Mode Group Resolved Analysis of Effects Induced by Macro Bending in a 50 μm Graded Index Multi Mode Fiber

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Abstract: The influence of macro bending in a 50 µm GIMMF is investigated in terms of losses and mode coupling. The results indicate that lower order mode groups are weakly influenced by macro bends.
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1. Introduction

State of the art optical communication systems based on Single Mode Fibers (SMF) are operating close to the capacity limit. Data transmission through different spatial channels has been demonstrated as a possible approach in order to further increase the capacity per fiber [1]. This Space Division Multiplexing (SDM) can be realized by using Multi Mode Fibers (MMF), Multi Core Fibers or a combination of both. Of these, MMF's have the highest spatial density. Signal transmission in MMF's is affected by Differential Group Delay (DGD) and cross talk between the modes. Therefore, signal processing using a multiple input multiple output (MIMO) approach is necessary. In recent publications 90x90 MIMO transmission over 45 spatial modes has been demonstrated [2] using a Graded Index Multi Mode Fiber (GIMMF) with a core diameter of 50 µm. Differing from usual OM4-type fibers their refractive index profile is optimized for a wavelength of 1550 nm. In GIMMF's the spatial modes are arranged in mode groups with nearly the same propagation constant. Transmission over single mode groups has been demonstrated as an approach for reducing DGD and MIMO complexity [3]. In MIMO-SDM transmission systems mode dependent loss (MDL) will lead to a reduction of transmission capacity [4]. Especially in large MMF's not all propagating modes are used for transmission and therefore, are not covered by the MIMO approach. In this case, strong MDL by mode coupling into undetected modes can occur. Therefore, an accurate estimation of mode coupling is necessary in order to design future SDM transmission links.

Macro Bending is expected to cause both, mode coupling and MDL. However, there are very few publications investigating macro bending in the context of SDM. In [5] a bending loss analysis of a two-mode- and a four-mode-GIMMF are presented. Their results are indicating that the mode group resolved bending loss is increasing with the mode group order. Especially the fundamental mode has been shown to be nearly unaffected until the bending radius is close to the breaking point of the fiber.

The 50 µm GIMMF [6], investigated in this contribution, is optimized for SDM at a wavelength of 1550 nm. Its refractive index profile is optimized for a low DGD at a wavelength of 1550 nm. In order to reduce bending losses a depressed-index region is added into the cladding. For the two highest propagating mode groups the bending losses are stated to be higher than 10 dB/turn for a bending radius of 10 mm.

Here, we are investigating bending losses and mode coupling behavior of the lower order mode groups for bending radii up to 1.33 mm. To our best knowledge we are the first to experimentally perform this investigation for a GIMMF with more than five propagating mode groups.

2. Experimental Set Up

The transmission through the bent MMF is characterized by the power transfer matrix. The matrix shows the power, which is detected in each output mode, when a specific input mode is excited. A block diagram of the experimental set-up to measure the power transfer matrix is shown in Fig. 1. As input signal an Amplified Spontaneous Emission (ASE)-source is used, which is filtered with a 3 dB-bandwidth of 0.52 nm around a wavelength of 1550 nm. A 3 dB-coupler and an optical power meter are used to determine the input power. With an optical switch the ASE-source is connected to one of the 15 inputs of the mode multiplexer by *Cailabs* [7]. It can excite and receive the first 15 modes in a 50 µm GIMMF, which is supporting 55 modes at a wavelength of 1550 nm. In the middle of the 4 m long GIMMF one turn of a defined bending radius is applied by bending the fiber around a rod. Here, the bending radius is understood as the radius of the bending rod. The coating diameter of about 0.25 mm of the bare fiber, which is investigated, is neglected. A second optical switch is connecting one of the 15 single mode outputs of the demultiplexer to the output power meter.

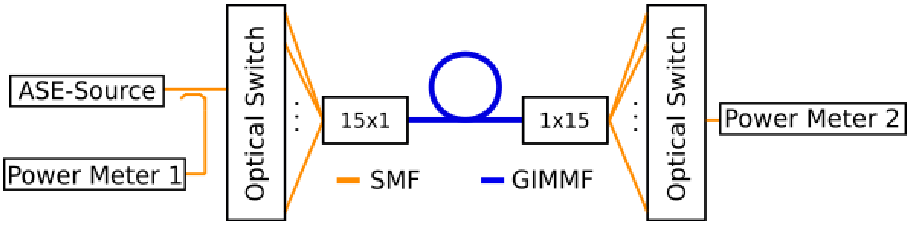


Fig. 1: Experimental set up for measuring the power transfer matrix for different bending radii.

3. Results

With the described experimental set up the power transfer matrix of the fiber under test is measured for different bending radii. In Fig. 2 power transfer matrices without bending (a) and with one turn of a bending radius of 1.33 mm (b) are shown. On the main diagonal the five investigated mode groups can be seen. Power transfer

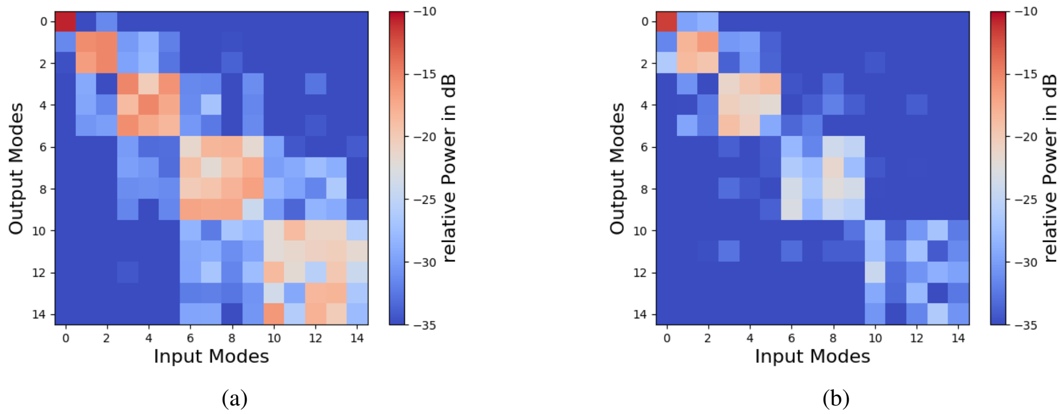


Fig. 2: Measured power transfer matrices of the 4 m long GIMMF between the multiplexers for a straight fiber (a) and a bending radius of 1.33 mm (b). The 15 LP modes are arranged by their propagation constant. The intensity represents the power level difference between the two power meters.

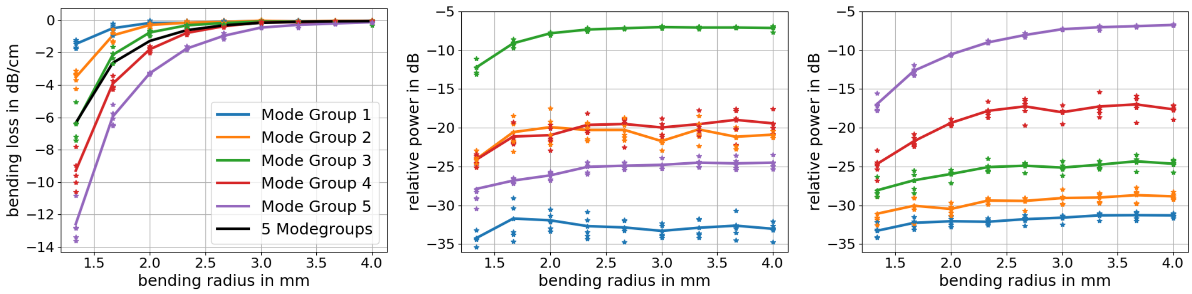
between modes particularly occurs within these mode groups. Coupling between mode groups is strongest for neighboring mode groups. The intensity pattern within the mode groups is nearly invariant, when the MMF is kept unmoved. It shows strong temporal fluctuations when the fiber is moved for changing the bending radius.

It can be noticed that bending affects the intensity transfer. The bent fiber shows a stronger intensity decrease for higher order mode groups than for lower order mode groups. This behavior can be explained by the stronger guidance of the lower order mode groups.

In Fig. 3 (a) the attenuation, which is introduced by the fiber bend, is shown in $\mathrm{dB\,cm^{-1}}$. It is calculated by dividing the total power within one mode group for a specific bending radius by the measured power of the same mode group in the straight fiber. In order to reduce the effect of measuring inaccuracies, averaged results of multiple measurements for every bending radius are presented. Bending with the highest investigated radius of 4 mm does not perceptibly influence the intensity in any investigated mode group. The lowest investigated radius of 1.33 mm is close to the breaking point of the fiber. For this radius the power of the 5th mode group is attenuated by about 13 $\mathrm{dB\,cm^{-1}}$, while the fundamental mode is attenuated by just about 1.5 $\mathrm{dB\,cm^{-1}}$. The overall bending loss averaged over the first five mode groups is close to the bending loss of the third mode group.

In Fig. 3 (b) and (c) the output powers when the third respectively the fifth mode group is excited are shown. The powers are relative to the input power, which is measured with the first power meter. The curve for the excited mode group equals to the corresponding curve in Fig. 3 (a). The other curves are representing the generated cross talk into other mode groups.

The cross talk powers for a bending radius of 4 mm are similar to the cross talk powers for an unbend fiber. They are generated in the multiplexers and the 4 m long fiber, independent of the bending radius. For decreasing bending radii the cross talk powers are decreasing for all investigated mode groups. This is expected to be caused by mode dependent attenuation within the fiber bend.



(a) (b) (c)

Fig. 3: Measured mode group resolved bend loss (a). Power in all measured mode groups, when exciting the third mode group (b) and the fifth mode group (c) for different bending radii. Results of multiple measurements for each bending radius are presented. The solid lines are connecting the averaged values.

Power coupling between the mode groups, which is introduced by the fiber bend, is expected to be increasing for decreasing bending radii. As the cross talk powers are decreasing for smaller bending radii, it can be concluded that the generated cross talk caused by the fiber bend is much smaller than the cross talk caused by the multiplexers and the 4m long fiber.

Our results are indicating that macro fiber bends are only weakly influencing signal transmission in the lower order mode groups of GIMMF's in terms of losses and cross talk.

4. Conclusions

Results of a mode group resolved measurement of the bending loss in a 50 µm GIMMF are presented, showing that the loss is increasing with the mode group order. Our results are indicating that a single macro fiber bend with a bending radius above 4 mm has weak influence on signal transmission in the first five mode groups of a 50 µm GIMMF. As shown in [5] for GIMMFs with a lower number of propagating modes, especially the fundamental mode will be nearly unaffected until the bending radius is close to the breaking point of the fiber. Furthermore, our results are indicating that even for very small bending radii the generated cross talk between the first five mode groups is negligibly small.

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