Comparison of Linear Mode Coupling Dynamics in Single Mode and Multi Mode Fibers

Christian M. Spenner(1), Klaus Petermann (2), Peter M. Krummrich(1)

(1) Technische Universität Dortmund, Friedrich-Wöhler Weg 4, 44227 Dortmund, Germany
christian.spenner@tu-dortmund.de
(2) Technische Universität Berlin, Einsteinufer 25, 10587 Berlin, Germany

Abstract *We investigate the mode coupling dynamics in different fiber types for mechanical movement. It is shown that the power fluctuations in graded index fibers are significantly smaller and slower than in step index fibers. The mode dependent dynamics are dominant over the polarization dependent ones.*

Introduction

A promising approach for increasing the capacity of a single fiber is space division multiplexing (SDM). SDM in multi mode fibers (MMFs) uses the different fiber modes in order to allow more signal channels. Due to mode coupling in the fiber, these SDM channels are not independent. A multiple input multiple output (MIMO) equalizer can be used, in order to compensate the mode coupling in the fiber. The differential mode group delay (DMGD) between fiber modes in MMFs is much higher than the differential group delay between the two polarization modes in single mode fibers (SMFs). Therefore, the memory length of the MIMO equalizer has to be much longer as compared to SMF transmission.

To ensure that the transmission works even in case of possible changes of the transmission matrix due to mechanical movements of the fiber, the MIMO must be able to compensate channel dynamics fast enough. Transmission experiments under mechanical movement demonstrate, that for SDM transmission in a 4 mode multi core fiber[1] and a 3 mode few mode fiber[2], the MIMO equalizer needs to be faster than for SMF transmission.

This raises the question of how much the linear mode coupling dynamics speed increases for fibers with significantly higher mode numbers. This investigation is important to estimate whether there is a realistic chance that MIMO equalizers can be developed that can follow the changes in these fibers sufficiently fast.

We are comparing the linear mode coupling dynamics of a SMF, a graded index multi mode fiber (GIMMF) and a step index multi mode fiber (SIMMF), both polarization resolved and non-polarization resolved. In particular, a comparison of the linear mode coupling dynamics in MMFs with the polarization change dynamics in a SMF will be performed. Since modern MIMO equalizers can follow these changes in a SMF, an information about the feasibility of MIMO equalizers for MMF-SDM systems would be highly desirable.

Experimental Set Up

The investigated MMFs have a core diameter of 50 µm. The numerical apertures are 0.2 for the GIMMF and 0.22 for the SIMMF. At a wavelength of 1555 nm the GIMMF is supporting 55 modes, excluding polarization modes, whereas 129 modes are supported in the SIMMF.

Fig. 1 shows an outline of the experimental set up for moving the fiber under test (FUT). A 50 cm long fiber section is arranged in the form of one loop with about 16 cm diameter. Start and end of the loop are fixed on the workbench. The top of the loop is attached to the end of a lever, which moves up and down with an amplitude of 12.5 cm. An electrical motor is used in order to move the lever up and down with a time period of 2.1 s.

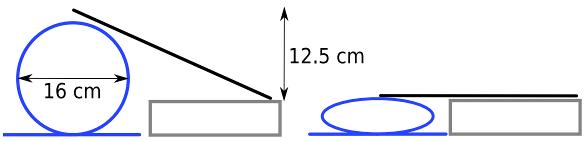

Fig. 1: Set up for applying mechanical movement to the fiber. The fiber loop has a diameter of 16 cm. A movable lever is compressing the loop by 12.5 cm with a time period of 2.1 s.

The experimental set up for the mode excitation and polarization resolved detection of power in the FUT is depicted in Fig. 2. As light source an external cavity laser operating at a wavelength of 1550 nm is used. The single mode output fiber of the laser is connected to a 2 m long fiber under test (FUT). In the SMF case a standard fiber connector is used. For the investigation of the MMFs a transversal offset of 10 µm is introduced between the fiber axes of the SMF and the FUT. In the middle of the FUT the set up for introducing a slow mechanical fiber movement is attached. At the other end the FUT is connected to another SMF, also with a transversal offset of 10 µm in the MMF case.

The transversal offset of 10 µm between the SMFs and the MMF is chosen such that a large

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number of modes is excited in the MMFs. This is to represent a real SDM channel in a MMF with mode coupling.

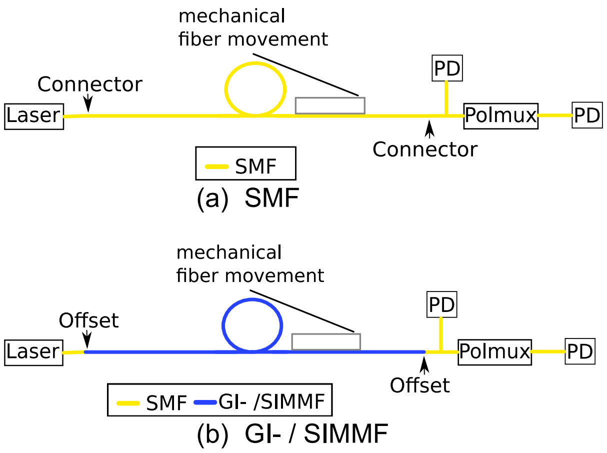


Fig. 2: Experimental set up for the measurement of the channel dynamics in different fiber types. In the MMFs a lateral offset between the FUT and the SMFs is introduced.

In Fig. 3 the calculated excitation coefficients for an offset launch from a SMF are shown for the two investigated MMFs. The coefficients are calculated by evaluating the overlap integrals between the mode fields of the MMF and the SMF with a transversal offset of 10 µm. For the simulation the angle between the orientation of the calculated mode fields and the axis of the offset is chosen to be 45 °.

For both MMFs the most power remains in the inner modes. Whereas there is still notable power in the highest order modes in the GIMMF, there is nearly no power launched into the 20 highest order modes in the SIMMF.

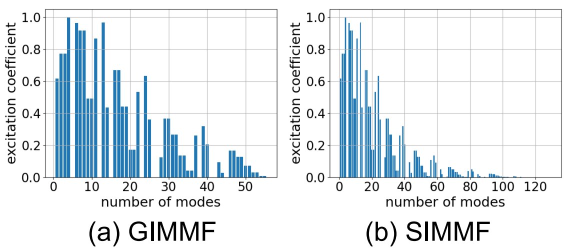


Fig. 3: Calculated relative excitation coefficients of the modes in the MMFs for an excitation by coupling form a SMF with a transversal offset of 10 µm.

Mode Dependent Channel Dynamics

Fig. 4 depicts the measured signal in the time domain for the three investigated fibers, both polarization resolved and non-polarization resolved. The powers are shown for the first 4 s of the measurement.

As there is no mode coupling in the SMF the non-polarization resolved signal in the SMF remains constant over time. In contrast, for the MMFs, both signals, with and without polarization resolution, are changing with nearly the same speed over time.

It stands out that the power fluctuations in the SIMMF are much faster than in the SMF and the GIMMF. While for SMF and GIMMF the maximum power in the considered time period is less than twice the average power, for SIMMF more than six times the average power is reached.

This is consistent with known results that the transmission matrix is significantly more robust in GIMMFs[3] than in SIMMFs and that the inner modes show the strongest variations in SIMMFs[4].

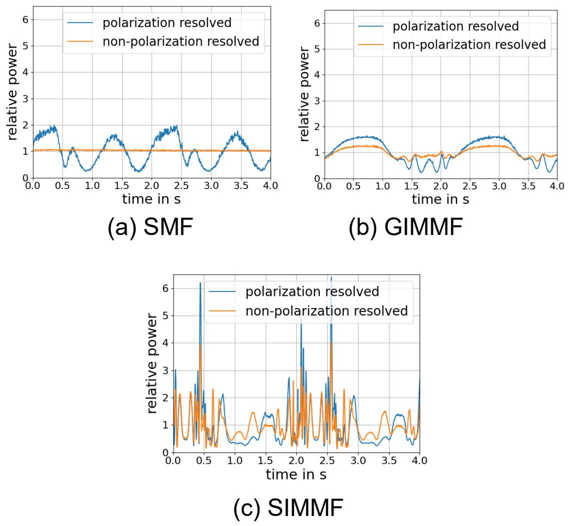


Fig. 4: Polarization resolved signal in time domain for different fiber types. The traces are normalized to their respective average power.

In order to further analyze the results in Fig. 5 the results are shown in the frequency domain. A fast fourier transformation is applied to a succession of 5 independent measurement results of each fiber in the time domain. A single measurement has been performed over a time of 24 s resulting in a combined measurement time of 120 s for each fiber. Between the 5 measurements the placement of the fiber before the mechanical movement device has been changed, resulting in a different polarization state. In the MMFs this also results in speckle pattern changes.

For all three types of fibers there is notable spectral power above the frequency of the mechanical movement of 0.48 Hz. The spectra reveal that SMF exhibits the slowest linear mode coupling dynamics. The curve has its maximum at low frequencies and is dropping with increasing frequencies. Above about 10 Hz the curve approaches the noise level. In the GIMMF there are stronger spectral components than in the SMF between about 4 and 16 Hz. For higher frequencies the curve runs in parallel to the curve representing the SMF. The spectrum of the SIMMF exhibits much stronger spectral components than the other two fiber types in the frequency range from 5 to 70 Hz.

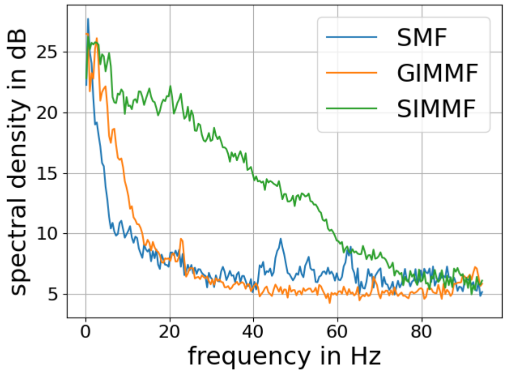


Fig. 5: Polarization resolved signal in frequency domain for different fiber types.

Polarization Dependent Channel Dynamics

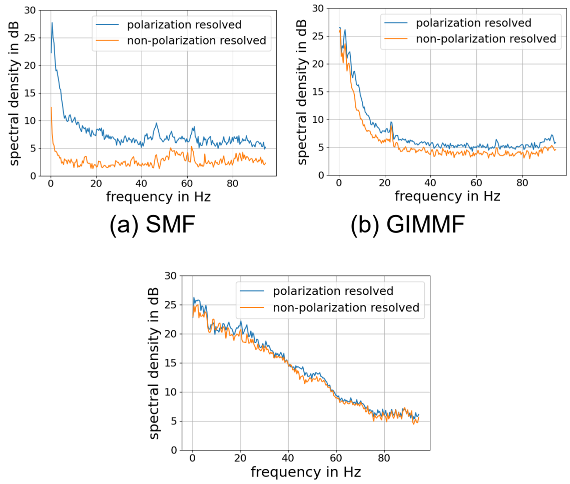
The diagrams, which are depict in Fig. 6, enable comparing the non-polarization resolved spectrum with the polarization resolved spectrum for the respective fiber type. As in the previous measurements, the excitation and detection of the signals in the MMFs is performed using an offset of 10 µm.

The spectral power density of the non-polarization resolved signal at the output of the SMF is expected to be containing just noise. Instead, for low frequencies a small increase of the spectral power density is visible. This is expected to be caused by bending losses, which are induced by the mechanical movement and polarization dependent losses in the experimental set up.

For the MMFs the difference between the polarization resolved and the non-polarization resolved spectral power densities is much smaller. In both cases the spectral power density of the polarization resolved curve is slightly higher.

Nevertheless, the influence of polarization onto the channel dynamics is much smaller than the polarization independent channel dynamics, which are introduced by changing the modal transfer matrix.

As visible in Fig. 5, the power fluctuations in the GIMMF are only insignificantly faster than in the SMF. Since current MIMO equalizers can follow the polarization changes in SMFs sufficiently fast, it can be assumed that the linear mode coupling dynamics in GIMMFs can also be compensated.



(a) SMF (b) GIMMF

(c) SIMMF

Fig. 6: Comparison between polarization resolved and non-polarization resolved measurements in the frequency domain for different fiber types.

Conclusions

The linear mode coupling dynamics resulting from an identical mechanical movement has been investigated for a SMF, a GIMMF and a SIMMF, both with and without polarization resolution.

Due to the absence of mode coupling, the signal powers in the SMF are shown to be most stable. While the mode coupling varies much faster in the SIMMF, the speed difference between the GIMMF and the SMF is comparatively small. Furthermore, it is shown that in the investigated MMFs the contribution of the polarization dependent coupling dynamic is small compared to the linear mode coupling dynamics.

In MMF-SDM systems equalization with a MIMO approach is significantly more complicated than in SMFs. This is due to the long DMGDs. However, the presented results suggest that the linear mode coupling dynamics in GIMMFs with 55 modes are not an unsurmountable obstacle.

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