Comparison of Polarization Rotations Caused by Fiber Bending in Single- and Multi-Mode-Fibers

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Abstract: We measure mode group resolved polarization rotations caused by fiber bending in a 10-mode-GI-Fiber. For the fundamental mode of the GI-Fiber, we observe faster rotations than predicted from simulations. © 2024 The Author(s)

1. Introduction

Mode Division Multiplexing (MDM) has been shown to be a promising approach for increasing the capacity of optical fibers. Compared to single mode fiber (SMF) transmission, MDM systems are affected by mode coupling and differential mode group delays (DMGDs). Both effects can be mitigated through the application of a multiple-input multiple-output (MIMO) equalization approach. The MIMO system requires a significantly higher number of filter tabs in MDM systems due to the substantially larger DMGDs in multi-mode fibers (MMFs) compared to differential group delays between the two orthogonal polarization modes in SMFs.

The time required for the MIMO system to adapt to changes in channel characteristics increases with the number of filter tabs [1]. Transmission experiments in a multicore fiber with four coupled single-mode cores [2] and a three-mode fiber [3] confirmed the necessity for a faster MIMO adaptation compared to SMF transmission.

The required MIMO speed also depends on the physical rate of change of the transmission channel properties in the multimode fiber. It is already known that the channels in graded-index (GI)-MMFs change significantly slower during fiber bending than in step-index (SI)-MMFs [4,5]. In our previous work [6], we compared the channel dynamics of a SMF with the dynamics a 50 µm-GI- and a 50 µm-SI-MMF during fiber bending. Thereby, the dynamics in the GI-MMF are shown to be just slightly faster than the dynamics in the SMF. Dynamics of mode coupling in MMF are closely related to dynamics of polarization coupling in SMF and can only be understood if polarization rotations of the modes in MMF are considered.

In this study, we investigate the polarization rotation in a 10-mode GI-MMF (GI10) in comparison to a single-mode fiber (SMF). In contrast to our previous work, we employ mode-selective excitation and detection, as opposed to offset excitation and detection. This enables a mode-resolved investigation of channel dynamics. However, due to the strong mode coupling within the mode groups of GI-MMFs, we perform a mode group resolved analysis of the channel dynamics. Our primary objective is to demonstrate that, even with a core diameter of about 20 µm, polarization effects predominantly contribute to channel dynamics in bent MMFs. Establishing an accurate understanding of polarization effects in MMFs, compared to well-known SMFs, is crucial for modeling channel dynamics in MMFs.

2. Experimental Setup

To compare the channel dynamics of the GI10 and the SMF we measure the angular rotation speed of the Stokes parameters on the Poincaré sphere for these two fibers. We understand a channel in the GI10 as a specific path through the MMF extending from a particular input of the multiplexer to a dedicated output of the demultiplexer. A laser operating at a wavelength of 1550 nm serves as the light source. The setup for applying the fiber bending is illustrated in Fig. 1 (a) and (b). In the initial configuration (a), the fiber-under-test is arranged in 4.5 overlapping loops, each with a constant bending radius of 7.25 cm. This results in a bent fiber section with a length of approximately 205 cm. The

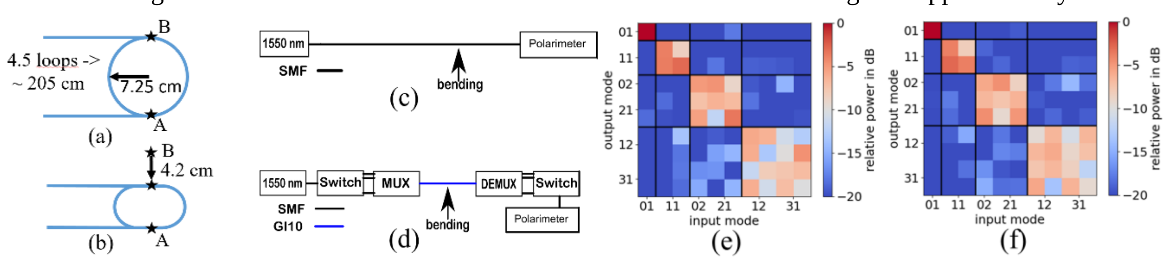
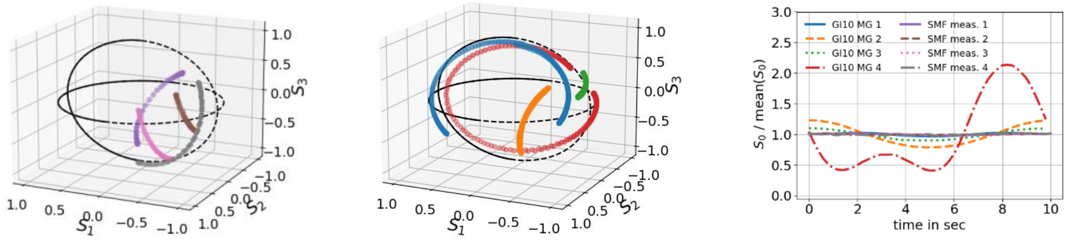


Fig. 1: Setup for applying the fiber bending with maximal bending radius of 7.5 cm (a) and minimal radius of 5.15 cm (b). Setup for measuring the Stokes parameters in the SMF (a) and GI10 (b). Measured power transfer matrix for the minimal (e) and maximal (f) bending radius.

fiber loops are anchored at points A and B. Point B has a linear range of motion of 4.2 cm. The vertical displacement follows a cosine function with a 10-second period. For the maximum vertical displacement of 4.2 cm (b), the loops form two half-circles with a radius of 5.15 cm, with roughly straight fiber sections in between. Consequently, the bending radius decreases while the length of the bent fiber section decreases.

For the investigation of the SMF, the output of the bent SMF section is directly connected to the polarimeter input, as shown in Fig. 1 (c). Fig. 1 (d) depicts the setup for the mode group resolved analysis of the GI10. Characteristics of the fiber are presented in [7]. The power is switched to one of the 10 single-mode inputs of a multi-plane lightwave-conversion mode multiplexer manufactured by *Cailabs* [8]. This mode multiplexer can selectively excite and receive modes in the GI10. The mode multiplexers are connected by a 20 m long fiber section of the GI10. Fiber bending is applied at varying positions of the GI10. After the output switch the Stokes parameters are measured using a polarimeter.

In Fig. 1 (e) and (f), we present the measured power transfer matrices (PTMs) for minimal (e) and maximal (f) bending radii. It has to be noted, that the matrix is not polarization resolved. In both cases, power is predominantly detected within the excited mode group, suggesting a negligible impact of the change in bending radius on coupling between mode groups. The intensity pattern within the second mode group remains roughly stable, while a noticeable change in the pattern is observed for the third mode group between the two matrices. In contrast, the pattern within the fourth mode group is almost completely scrambled.



(a) (b) (c)

Fig. 2: Trace of the normalized Stokes parameters on the Poincare sphere for the SMF (a) and GI10 (b). Normalized S_0-parameter (c)

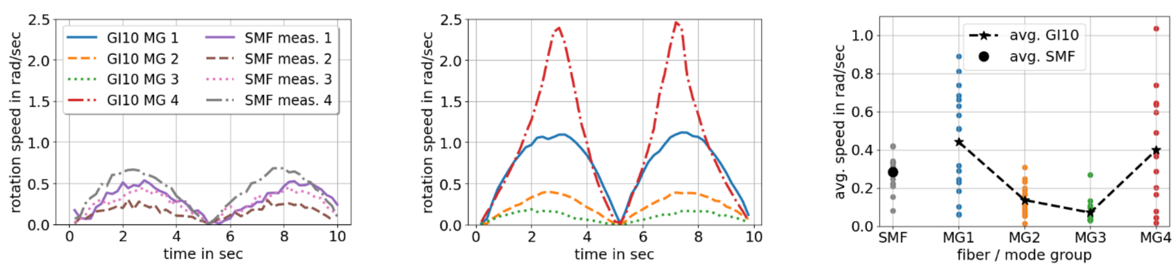
3. Measurement of the Stokes-Parameters

Fig. 2 (a) displays the traces of normalized Stokes parameters on the Poincaré sphere for the SMF. Results from four measurements are presented, where both input polarization and the position of the bend fiber section within the fiber-under-test were systematically altered between measurements. These traces correspond to arcs on the Poincaré sphere.

For the investigation of the GI10, the top-left field in each mode group is investigated. Due to the strong mode coupling within the mode groups, we expect identical behaviour for all fields within one mode group. The corresponding traces for one measurement of the GI10 are presented in Fig. 2 (b). Similar to the SMF, the traces correspond to the arcs on the Poincare sphere. However, notably faster polarization changes are observed for both the fundamental mode and the fourth mode group.

Normalized Stokes parameters lack information about detected power. Therefore, we present the course of the S_0-parameter for the corresponding Poincaré traces in Fig. 2 (c). For the SMF and the fundamental mode of the GI10, S_0 exhibits negligible dynamics, attributable to the small impact of bending losses and polarization-dependent attenuation of the components used. In contrast, higher mode groups show significant changes in S_0, reflecting dynamics observed in the PTMs.

Fig. 3 (a) and (b) present the rotation speeds corresponding to the Poincaré traces. The length of the arc on the Poincare sphere corresponds to the mean rotation speed. It depends on randomized parameters like the input polarization, fiber arrangement and position of the bend fiber section within the fiber-under-test. To average out these



(a) (b) (c)

Fig. 3: Rotation speed for the Poincaré traces of the SMF (a) and GI10 (b). Mean rotation speed of 16 measurements of the SMF and GI10 (c).

effects, we consider the rotation speed averaged over 16 measurements, changing input polarization between each measurement and varying the position of the bend fiber section after every three measurements.

Mean rotation speeds for each measurement of both fibers are presented in Fig. 3 (c). For the SMF an average rotation speed of 0.285 rad/sec is obtained with a maximum rotation speed of 0.420 rad/sec. Additionally, we present the corresponding values for all four mode groups of the GI10. Differences in both maximum and average rotation speeds are evident among the mode groups. The fundamental mode of the GI10 exhibits an average rotation speed of 0.441 rad/sec with a maximum of 0.891 rad/sec. Noticeably lower speeds are measured in the second and third mode group, whereas in the fourth mode group, both the average and the maximum rotation speeds are comparable to the fundamental mode.

4. Discussion

Since there is almost no mode coupling between mode groups in the GI10, the channel dynamics in the fundamental mode of the GI10 are expected to be comparable to a SMF. In bent optical fibers, both stress birefringence and geometric birefringence due to the tilting of the refractive index profile occur. In SMFs, the stress birefringence is several orders of magnitude larger compared to the geometric birefringence [9]. Since the effective area of the fundamental mode in the GI10 is 80 µm² [7], which is not significantly larger than that of a SMF, we attribute the dynamics in the fundamental mode mainly to stress birefringence.

Utilizing the model outlined in [10], we calculate the change in birefringence in the fundamental mode for a bending radius decrease from 7.25 cm to 5.15 cm. For the SMF, the birefringence changes by 0.29 rad/m. In the fundamental mode of the GI10, we obtain a slightly smaller value of 0.23 rad/m. This prompts the question of why the measured rotation speed of the fundamental mode of the GI10 is noticeably higher than in the SMF.

Interpreting the measured Poincaré traces for higher-order mode groups is challenged by the dynamics of S_0 due to the change in the intensity pattern within the mode groups. It should be noted that the true fiber modes propagating in round fibers mostly have identical field components in the horizontal and vertical field components, regardless of the orientation of the axis of reference. For these modes, the effect of stress birefringence can be expected to average out. In the fourth mode group, increased dynamics of the S_0-parameter are observed. However, the measured polarization rotation within the fourth mode group remains in the same order of magnitude as that in the fundamental mode. Overall, it can be concluded that for MMFs with a core radius of about 20-µm, the effect of stress birefringence is still the predominant effect in the bent induced polarization rotation. This constitutes an important finding for the understanding of the dynamics of mode coupling in MMF.

5. Conclusions

We presented a mode group resolved analysis of polarization rotation in a graded-index multi-mode fiber supporting 10 propagating modes. The polarization rotations for the second- and third mode group are slower than for the fundamental mode. In particular, for the fundamental mode of the GI10, we observe a polarization rotation that is unexpectedly more than twice as fast as that in an SMF. This observation cannot be reproduced by applying previously published modelling approaches for the expected stress birefringence. Further investigation is necessary. However, the observed polarization rotations are still in the same order of magnitude as in the SMF. Consequently, we are convinced that the conclusion concerning the comparable requirements for the MIMO in terms of tracking speed for GI-MMF and SMF is still valid.

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6. References

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