Study of Inter-Modal Four Wave Mixing in Two Few-Mode Fibres with Different Phase Matching Properties

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Abstract *We experimentally study inter-modal four-wave mixing (FWM) in few-mode fibres with different phase matching properties. The possibility of transmitting two spatial modes without inter-modal FWM cross-talk in the C-band is presented.*

Introduction

Four-wave mixing (FWM) among waves at different frequencies occupying distinct spatial modes in a few tens of metres of multi-mode fibre was first observed by Stolen et al. back in the 1970's[1] and still attracts the interest of researchers[2-5]. Recent developments in fibre optic applications, mainly in the context of space-division multiplexed (SDM) communications, have prompted a re-visit to the detailed propagation properties of multi-mode fibres and prompted their better understanding in terms of inter-modal nonlinear interactions both experimentally and theoretically[2-9]. While these complex nonlinear effects need to be minimized in SDM transmission, they can potentially enhance all-optical signal processing, adding an extra degree of freedom relative to current single mode processes[2-5]. However, still relatively little work has been carried out on inter-modal FWM for signal processing.

In this paper, we perform a comparative experimental study of two intermodal FWM processes, namely phase conjugation (PC) and Bragg scattering (BS), in two commercially available km-long few-mode fibres[10] with largely dissimilar inter-modal phase matching properties. The first fibre is a typical graded-index FMF, commonly deployed for SDM transmission with relatively low differential group delay (DGD) showing some phase matching between the two spatial modes in the C-band. The second is a step-index FMF with high DGD where no phase matching is exhibited among the modes for any wavelengths within the C-band. Our experiments demonstrate that inter-modal FWM is significant in the first fibre but is largely suppressed in the second fibre, as expected. The capability of adjusting the fibre properties to either excite or completely suppress inter-modal cross-talk at will is potentially interesting for a variety of signal processing applications.

Experimental Set-up

Our experimental set-up is shown in Fig. 1(a), and the arrangement of the pumps and signal for the observation of the nonlinear processes in Fig. 1(b). Three continuous-wave tunable laser sources (TLSs) are used as the two pump and the signal waves, respectively. To avoid stimulated Brillouin scattering and increase the peak power into the fibre under test (FUT), all three sources are gated with a 10% duty cycle at a repetition rate of 10 MHz. One pump (p1) and the signal (s) waves (with the signal power being about 21 dB lower than the pump) are launched into the LP01 mode whereas the second pump (p2) wave is launched into the LP11 mode using a mode-multiplexer (MMUX) based on a phase plate (PP), see Fig. 1(a).

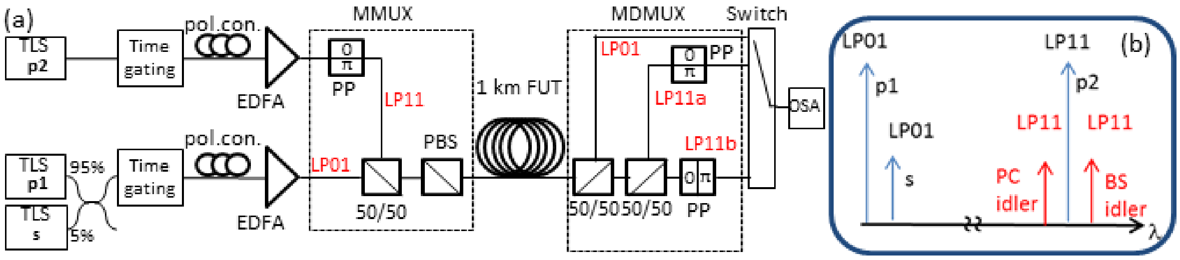

Fig. 1: Experimental set-up to observe inter-modal FWM in the few-mode fibres under test supporting LP01 and LP11 modes. (b) Pump- signal configuration highlighting the phase conjugation and Bragg scattering nonlinear processes.

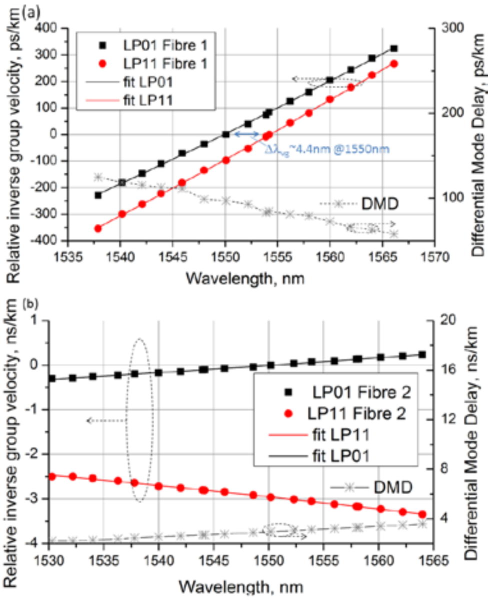

Fig. 2: Measurement of the RIGV of the LP01 and LP11 modes for (a) Fibre 1 and (b) Fibre 2, and corresponding DMD.

Polarization controllers (pol. con.) and a polarization beam splitter (PBS) guarantee that the launched waves are co-polarized. Two erbium-doped fibre amplifiers (EDFAs) are used to achieve about 20.5 dBm (for Fibre 1) or 16.5 dBm (for Fibre 2) average power in each pump at the input of the FUT.

At the output of the FUT, we extract the different spatial modes using a mode-demultiplexer (MDMUX) based on PPs followed by single-mode fibres (SMFs). Note that even though the MMUX excites only one of the LP11 modes, both LP11a and LP11b modes become completely mixed after propagation along the FUT and, thus, having two orthogonally orientated PPs in the DMMUX is essential in order to collect the total power in LP11[5]. A switch enables selection and independent measurement of each of the three output ports of the MDMUX on an optical spectrum analyser (OSA) with 0.01 nm resolution.

Two different types of 1-km long FMFs were tested in our experiment. Fibre 1 is a graded-index FMF supporting LP01 and LP11. The calculated effective areas of the LP01 and LP11 modes are 161 μm^2 and 170 μm^2, respectively. The measured chromatic dispersions (CDs) are $D^{(01)}$ = 19.8 ps/(km nm) and $D^{(11)}$ = 21.8 ps/(km nm) at 1550 nm, respectively and they have similar and relatively small dispersion slopes[10]. Figure 2 (a) shows the measured relative inverse group velocity (RIGV), $v_g^{-1}=\beta_1$, of the two modes. From these measurements, we observe that the waves in the two modes propagate at the same group velocity at a wavelength separation, $\Delta\lambda_{vg}$, of about 4.4 nm at 1550 nm, with small deviations across the C-band. On the other hand, Fibre 2 is a step-index FMF supporting LP01 and LP11 in the C-band[10]. At λ=1550 nm the calculated effective areas of the LP01 and LP11 modes are 41 μm^2 and 75 μm^2, respectively, and their measured CDs are $D^{(01)}$ = 16.7 ps/(km nm) and $D^{(11)}$ = -26.5 ps/(km nm), respectively, with different dispersion slopes, see Fig. 2(b). The measurements show that the waves in the two modes do not propagate at the same group velocity for any wavelength separation across the C-band.

Experimental Results

Figure 3(a)-(c) and Fig. 4(a)-(c) show typical spectra obtained on the LP01 output port (top) and the two combined LP11a and LP11b ports (bottom) for Fibre 1 and Fibre 2, respectively, when setting λ_{p1}=1549 nm and λ_s=1549.3 nm, and sweeping λ_{p2} across the C-band. Each port of the MDMUX extinguishes the other mode-group with an efficiency of about 15-20 dB (labelled as leakage in the corresponding figures). Looking at the LP01 port (top rows in Figs. 3 and 4), we can clearly observe in all cases comparable intra-modal FWM effects, implying that similar nonlinear phase shifts (given by the product of nonlinear coefficient, pump power and fibre length) were achieved in both fibres. On the other hand, the inter-modal FWM effects are very different in the two fibres (bottom rows in Figs. 3 and 4) and in particular, in the case of Fibre 1, the results depend strongly on the value of λ_{p2}. In more detail, Fig. 3(a) shows the corresponding optical spectra when λ_{p2} is chosen such that inter-modal phase matching is fully satisfied in Fibre 1 (λ_{p2}=1553.4 nm), thus achieving the generation of the highest PC and BS idler powers with a PC/BS idler-to-pump2 ratio of about -29 dB (signal-to-pump1 ratio of -21 dB), see Fig. 3(a)-bottom. As we move away from the inter-modal phase matching condition, achieved by detuning λ_{p2}, the efficiency of the generated idlers reduces, see Fig. 3(b) for λ_{p2}=1559 nm (PC/BS idler-to-pump2 ratio of about -57 dB, Fig. 3(b)-bottom), till it vanishes, Fig. 3(c) for λ_{p2}=1567 nm. In the case of Fibre 2, where no phase matching is predicted from Fig. 2(b), no inter-modal FWM process can be observed for any value of λ_{p2}, as expected. Figure 4 shows only three examples of such spectra measured across the C-band, all showing the same result. It is worth noting that similar spectral measurements were carried out where the signal was tuned 0.3 nm away from p2 and launched in the LP11 mode, achieving very similar results. The capability of exciting signals in different modes without inter-

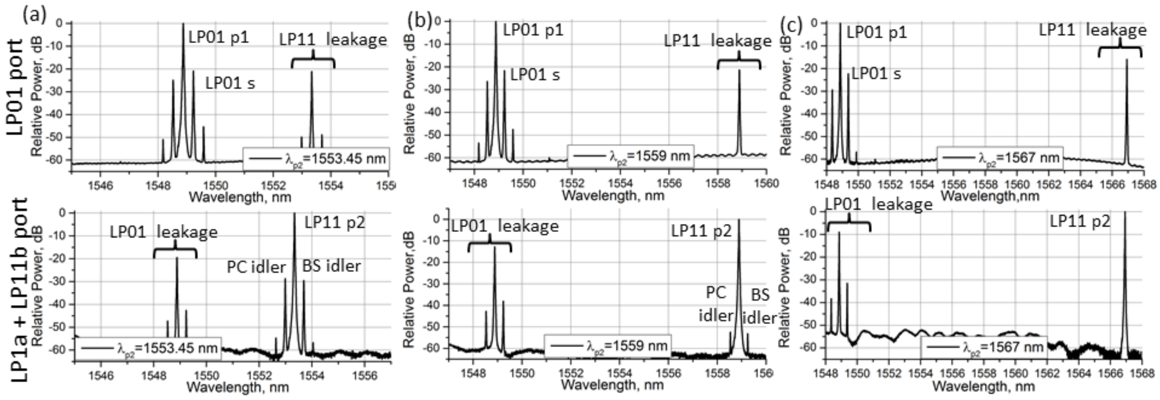

Fig. 3: MDMUX spectra of LP01 port outputs (top) and combined LP11a and LP11b ports outputs (bottom) for λ_{p2}=1553.45 nm (a), λ_{p2}=1559 nm (b), λ_{p2}=1567 nm (c) for Fibre 1.

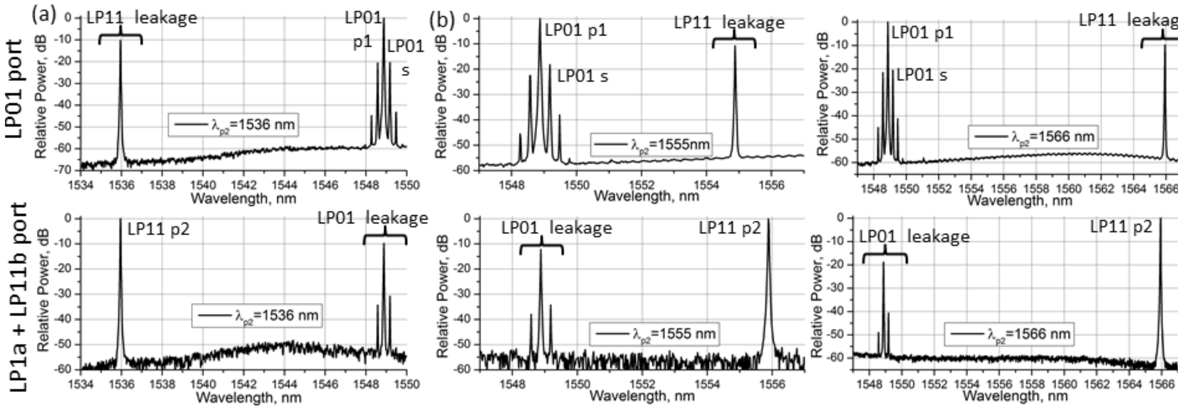

Fig. 4: MDMUX spectra of LP01 port outputs (top) and combined LP11a and LP11b ports outputs (bottom) for λ_{p2}=1536 nm (a), λ_{p2}=1555 nm (b), λ_{p2}=1566 nm (c) for Fibre 2.

modal cross-talk, i.e. each mode behaves independently from the others, or controlling it, while achieving intra-modal effects and keeping the relative phases insensitive to environmental perturbations, could be very interesting for a number of signal processes, where guaranteeing identical optical paths is a key requirement.

Conclusions

Our measurements have shown that in fibres exhibiting a relatively low DGD, as typically is the case in long-haul SDM transmissions, the inter-modal FWM can be appreciable at wavelengths that satisfy the inter-modal phase matching condition. The capability of adjusting the fibre properties to either excite or completely suppress inter-modal cross-talk at will is potentially interesting for a variety of signal processing applications. Future work will include the demonstration of some such devices.

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