C_{21} + 1/C_{23})$ calculated by using BP-NN trained in the second step, is utilized to find the optimal RIP with maximum value of *Fit* under the fiber-structure constraints mentioned before. Finally, the obtained optimal RCF design is double verified using COMSOL Multiphysics. Further optimization of the BP-NN model and the GA algorithm will be implemented if there are non-negligible differences between the values of C_{21} and C_{23} calculated by the proposed model and the COMSOL Multiphysics.

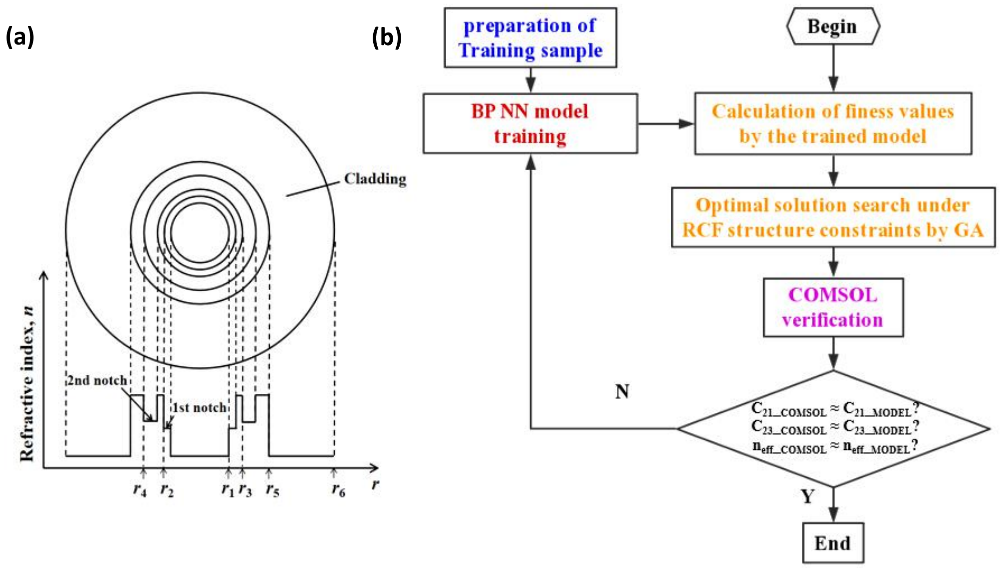
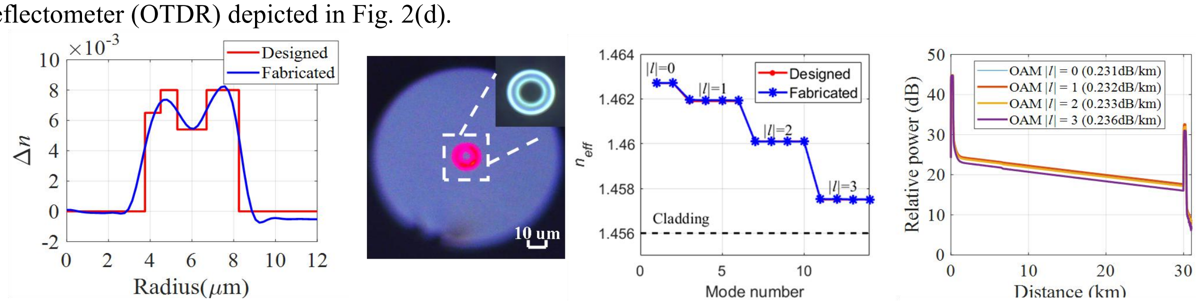


Fig. 1. (a) Diagram of RCF RIP with four-core-layer structure; (b) The brief flowchart of the optimization process for the design of RCF.

3. Fabrication and Characterization of the RCF

Based on above process, the RIP of the optimized design is depicted in Fig. 2(a). The proposed RIP-optimized RCF has also been successfully fabricated, as the RIP and cross section of the fabricated RCF shown in Fig. 2(a) and (b), respectively. The fiber preform was manufactured by a plasma chemical vapor deposition (PCVD) technique. Suitable furnace temperature, power and speed were set to maintain the homogeneity and consistency of the fiber. The preform was packaged by the core rod and low refractive index cylinder, which can reduce the element doping in the ring-core layer. Afterwards the preform was drawn into fiber with a diameter of 125 ± 0.7 μm in a standard drawing tower. It can be seen from Fig. 2(a) that there are some distortions of the fabricated-RCF RIP compared with the designed one, which may result from fusion of the adjacent fiber-core layers during fiber drawing. However, there are nearly no differences between n_{eff} values calculated based on the fabricated and designed RIP of the RCF for all guide OAM MGs, as shown in Fig. 2(c). In addition, low fiber attenuation of ~0.23 dB/km for all the four guide MGs of the fabricated RCF can also maintained, as the results measured by an optical time domain reflectometer (OTDR) depicted in Fig. 2(d).



(a) (b) (c) (d)

Fig. 2. (a) The design refractive index profile of the optimal RCF; (b) cross section of the proposed RCF; (c) calculated n_{eff} of 4 supporting OAM mode groups. (d) mode dependent attenuation measured by OTDR.

In order to evaluate and verify the power coupling coefficient between the adjacent high-order OAM MGs and their DGD, an experimental setup is also built up to measure the time-domain impulse response of the fabricated RCF according to the technique presented in [6], as shown in Fig. 3(a). The RF signals with a frequency range from 10 MHz to 20 GHz, which were generated from a vector network analyzer (VNA) operated in impulse response mode, were utilized to modulate the optical carrier at a wavelength of 1550.12 nm through a Mach-Zehnder modulator (MZM). After amplified by an erbium doped fiber amplifier (EDFA), the obtained optical signal was incident on a spatial light modulator (SLM) to generate the required OAM beam, which was subsequently changed to circularly polarization by a quarter-wave plate (QWP) before collimated into a 1-km RCF. After RCF transmission, the received optical beams were directly coupled to a multi-mode-fiber (MMF) pig-tailed photo detector (PD) and the detected RF signals were fed back to the VNA for impulse-response measurement. The measured results of time-domain impulse response of OAM MGs $|l|$ = 2 and $|l|$ = 3 are illustrated in Fig. 3(b). Here noted that the temporal regions before the dominant pulses are select to evaluate the distributed mode coupling between the adjacent MGs since these regions negligibly suffer from the impulse-response distortions due to limited RF bandwidth of the devices used in the experiment [8]. The measured DGD relative to the $|l|$ = 0 OAM MG and coupling coefficient h between adjacent MGs are shown in Table I. Ultra-low coupling coefficient of < -58 dB/km has been measured between MGs $|l|$ = 1 and 2 as well as MGs $|l|$ = 2 and 3, which proves the reliability and effectiveness of the proposed design methodology. Because the coupling coefficient is derived from the average floor between the peaks of the modal impulse response, some uncertainty results from the noise at such low signal levels, however it is with high confidence that the coupling coefficient is <-55 dB/km.

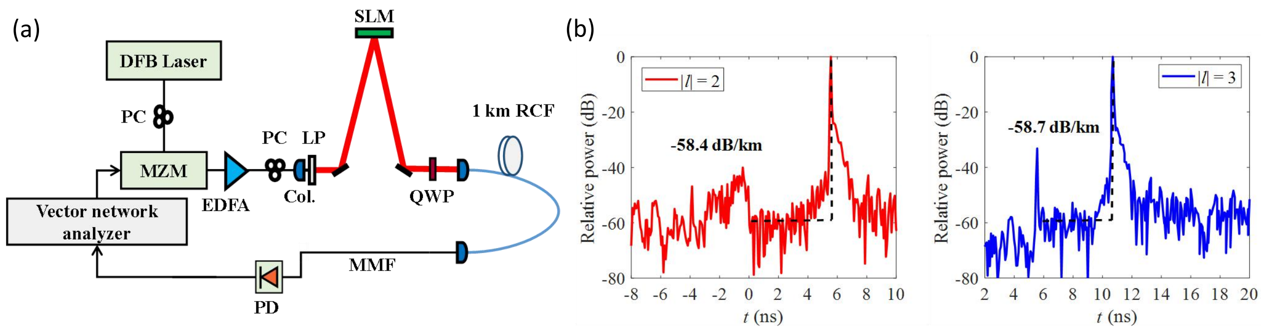


Fig. 3. (a) Experiment setup. PC: polarization controller; LP: linear polarizer; MR: mirror; QWP: quarter-wave plate; Col.: collimator; MMF: multi-mode fiber; PD:photo detector; MZM: Mach-Zehnder modulator; EDFA: erbium doped fiber amplifier; (b) the measured impulse response.

Table I. Characteristics of fabricated RCF with modulated RIP

<table>
<tr><th></th><th colspan="2">OAM |l|=0</th><th colspan="2">OAM |l|=1</th><th colspan="2">OAM |l|=2</th><th colspan="2">OAM |l|=3</th></tr>
<tr><td>Propagation Loss (dB/km)</td><td colspan="2">0.231</td><td colspan="2">0.232</td><td colspan="2">0.233</td><td colspan="2">0.236</td></tr>
<tr><td>DGD to OAM |l| =0 (ns/km)</td><td colspan="2">0</td><td colspan="2">3.8</td><td colspan="2">8.9</td><td colspan="2">13.9</td></tr>
<tr><td>Δn_{eff}</td><td colspan="3">0.8×10^{-3}</td><td colspan="2">1.8×10^{-3}</td><td colspan="3">2.6×10^{-3}</td></tr>
<tr><td>Measured power coupling coefficient (dB/km)</td><td colspan="3">NA</td><td colspan="2">-58.4</td><td colspan="3">-58.7</td></tr>
</table>

4. Conclusions

In this paper, we have designed and fabricated a ring-core fiber with ultra-low inter-mode-group coupling, whose refractive-index profile is optimized using BP NN and genetic algorithm under fiber fabrication constraints. Fiber attenuation of ~ 0.23 dB/ km has been achieved for all guided modes and the averaged power coupling coefficients between adjacent high-order OAM MGs is measured < -55 dB/km, confirming the superior performance of the RCF after optimization.

5. Acknowledgements

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