Joint Transmission and Sensing in Few-Mode Fibre

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Abstract We experimentally demonstrate the coexistence of transmission and sensing using an innovative commercial 15-mode few-mode fibre system. With respect to previous works where the cascade of single-few-single mode fibres has been used, our system features a mode multiplexer and demultiplexer. By transmitting a telecommunication signal over the fibre fundamental mode, the sensing capabilities of the few-mode fibre are demonstrated analysing the power variation of the higher-order modes directly excited by the fundamental mode itself owing to the intermodal crosstalk perturbation.

Key words Few-Mode Fibre, Sensing, Transmission

1. Introduction

The recent huge capacity increase demand of the last years is posing new challenges for the optical network, as the standard single mode fibre (SMF) capacity is fixed by Shannon's limit [1]. Multiplexing techniques such as wavelength division multiplexing (WDM), and polarization division multiplexing (PDM) allow to increase the optical network capacity by using parallel channels able to transfer parallel data streams. To further increase the network performance, addressing Terabit- and Petabit-per-second capacities, space as third multiplexing dimension has been explored in the last decade in the so-called spatial division multiplexing (SDM). This new approach requires special fibres like multi-core fibres (MCFs) or multimode fibres (MMFs). Due to the potential higher data density, MMFs are a very attractive solution, but they present two issues to be faced. The first one is the high modal dispersion, that quickly worsens the system performance. By using few-mode fibres (FMFs) supporting a limited number of modes, the modal dispersion limitation in reach can be weakened [2,3]. The second issue is represented by intermodal crosstalk (IMXT), accumulated during the propagation and introduced by the non-ideal behaviour of the modal devices. This unavoidable impairment requires a huge digital signal processing (DSP) effort at the receiver side for compensating its detrimental effects.

At the same time, optical fibre sensing could benefit from these novel FMFs, since they can be exploited as assets to develop innovative sensing techniques. In particular, the coexistence of multiple modes inside the core and their interaction due to IMXT could be turned from a problem into an opportunity. The major part of the works in this field concerning FMFs up to date has been concentrating mainly on a configuration named single-multi-single (SMS), where the discontinuities between a perturbed FMF spliced at both ends with a SMF allow to excite the higher-order modes [2,3,4]. These ones, then, sense the perturbation (or even more perturbations) in a different way owing to the different field spatial

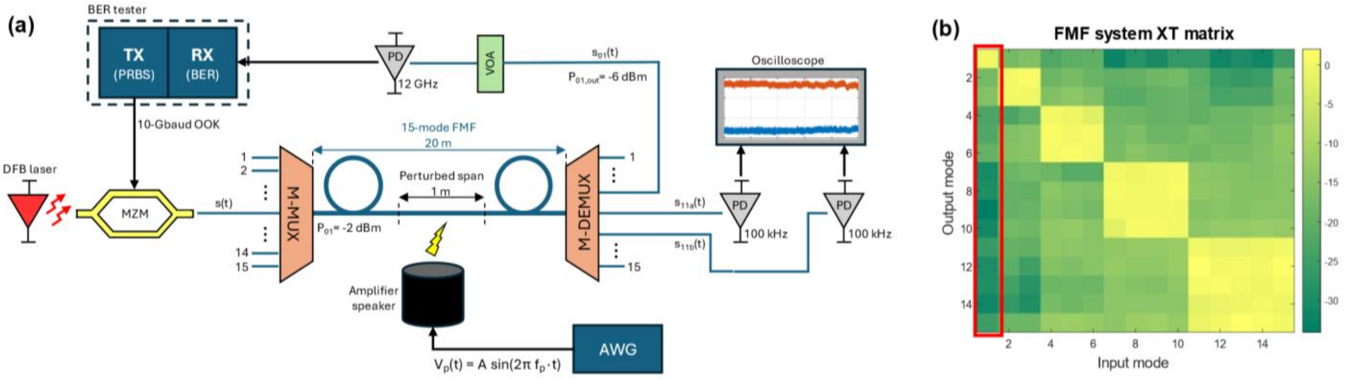

Fig. 1 Experimental set up of the FMF-based system for the transmission-sensing experiment *(a)*. Measured FMF IMXT matrix in the unperturbed condition. The red rectangle highlights the column related to the IMXT from LP_{01} mode to all the other modes *(b)*.

distribution and can be used to extract the information [4].

In this paper, we propose a system structure merging transmission over a FMF supporting 15 spatial modes [5] and sensing of mechanical perturbations. We transmit a telecommunication (TLC) 10 Gbit/s on-off keying (OOK) modulated signal on the fundamental mode of the FMF, which excites higher-order modes thanks to the IMXT, mainly induced by the use of a pair of non-ideal mode multiplexer/demultiplexer (MUX/DEMUX). A sinusoidal vibration at different frequencies applied to the FMF affects the IMXT and is monitored by analysing the received optical power for the excited higher-order modes. The results show the effectiveness of this method, and BER measurements of the TLC signal confirm the possibility of the coexistence of transmission and sensing over FMF-based systems.

2. Experimental setup

The experimental setup is shown in Fig. 1(a). A distributed feedback (DFB) laser at a 1550 nm is OOK modulated at 10-Gbit/s by a $LiNbO_3$ Mach-Zehnder modulator (MZM) with a pseudo-random bit sequence (PRBS) having length 2^{16}-1. The modulated optical signal, named s(t), is then sent to a mode multiplexer (M-MUX), based on 15 spatial modes multi-plane light conversion (MPLC) [6]. The optical signal is injected in the input port corresponding to the fundamental LP_{01} mode of the FMF in output. The launch power P_{01} of the LP_{01} mode after the M-MUX is around -2 dBm. At the same time, due to the M-MUX non idealities, IMXT is generated, meaning that a fraction of the input power that should be part of the fundamental mode is actually coupled to all the other higher-order modes. Fig. 1(b) shows the IMXT matrix of the system: it is clear that the coupled power is inversely proportional to the mode order. In particular, the modes receiving the most power owing to IMXT are the two degenerate modes LP_{11a} and LP_{11b} as the closest ones to the LP_{01} mode. After the propagation in the 20-m long 15-mode FMF, the fundamental mode and the higher-order modes excited by the IMXT, introduced by the M-MUX and the FMF propagation, are demultiplexed by a MPLC-based mode demultiplexer M-DEMUX), transforming the input FMF modes into the various SMF outputs with the same principle of the M-MUX. A mechanical vibration is applied to the FMF: a fibre span approximately 1-m long is fixed to the membrane of an amplifier speaker, whereas the fibre ends are blocked. The membrane is driven with a voltage sinusoidal signal generated by an arbitrary waveform generator (AWG) at a desired frequency f_p, and its movement results into the vibration of the FMF span. Among all the M-DEMUX outputs, just the ones related to the LP_{01}, LP_{11a} and LP_{11b} modes (signals $s_{01}(t)$, $s_{11a}(t)$ and $s_{11b}(t)$ respectively) are relevant for our analysis: the first one since it is the TLC data-carrying signal; the other two because they are the most powerful IMXT contributions. The signal $s_{01}(t)$, having approximately a -6 dBm power, is monitored during the application of the mechanical vibration to verify that its performance in terms of BER remains unchanged. It passes through a variable optical attenuator (VOA) and then is directly sent to a 12-GHz bandwidth photodiode (PD) for direct detection, and to a BER tester for BER computation. Signals $s_{11a}(t)$

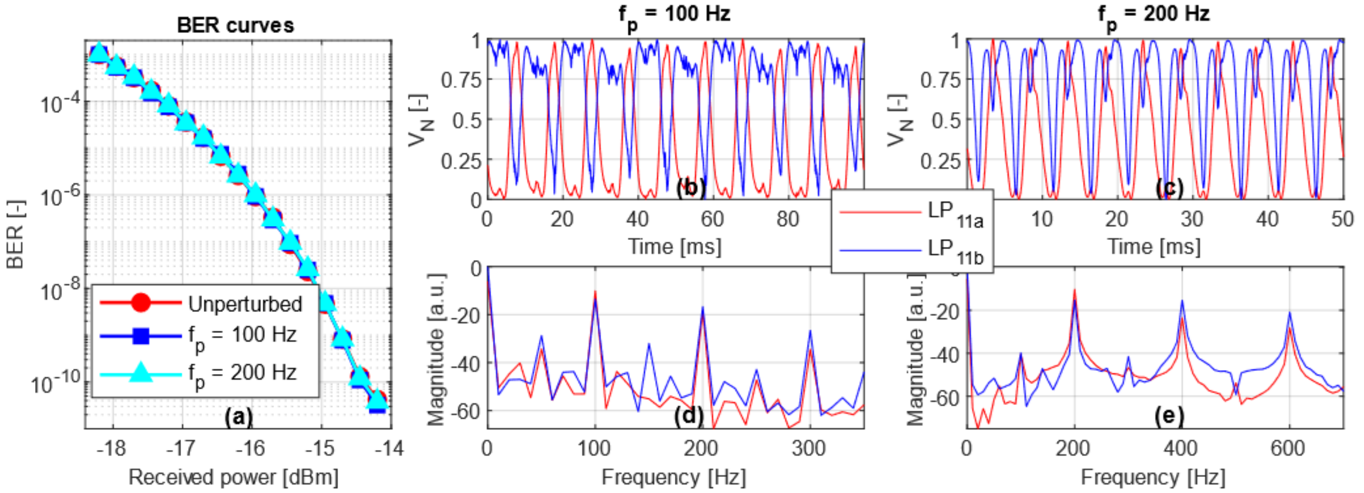

Fig. 2 Results of the coexistence transmission-sensing experiment. *(a)* Measured BER for the LP_{01} mode with unperturbed FMF (red line), FMF perturbed at 100 Hz (blue line), and FMF perturbed at 200 Hz (cyan line); *(b)-(c)* Normalized voltage V_N for LP_{11a} and LP_{11b} modes with f_p = 100 Hz (b), and f_p = 200 Hz (c); *(d)-(e)* power spectra of V_N with f_p = 100 Hz(d), and f_p = 200 Hz (e). For figures *(b)-(e)*, mode LP_{11a} is in red and mode LP_{11b} in blue.

and $s_{11b}(t)$, instead, are detected by two low-noise 100-kHz bandwidth PDs, and monitored by means of an oscilloscope.

3. Results and discussion

The results of the work are summarized in Fig. 2. For the transmission part, Fig. 2(a) shows the BER curves obtained in three different conditions: unperturbed fibre (red curve with circles), perturbed fibre with a 100 Hz vibration (blue curve with squares), and perturbed fibre with a 200 Hz vibration (cyan curve with triangles). Each curve is built by measuring the BER at 17 different power values, ranging from -18.2 dBm (corresponding to a 10^{-3} BER) up to -14.2 dBm (corresponding approximately to a $4 \cdot 10^{-11}$ BER). The three curves are superimposed, indicating that the mechanical perturbation has no relevant effect on the propagation of the TLC signal inside the FMF thanks to the high robustness of the fundamental mode. Therefore, both with and without the vibration, the 10-Gbit/s transmission performance is the same.

The sensing experiment results, are shown in Fig. 2(b)-(e). Since the variations are the most important aspect in this case, the waveforms reported in Fig. 2(b) and Fig. 2(c) are obtained starting from the oscilloscope acquired traces, applying a low-pass filter to erase the high-frequency noise without affecting the perturbation sinusoid harmonics (at least up to the third order), and finally performing an amplitude normalization using the law $V_N(t) = [s(t)-m]/(M-m)$, where s(t) is the acquired oscilloscope trace, and M and m are respectively its maximum and minimum values. Therefore, they represent the normalized received power in time for the LP_{11a} and LP_{11b} modes (red and blue line respectively) apart for a factor corresponding to the PDs transimpedance gain (which, being a constant, can be disregarded in the discussion). Fig. 2(b) shows the waveforms when a perturbation at 100 Hz is applied (mode LP_{11a} and LP_{11b} in blue), and Fig. 2(d) represents the spectra of the signals (with the same colour association); Fig. 2(c) and Fig. 2(e) play the same roles but for the 200 Hz perturbation. Two aspects can be immediately noted from these figures. The first one is that the LP_{11a} and LP_{11b} modes actually sense the perturbation that is applied to the FMF, and the waveforms periodicity is exactly f_p. Indeed, looking at the power spectra, it is evident the presence of a peak in correspondence of the used vibration frequency. This result derives from the variation of the amplitude coupling coefficients (describing the IMXT in the FMF) determined by the perturbation action: being the vibration periodical with frequency f_p, the coupling coefficients vary with the same behaviour, resulting in the sinusoidal variation of the optical power of LP_{11a} and LP_{11b} modes that can be seen. However, the effect that the perturbation is producing on the modes is completely different. First of all, the two power trends are complementary one with respect to the other: when LP_{11a} mode power increases, LP_{11b} mode power decreases (and viceversa). Second, especially looking at the spectra, it is easy to see that both modes suffer from higher-order harmonics due to the mechanical system non-linear response and non-idealities, but mode LP_{11b} is sensing them much more than mode LP_{11a}. This is particularly evident for the 200 Hz perturbation case. In fact, if we define a harmonics signal-to-noise ratio (H-SNR) as the difference between the power of the peak of the fundamental harmonic and the power of the peak of the second-order harmonic, we have a value of 13.25 dB for the LP_{11a} mode, and a value approximately equal to 0 dB for the LP_{11b} mode. The same holds true also for the comparison between the first and third harmonics with a 200 Hz vibration. The discussion can be extended to the 100 Hz perturbation case: the difference between the H-SNRs is more limited (8.33 dB for LP11a and 3.16 dB for LP11b), but the conclusions are the same. This shows in first place the effectiveness of using a FMF and a non-ideality such as IMXT to sense perturbations (vibrations in our case) of the system. Secondly, these results allow to use different modes, which are variously affected by external factors, for different sensing purposes.

4. Conclusions

We have presented and experimentally demonstrated a system integrating transmission and sensing employing an innovative 15-mode FMF with a M-MUX and M-DEMUX pair. The system uses the multiple modes and the IMXT among them as an opportunity to merge the two purposes. Considering the two second-order modes LP_{11a} and LP_{11b}, we were able to detect a vibrational perturbation applied to the fibre exploiting the IMXT variation caused by the vibration itself. At the same time, we confirmed the transmission of a TLC signal over the FMF fundamental mode, without impairments by the mechanical vibrations.

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References

[1] Mitra, Partha P., and Jason B. Stark. "Nonlinear limits to the information capacity of optical fibre communications." *Nature* 411.6841 (2001): 1027-1030.

[2] Wang, Meng, et al. "Few-mode fiber based Raman distributed temperature sensing." *Optics Express* 25.5 (2017): 4907-4916.

[3] Liu, Yinping, et al. "Long-range Raman distributed temperature sensor with high spatial and temperature resolution using graded-index few-mode fiber." *Optics express* 26.16 (2018): 20562-20571.

[4] Li, An, et al. "Few-mode fiber multi-parameter sensor with distributed temperature and strain discrimination." *Optics letters* 40.7 (2015): 1488-1491.

[5] P. Sillard et al., "Low-differential-mode-group-delay 9-LP-mode fiber", J. Lightw. Technol., vol. 34, no. 2, pp. 425-430, 2016.

[6] G. Labroille, B. Denolle, P. Jian, P. Genevaux, N. Treps and J.-F. Morizur, "Efficient and mode selective spatial mode multiplexer based on multi-plane light conversion", Opt. Exp., vol. 22, no. 13, pp. 15599-15607, 2014.