Reducing group delay spread in a 9-LP mode FMF using uniform long-period gratings

Huiyuan Liu(1), He Wen(1,2), Rodrigo Amezcua-Correa(1) Pierre Sillard(3), and Guifang Li(1,2)
(1)CREOL, The College of Optics & Photonics, University of Central Florida, Orlando, FL 32816, USA
(2)The College of Precision Instruments and Opto-electronic Engineering, Tianjin University, Tianjin,300072, P.R. China
(3)Prysmian Group, Parc des Industries Artois Flandres, Douvrin 62138, France
Email: huiyuan@knights.ucf.edu

Abstract: We experimentally demonstrate, for the first time, reducing group delay spread in graded-index few-mode fibers with many LP modes using simple, uniform long-period gratings which have only one grating period.
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1. Introduction

As single-mode fiber (SMF) systems approach their capacity limit, space-division multiplexing (SDM) has attracted more interest in recent years [1, 2]. SDM uses spatial modes to increase the number of parallel independent data channels in an optical fiber. Compared with multiple SMFs, few-mode fibers (FMFs) could reduce the physical complexity and cost of transmission systems by integration of fibers, amplifiers, detectors, and other components. However, random mode crosstalk and modal dispersion in FMFs distort mode-division multiplexed (MDM) signals after propagation. Multiple-input-multiple-output (MIMO) digital signal processing (DSP) is needed to recover independent data channels at the receiver. The high complexity of MIMO equalization, due to long group delay (GD) spread, leads to high power consumption for MDM receivers. To relieve this problem, several methods have been proposed to reduce GD spread, including GD compensation [3] and optimized fiber design [4]. However, these methods are effective only for short transmission distances and a small number of modes [5].

Strong mode coupling is another method to reduce GD spread [6]. When modes in a FMF are strongly coupled, each MDM signal would have an equal probability of traveling on different modes, thus reducing GD spread due to modal dispersion. When modes are weakly coupled, the GD spread increases linearly with the transmission distance whereas it increases with the square root of the transmission distance when modes are strongly coupled. Usually, a different grating is required for each mode pair (or mode group pair) to ensure strong coupling among all modes [6, 7], leading to higher complexity, and higher loss. Here, we use a uniform mechanical long-period grating (LPG) with only one grating period to couple modes in a 9-LP-mode graded-index (GRIN) FMF. The underlying reason why one grating period is sufficient is that the effective indices of each mode group are nearly equally spaced in a GRIN FMF. We experimentally demonstrate the reduction of the root-mean-squared (RMS) pulse width, which represents GD spread. More importantly, because of the simplicity of the uniform, single-period grating, the loss associated with reducing GD spread is negligibly small.

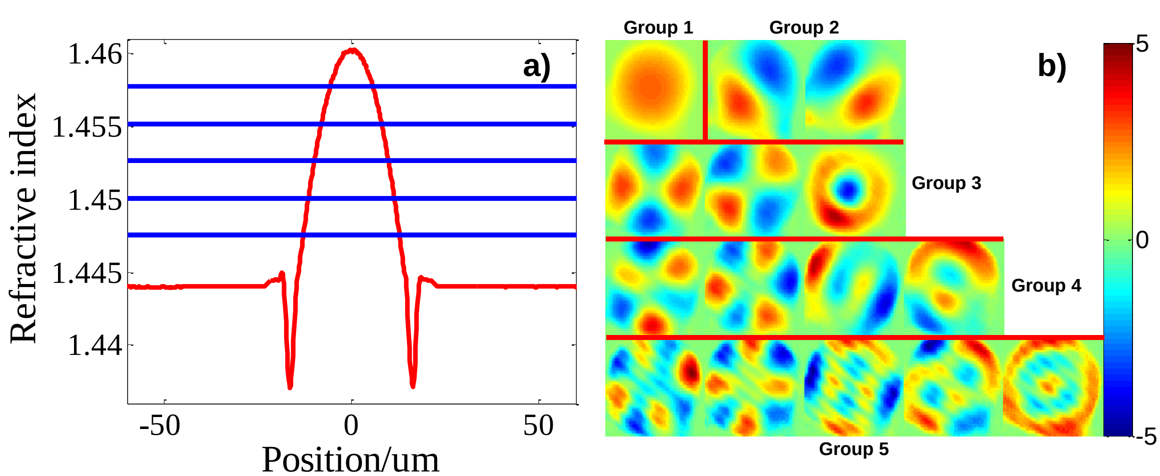

Fig. 1: (a) Index profile of FMF and effective indices of 5 mode groups. (b) Measured mode profiles of each mode group from S^2 experiment.

2. 9-LP-mode graded-index few-mode fiber

The FMF used in this work supports five mode groups (9 LP modes) at 1550 nm [4]. The index profile of the FMF and the effective indices of the five mode groups are shown in Fig. 1(a). It was optimized to achieve low crosstalk/mode group coupling and low differential mode group delays (DMGDs) (<155 ps/km) with low attenuation (<0.22 dB/km). The nearly-parabolic graded index profile ensures that the effective-index differences between successive mode groups are nearly equal. For this particular fiber, the effective index difference is ~2.6×10^{-3} at 1550nm, leading to weak coupling and a linear scaling of GD spread with transmission distance.

To characterize mode profiles of different mode groups, we employed standard spatially and spectrally resolved imaging (S^2). A camera was used to record output images of the FMF when light of different wavelengths was launched. By using principal component analysis (PCA) and independent component analysis (ICA) [8, 9], we could acquire profiles of all 9 LP modes shown in Fig. 1(b).

3. Reducing GD spread using uniform single-period LPGs

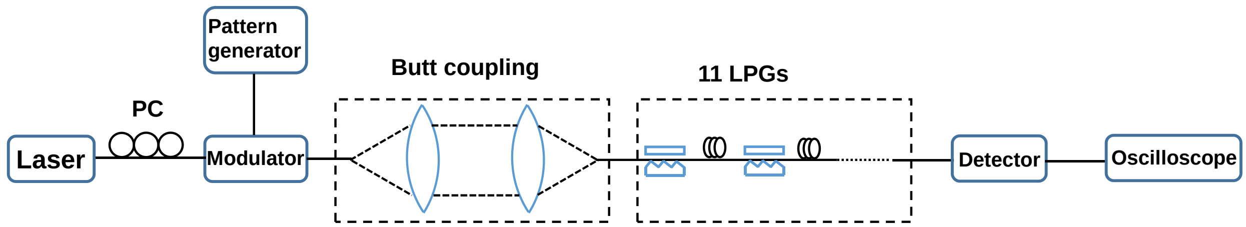

Fig. 2: Experiment setup for impulse response.

We first demonstrate enhanced mode coupling among all 9 LP modes using a uniform single-period LPG. Subsequently, we use a series of such LPGs to reduce GD spread. The mechanical LPG consists of a replaceable plate with gratings cut into it, and an upper flat steel plate over which an adjustable screw is used to apply pressure to the fiber, which is sandwiched between these two plates [10]. Figure 2 is the experimental setup for demonstrating the proposed mode coupling and reduction of GD spread. A data pattern from the pattern generator was used to modulate the light from a laser after it passed through the polarization controller (PC). The pattern generator produced a short pulse, which consisted of one bit 1 and a long series of bit 0s. After modulation, the light was launched into the FMF by butt coupling. To study the effect of mode coupling due to a single LPG, one mechanical LPG was applied to the FMF. To investigate reduction of GD spread, 11 mechanical LPGs were applied about every four hundred meters to the 4.3 km long FMF. The relative angle between the fiber and the LPG could be adjusted to change the effective grating period to satisfy the phase matching condition for efficient mode coupling. To simplify the experimental operation, the wavelength of the laser was adjusted instead to achieve phase matching. After propagation through the FMF, the signal was detected by a multimode InGaAs PIN+TIA receiver. The receiver was connected to the oscilloscope to record the impulse response waveforms.

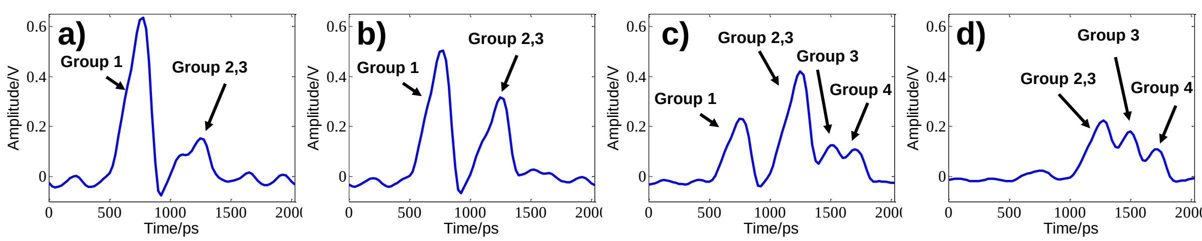

Fig. 3: Measured impulse response waveforms with one LPG at (a) no force, and (b)(c)(d) increasing forces.

When only one uniform single-period LPG was used, we verified that the LPG could achieve mode coupling between all mode groups in the FMF with representative results shown in Fig. 3. The lateral offset between the SMF and FMF in butt coupling was adjusted to excite different combinations of modes. When there was no force applied on the mechanical LPG, there was one main peak, representing that the power was mainly in the LP01 mode, as shown in Fig. 3(a). After force was applied to the LPG, more peaks appeared in the waveform, signifying that the power in the LP01 mode had been coupled into other mode groups. Figures 3(b) to (d) show the effect of mode coupling as the force on the mechanical LPG was successively increased. It can be concluded that a uniform single-period LPG could couple all the LP modes of the 5 mode groups.

We then demonstrate a reduction of GD spread using 11 LPGs distributed along the 4.3 km FMF. For each waveform measured under different mechanical force/coupling efficiency, the RMS pulse width representing the GD spread in the FMF was calculated. Meanwhile, for each applied force, the loss induced by the 11 LPGs was also measured. The RMS width as a function of measured loss induced by the 11 LPGs is shown in Fig. 4. The RMS width decreased as the total loss/applied pressure increased. For a total loss of 0.7 dB (0.06 dB per LPG), the RMS width could be reduced to below 220 ps from the initial 300 ps – approximately 27%. For a total loss of 2.7 dB (0.245 dB per LPG), the RMS width was reduced by 33%. The insets are waveforms corresponding to different total losses/pressures. The reduced RMS width leads to smaller GD spread and lower complexity in MIMO equalization.

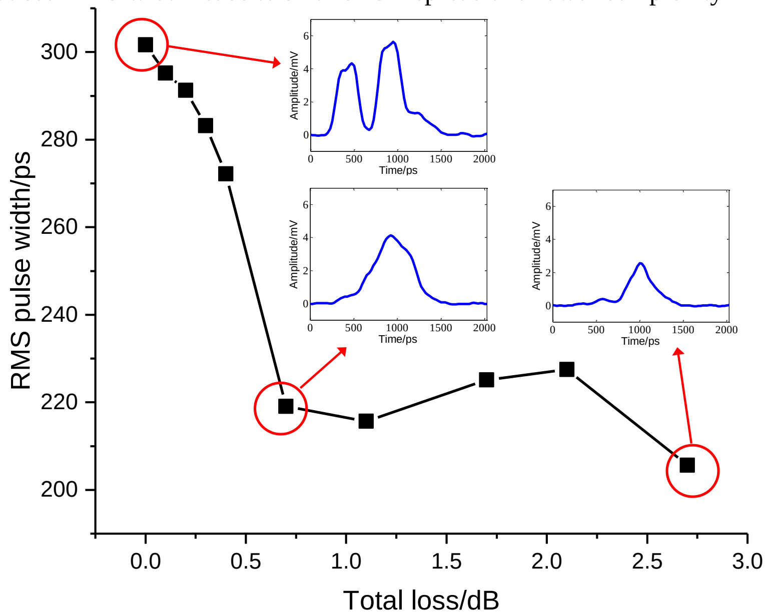

Fig. 4: RMS pulse width as a function of measured loss as pressure increased. Insets are waveforms corresponding to different losses/pressures.

4. Conclusion

In conclusion, we experimentally demonstrate, for the first time to our knowledge, that the GD spread can be reduced in FMFs with many LP modes using LPGs which are uniform and have only one grating period. The LPG with only one grating period could couple all 5 mode groups in the FMF, since their effective indices are nearly equally spaced. The RMS pulse width was reduced significantly while LPG induced loss remains negligibly small. These results illustrate that simple LPGs can serve as a practical tool to reduce the GD spread in the FMF, which in turn can reduce the complexity of MIMO DSP in MDM system.

5. References

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