FEW-MODE FIBRE DELAY LINES WITH INSCRIBED LONG PERIOD GRATINGS FOR RADIOFREQUENCY SIGNAL PROCESSING

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Keywords: Microwave Photonics; optical fiber devices; fiber gratings.

Abstract

We propose and experimentally demonstrate distributed radiofrequency signal on a few-mode-fibre device. The inscription of long period gratings at specific locations along the fibre allows the excitation of the higher-order modes while adjusting the modal group delays required for sample true time delay line operation.

1 Introduction

Despite space-division multiplexing (SDM) fibres [1] emerged as distribution media for core and metro optical networks, they can be applied to a wider range of scenarios from radio access networks to microwave photonics (MWP) signal processing and sensing [2], benefiting in terms of compactness, weight, and performance versatility. We have recently proposed different SDM solutions, based on either multicore [3], [4], or few-mode (FMF) [5] fibres that act as sampled true time delay lines (TTDLs), which are the basis of most radiofrequency (RF) signal processing functionalities, such as signal filtering, optical beamforming and arbitrary waveform generation [2]. In [5], we reported 3-sampled TTDL operation on a 60-m 4-LP-mode fibre where 3 modes were injected at the fibre input and a long period grating (LPG) was inscribed to adjust the time delay of the sample associated to the LP_{02} mode.

Here, we improve the TTDL performance by extending the operation up to 4 signal samples and making the system independent of any distribution link (either single-mode or few-mode) that may be placed before the TTDL since only the LP_{01} mode needs to be injected into the fibre. A set of 3 LPGs inscribed at proper positions along the FMF-based device excite the remaining higher-order modes with the pertinent sample amplitude and group delay required for TDDL operation. We validate the proposed device by successfully demonstrating RF signal filtering on different link conditions.

2 True time delay line concept

We propose to implement a sampled TTDL over a 4-LP-mode step-index fibre provided by Prysmian with a 15-µm core diameter, a 125-µm cladding diameter and a refractive index contrast of 1.1 %. The typical mode differential group delays (DGDs) relative to LP_{01} mode per unit length, at a wavelength of 1550 nm, are 4.4, 8.9 and 7.9 ps/m, respectively for LP_{11}, LP_{21} and LP_{02} modes. The chromatic dispersions are 21, 26, 19 and 8 ps/nm/km for LP_{01}, LP_{11}, LP_{21} and LP_{02} modes at 1550 nm. Mode multiplexers from CaiLabs inject/extract the optical signal into/from each mode [6].

Sampled TTDL operation for discrete-time signal processing requires constant basic differential delays T between adjacent samples, [2]. In our approach, the signals carried by the 4 LP modes at the FMF output correspond to the 4 TTDL samples. Initially, one can see that the mode DGDs do not allow TTDL operation unless some time-delay engineering is implemented, as we previously discussed in [5]. To obtain 4 equally-spaced samples, we propose to excite only the fundamental mode at the FMF input. Then, 3 mode converters based on LPGs are inscribed at certain positions along the fibre to couple the signal to the remaining modes while adjusting the delay of the corresponding samples. We inscribed 3 LPGs to convert: 1) LP_{01} to LP_{11} mode; 2) LP_{11} to LP_{21} mode; and 3) LP_{01} to LP_{02} mode. Ideally, every LPG should couple 50% of the power from the coming to the generated mode, so that the output samples would have similar amplitudes.

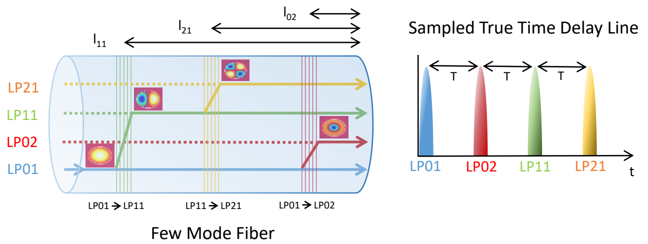

Fig. 1 TTDL scheme implemented on FMF by using 3 LPGs as mode converters.

As Fig. 1 shows, at a given distance l_{11} from the fibre output, half the power of LP_{01} will couple to LP_{11} mode in the corresponding LPG mode converter. The mode time delay is then given by $t_{01} = l_{11}\tau_{01}$ and $t_{11} = l_{11}\tau_{11}$, respectively for LP_{01} and LP_{11}, being τ_{lm} the group delay per unit length of the LP_{lm} mode. At a given distance l_{21} from the fibre output, a second LPG is set to couple half the power of LP_{11} into LP_{21} mode, where $0 < l_{21} < l_{11}$, so that the delay of the sample carried by LP_{21} mode is given by $t_{21} = (l_{11} - l_{21})\, \tau_{11} + l_{21}\, \tau_{21}$. In a similar way, at a distance l_{02} from the fibre output, where $0 < l_{02} < l_{11}$, the last LPG is inserted to couple half the remaining LP_{01} power into LP_{02} mode, so that the sample delay from LP_{02}

mode satisfies $t_{02} = (l_{11} - l_{02})\ \tau_{01} + l_{02}\ \tau_{02}$. For TTDL operation, the time delay difference between the samples coming from modes LP_{11}, LP_{21}, LP_{02} related to LP_{01} must then satisfy:

$$\begin{pmatrix} t_{02}-t_{01} \\ t_{11}-t_{01} \\ t_{21}-t_{01} \end{pmatrix} = \begin{pmatrix} \tau_{02}-\tau_{01} & 0 & 0 \\ 0 & \tau_{11}-\tau_{01} & 0 \\ 0 & \tau_{11}-\tau_{01} & \tau_{21}-\tau_{11} \end{pmatrix} \begin{pmatrix} l_{02} \\ l_{11} \\ l_{21} \end{pmatrix} = \begin{pmatrix} T \\ 2T \\ 3T \end{pmatrix}, \qquad (1)$$

Once we fix T and the desired operation wavelength, we can easily obtain the lengths l_{11}, l_{21} and l_{02} from (1).

3 Inscription of LPGs as mode converters

An LPG can be understood as a periodic perturbation on the refractive index of an optical fibre that can be generated by applying pressure points mechanically or by modifying permanently the core refractive index by using ultraviolet (UV) radiation. These periodic perturbations couple the energy from one of the propagating modes to another forward-propagating mode (or cladding mode) at a specific wavelength λ_B given by the Bragg condition [7]: $\lambda_B = \Lambda\,|n_{eff,1} - n_{eff,2}|$, where Λ is the perturbation period, and $n_{eff,1}$ and $n_{eff,2}$ are the effective indices of both modes involved.

We inscribed 3 different LPGs using direct point-by-point UV radiation provided by a frequency-doubled argon-ion laser emitting an output power of 60 mW at 244 nm. Prior to inscription, the fibre was hydrogen-loaded at ambient temperature for 2 weeks at a constant pressure of 50 bar to increase its UV absorption capacity. We set the width of the light spot at the inscription point to 100 µm and swept along the fibre at a rate of 7 µm/s until the required period is completed. The length of every LPG was set in real time during the inscription once the energy begins to couple back to the input mode. For the asymmetrical mode conversions (i.e., LP_{01} to LP_{11} and LP_{11} to LP_{21}), the LPGs were inscribed with a certain tilt to optimize the mode conversion and reduce the total length. We set the angle to 15º measured perpendicularly to the fibre propagation axis. We selected the LPG periods for mode conversion around 1560 nm. Table 1 summarizes the LPG periods and lengths.

Table 1 Characteristics of the inscribed LPGs

	LP_{01} to LP_{11}	LP_{11} to LP_{21}	LP_{01} to LP_{02}
Period (µm)	685.0	545.2	262.5
Length (mm)	59.64	40.21	34.91
Tilt (deg)	15	15	0

After the inscription, heat annealing was done to assure LPG stabilization by heating up the fibre to 200 ºC for 2 hours [8]. Figure 2 shows the optical spectra for the three LPGs after the whole process. A minimum extinction ratio on the transmitter mode of -10 dB is achieved in all cases at λ_B, and almost all power is coupled to the mode excited, which is by far sufficiently to allow 50% coupling efficiency at a given wavelength near λ_B. Note that, respectively for Figs. 2 (a) and (b), the sum of both spatial modes $LP_{11a} + LP_{11b}$ and $LP_{21a} + LP_{21b}$ is represented, since the high coupling between them forces the signal to travel shared in both modes inevitably. The mode optical output powers can be adjusted by slightly tuning the operating wavelength to improve or decrease the mode conversion efficiency. At the wavelength of $\lambda_0 = 1558$ nm, the mode conversion efficiency for each LPG is almost -3 dB, which allows us to keep a similar amplitude level in all samples at the fibre output.

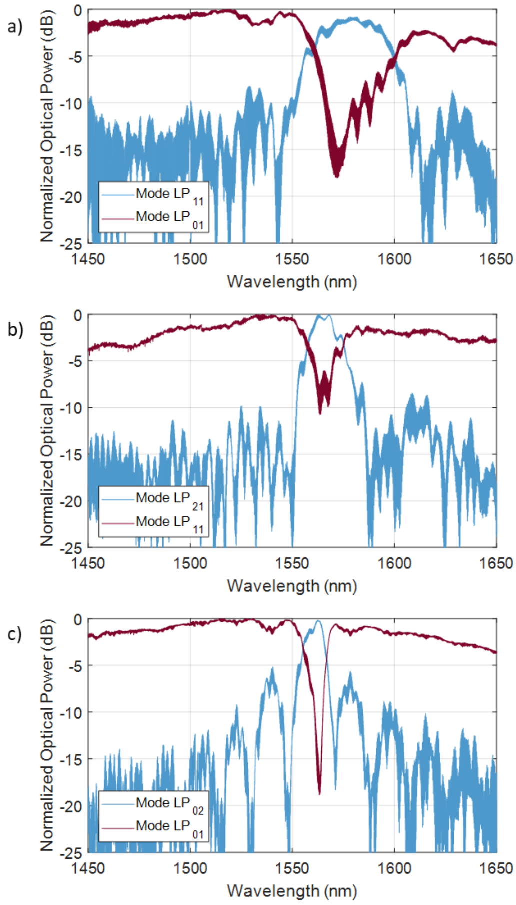

Fig. 2 Measured optical spectral response for the modes involved in the inscribed LPGs.

4 Experimental validation and application to MWP signal filtering

We have experimentally demonstrated the proposed FMF-based TTDL for an operation wavelength of $\lambda_0 = 1558$ nm. We first measured the mode DGDs per unit length at λ_0 by using an optical interferometric-based technique over a small piece of FMF, [9]. The longitudinal positions of the LPGs were then calculated from (1) considering a sample differential delay of T = 100 ps, which translates into a RF filtering free spectral range (FSR) of 10 GHz: l_{11} = 44.4, l_{21} = 22.1 and l_{02} = 11.6 m. Since only the fundamental mode is launched at the fibre input, the total length of the TTDL corresponds to the distance between the first LPG and the mode demultiplexer, l_{11}.

The validation of the TTDL was carried out by the implementation of MWP signal filtering. First, we used the 44.4-m TTDL fibre segment directly spliced to both mode multiplexers, as Fig. 3 shows. The optical signal coming from a broadband source (BS) followed by a 0.1-nm-bandwith

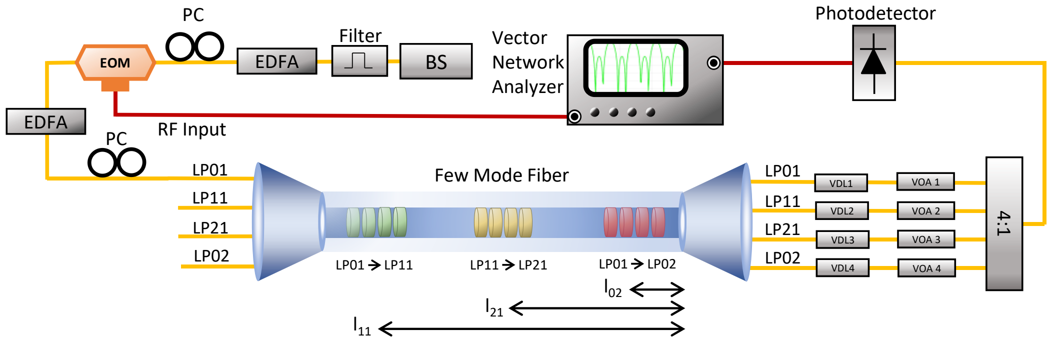

Fig. 3 Experimental setup for RF signal filtering based on the implemented 4-sample delay line.

optical filter is modulated in single-sideband by an electro-optical intensity modulator with the RF signal generated by the vector network analyser (VNA). The broadband source is required to avoid optical coherent interference. An additional polarization controller at the TTDL input sets the optimum polarization for the subsequent mode conversions. The signal is injected to the FMF fundamental mode, which properly distributes the signal to the rest of modes through the LPGs. Then, all output modes are demultiplexed and coupled together before detection. We include variable optical delay lines (VDLs) at the TTDL output to compensate any inference to the DGD that is not produced by the TTDL itself but by external mismatches (as, for instance, those produced by inevitable differences in the lengths of the coupler arms or multiplexers). We use variable optical attenuators (VOAs) to finely equalize the output power of the samples for uniform amplitude windowing.

In a second experiment, the same TTDL is used to build the same MWP filter, but a distribution 1-km FMF link is inserted between the mode multiplexer and the TTDL. At the TTDL operation wavelength, only the fundamental mode is injected to the FMF link to maintain the TTDL performance. We must note that at any other wavelength outside the LPGs operation spectrum, all modes can behave as mere distribution channel media (i.e., without processing the signal) without any significant degradation caused by the LPGs.

Figure 4 shows the measured 4-tap filter transfer functions as compared to the theoretical one, where the black dotted line corresponds to the computed ideal response with uniform sample distribution; the green-dashed line to the experimental response when only the 44.4-m TTDL segment is considered; and the red-solid line to the experimental response when the 1-km FMF link is added before the TTDL. We see that both experimental results are in a good agreement with the theory up to a frequency of 40 GHz. Slight discrepancies in the main to sidelobe levels come as a consequence of random variations in the amplitude of the TTDL samples that may be produced mainly by: (1) small temperature variations or vibrations that affect the mode conversion efficiency of the LPGs, since these are not protected by any fibre coating; and (2) low intermodal crosstalk, which is more significant in the 1-km FMF link

The distortion we appreciate at high frequencies for the 1-km link is attributed to the frequency limitations of some of the RF components employed, such as cables, transitions and a 90º hybrid. These RF components are required to implement single-sideband modulation, which is actually needed to avoid high-frequency fading effects arisen by the use of a broadband source when the 1-km link is inserted, [10].

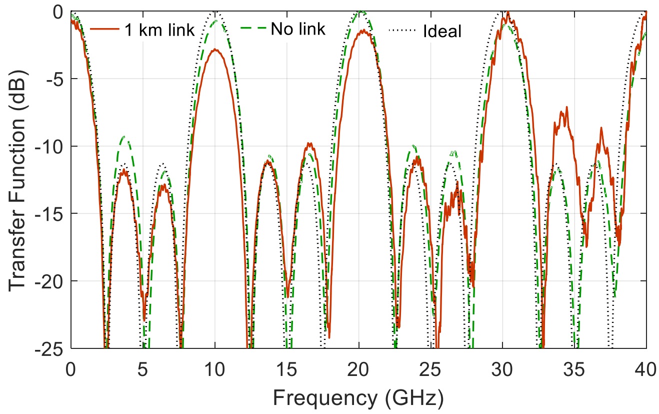

Fig. 4 RF signal filter response. Black dotted line: theoretical; green-dashed line: measured for the TDDL segment; red-solid line: measured for 1-km FMF link + TTDL segment.

5 Conclusions

We have proposed and experimentally demonstrated a new approach for 4-sample TTDL operation, basis of time-discrete RF signal processing, built upon a 4-LP-mode-based device. While only the fundamental mode is injected at the fibre, a set of 3 LPGs excite the remaining LP modes at convenient fibre longitudinal positions so that the sample delays are adjusted to provide TTDL operation (i.e., constant differential delay). We successfully demonstrated RF signal filtering with an FSR of 10 GHz on a 44.4-m FMF segment, demonstrating as well that this scheme can be combined with a previous 1-km distribution FMF link. Other RF processing applications such as optical beamforming or arbitrary waveform shaping can also be implemented using this approach in short-reach direct-detection fibre-wireless scenarios.

6 Acknowledgements

This research was supported by the ERC Consolidator Grant 724663, Universitat Politècnica de València PAID-01-18 scholarship for J. Madrigal and the Spanish MINECO through: TEC2016-80150-R Project, BES-2015-073359 scholarship for S. García, IJCI-2017-32476 fellowship for D. Barrera and RYC-2014-16247 fellowship for I. Gasulla. We thank Prysmian for providing the FMF and Cailabs for providing the mode multiplexers.

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