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Sampled true time delay line operation by inscription of long period gratings in few-mode fibers

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Abstract: We propose and experimentally demonstrate distributed microwave photonics signal processing over a few-mode fiber link by implementing 4-sample true time delay line operation. The inscription of a set of long period gratings at specific locations along the few-mode fiber allows the excitation of the higher-order modes while adjusting the individual sample group delays and amplitudes that are required for sampled true time delay line behavior. Since solely the injection of the fundamental mode at the few-mode fiber input is required, we render this signal processing system independent of any preceding fiber link that may be required in addition to distribute the signal. We experimentally validate the performance of the implemented true time delay line when applied to radiofrequency signal filtering.

1. Introduction

Space-division multiplexing (SDM) considering both multicore (MCF) and few-mode (FMF) fiber approaches emerged as a promising solution to overcome the optical network capacity crunch while supporting cost-effective capacity scaling [1]. Although SDM fibers were conceived from the beginning as distributed media for core and metro optical networks, they can be applied to a variety of scenarios including centralized radio access networks for wireless communications [2], data-center interconnects as well microwave photonics (MWP) signal processing and sensing [3]. In the context of MWP, we have recently proposed and demonstrated the exploitation of different SDM technologies to implement distributed signal processing for radiofrequency (RF) with associated benefiting in terms of compactness, weight, and performance versatility. We demonstrated that approaches based on homogeneous MCFs with inscribed fiber Bragg gratings (FBGs) [4], heterogeneous MCFs [5] or FMFs [6] can act as sampled true time delay lines (TTDLs), which are the basis of most RF signal processing functionalities, such as microwave signal filtering, optical beamforming for phased-array antennas and arbitrary waveform generation [3].

Regarding FMFs, we have reported 3-sample TTDL operation for RF signals on a 60-m 4-LP-mode fiber where 3 of the propagated modes acted as the carriers for the delay line samples. In that work, the 3 modes involved were injected at the fiber input and a long period grating (LPG) was inscribed to generate and adjust the time delay of the sample associated to the LP_{02} mode. However, since that scheme requires to excite 3 specific modes at the input, it does not allow to combine the signal processing 60-m FMF link with any preceding singlemode or FMF distribution link that may be required, for instance, in radio access network scenarios.

In this paper, we improve the TTDL performance of the FMF link by extending the TTDL operation up to 4 signal samples, therefore leveraging the 4 spatial modes the fiber supports. In addition, we render the TTDL system independent of any previous distribution link that may be needed to transmit the data signal before actually processing it. We achieve this by

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exciting only the fundamental mode while the remaining 3 higher-order modes are excited by 3 LPGs that are inscribed at proper positions along the FMF. These LPG-based mode converters excite the LP_{11}, LP_{21} and LP_{02} modes with the pertinent sample amplitude and group delay required for TDDL operation. We experimentally validate the proposed device by successfully demonstrating RF signal filtering on different FMF link conditions.

2. Principle of operation

We present a sampled TTDL built over a 4-LP-mode step-index fiber, which is provided by Prysmian. The fiber has a 15-µm-diameter core surrounded by a 125-µm-diameter cladding with a relative index contrast of 1.1%. The typical mode differential group delays per unit length (DGDs) relative to LP_{01} mode 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 respectively for LP_{01}, LP_{11}, LP_{21} and LP_{02} modes at 1550 nm. The light is injected/extracted into/from each mode by using mode multiplexers based on multi-plane light conversion that are provided by Cailabs. The average insertion losses and maximum modal crosstalk at 1550 nm for the pair comprising the mode multiplexer and demultiplexer when they are spliced together are 7.4 dB and below −20 dB, respectively.

Sampled TTDL operation for discrete-time signal processing requires a constant basic differential delay T between adjacent samples [3]. In our approach, the signals carried by the 4 LP modes at the FMF output correspond to the 4 TTDL samples. For each fiber mode n, the group delay per unit length τ_n can be expanded in first-order Taylor series around an anchor wavelength λ_0 as:

$$\tau_n(\lambda) = \tau_n(\lambda_0) + D_n(\lambda_0)(\lambda - \lambda_0), \tag{1}$$

where $n = \{01, 11, 21, 02\}$ and D_n is the chromatic dispersion parameter of n-th mode at λ_0. Particularizing Eq. (1) with the current fiber mode parameters indicated above, we see that there is no solution for 4-sample TTDL operation in the C + L optical communications bands unless some time-delay engineering is implemented. To obtain 4 equally-spaced time samples, we propose to excite only the fundamental mode LP_{01} at the FMF input. Then, 3 mode converters based on LPGs are inscribed at certain positions along the fiber to couple the signal to the remaining modes while adjusting the amplitude and delay of the corresponding samples. The 3 LPGs convert: 1) LP_{01} to LP_{11} mode; 2) LP_{11} to LP_{21} mode; and 3) LP_{01} to LP_{02} mode. Each LPG must couple 50% of the power from the incoming to the generated mode to maintain the output samples with similar power level. Figure 1(a) depicts this concept.

Figure 1(b) shows the temporal evolution of the four samples referred to the first sample, t-t_{01}, as a function of the propagation length z. At a given distance l_{11} from the fiber output, half the power of LP_{01} mode (blue) couples to LP_{11} mode (green) in the corresponding LPG mode converter. At the fiber output, the time delay of these samples is given by $t_{01} = l_{11}\tau_{01}$ and $t_{11} = l_{11}\tau_{11}$, respectively for sample 1 (output LP_{01} mode) and sample 3 (output LP_{11} mode), being τ_n the group delay per unit length of the n-th LP mode, $n = \{01, 11, 21, 02\}$, as given by Eq. (1). At a given distance l_{21} measured from the fiber output, a second LPG is inscribed to couple half the power of LP_{11} into LP_{21} mode (yellow), $0 < l_{21} < l_{11}$, so that the delay of sample 4 (output 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 fiber output, $0 < l_{02} < l_{11}$, the last LPG is inserted to couple half the remaining LP_{01} power into LP_{02} mode (red), so that the delay of sample 2 (output LP_{02} mode) satisfies $t_{02} = (l_{11} - l_{02})\tau_{01} + l_{02}\tau_{02}$. For TTDL operation the time delay difference coming from modes LP_{11}, LP_{21}, LP_{02} related to LP_{01} mode must satisfy:

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$$\begin{pmatrix} t_{02}-t_{01} \\ t_{11}-t_{01} \\ t_{21}-t_{01} \end{pmatrix} = \begin{pmatrix} \tau_{02}-\tau_{01} & 0 & 0 \\ 0 & \tau_{11}-\tau_{01} & 0 \\ 0 & \tau_{11}-\tau_{01} & \tau_{21}-\tau_{11} \end{pmatrix} \begin{pmatrix} l_{02} \\ l_{11} \\ l_{21} \end{pmatrix} = \begin{pmatrix} T \\ 2T \\ 3T \end{pmatrix}. \tag{2}$$

Once we fix T and the operation wavelength, we obtain the lengths l_{11}, l_{21} and l_{02} from Eq. (2).

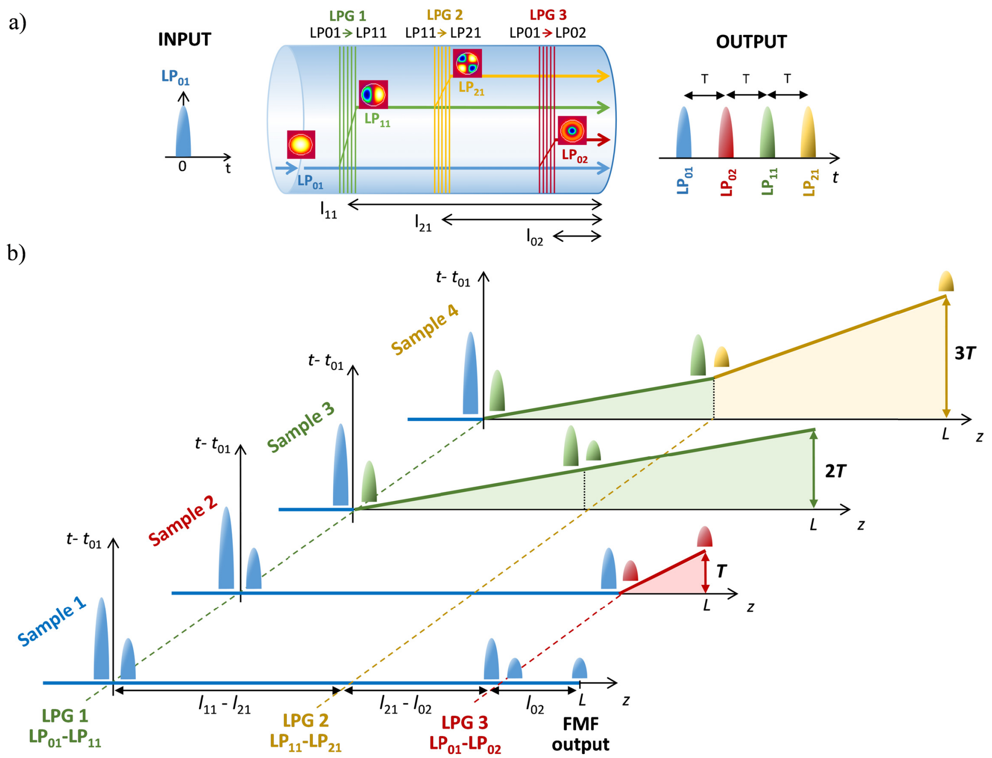

Fig. 1. TTDL principle of operation: a) Scheme of the FMF-based TTDL built upon the inscription of 3 LPGs; b) Evolution of the group delay normalized to the first sample group delay (t-t_{01}) of the 4 TTDL samples with the propagation length z. LPG: long period grating.

3. Mode conversion using LPGs

An LPG introduces a periodic perturbation on the refractive index of an optical fiber that can be generated either 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]: $\lambda_B = \Lambda(n_{eff,1} - n_{eff,2})$, being Λ the perturbation period, and $n_{eff,1}$ and $n_{eff,2}$ the effective indices of the modes involved. Mode conversion by using LPGs has been demonstrated in previous work [6,8].

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 an optical wavelength of 244 nm. Prior to the inscription, we hydrogen loaded the FMF at ambient temperature for 2 weeks at a constant pressure of 50 bar to increase the fiber UV absorption capacity. We set the width of the light spot at the inscription point at 100 µm and swept along the fiber 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 process once the energy began to couple back to the input mode. To optimize the LPG length for the asymmetrical mode conversions (i.e., LP_{01} to LP_{11} and LP_{11} to LP_{21} transformations), the LPGs were inscribed with a specific tilt of 15°,

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measured perpendicularly to the fiber longitudinal axis. This tilt angle was determined experimentally and is given by a tradeoff between a bigger angle, which would produce a reduction on the visibility of the fringe pattern, and a lower angle, which would reduce the coupling efficiency and thus increase the coupling length. We must note that the power conversion efficiency of these asymmetrical modes strongly depends on the polarization state of the incoming optical field, so we must ensure operation at the optimal polarization state. Table 1 summarizes the main parameters describing the inscribed LPGs.

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 ensure LPG stabilization by heating up the fiber to 200 °C for 2 hours [9], accelerating the degradation effects derived from hydrogen diffusion and refractive index thermal decay, as reported in [6]. Figure 2 shows the optical spectrum in transmission of the three LPGs for all the LP modes once the LPGs reached a stable state after heat annealing. In the case of the asymmetrical LP modes, we represent the sum of both degenerate spatial modes, that is, $LP_{11a} + LP_{11b}$ and $LP_{21a} + LP_{21b}$. The worst-case extinction ratio on the input mode is −10 dB (i.e., LP_{11} to LP_{21}) at the optical wavelength λ_B, where almost all power is coupled to the mode excited, which is by far sufficient to allow the required 50% coupling efficiency for our TTDL scheme at a given wavelength near λ_B. The desired mode optical output powers can be adjusted by slightly tuning the operating wavelength to modify the mode conversion efficiency. At the wavelength of λ_0 = 1558 nm, the mode conversion efficiencies are 0.58, 0.54 and 0.46 for each LPG (LP_{01} to LP_{02}, LP_{01} to LP_{11} and LP_{11} to LP_{21}, respectively), which allows to keep a similar amplitude level in all samples at the fiber output. Regarding crosstalk raised by the LPGs, we can see intermodal coupling values below −18 dB in all cases for the operating wavelength of 1558 nm, which are mainly due to the refractive index perturbation introduced by the LPG itself.

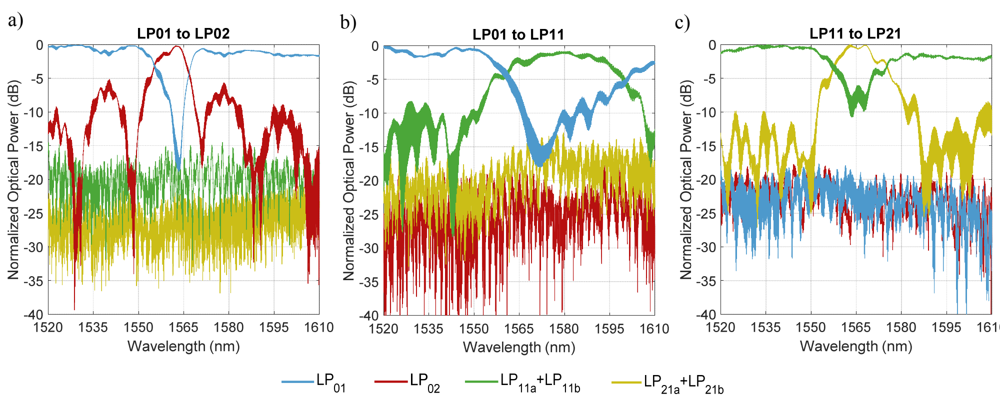

Fig. 2. Measured optical spectral response of each LPG in transmission for all the LP modes propagated through the FMF: a) LP_{01} to LP_{02} conversion; b) LP_{01} to LP_{11} conversion; c) LP_{11} to LP_{21} conversion.

4. Experimental validation: application to MWP signal filtering

We have experimentally evaluated the performance of the implemented FMF-based TTDL in the context of MWP signal filtering. We set the operation wavelength to λ_0 = 1558 nm and we looked for a sample differential delay of T = 100 ps, which translates into a RF filtering free spectral range (FSR) of 10 GHz. Prior to the LPG inscription, we characterized the DGDs of

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the fiber modes at λ_0 to properly set the positions of the LPGs. We measured the mode DGDs per unit length at λ_0 by using an optical interferometric-based technique [10] over a small piece of FMF, getting for each mode τ_{11}- τ_{01} = 4.5 ps/m, τ_{21}- τ_{01} = 9.0 ps/m and τ_{02}- τ_{01} = 8.6 ps/m. Inserting these values into Eq. (2) for T = 100 ps, the longitudinal positions where the LPGs should be inscribed resulted in: l_{11} = 44.4, l_{21} = 22.1 and l_{02} = 11.6 m. Since only the fundamental mode is launched into the fiber, the total length of the TTDL corresponds to the distance between the first LPG and the mode demultiplexer, l_{11}.

The application of the TTDL to MWP signal filtering was carried out by considering two different scenarios depending on the existence of a distribution FMF link in addition to the processing FMF device. In the first scenario, we consider only the 44.4-m processing FMF segment, which was directly spliced to both mode multiplexers, as the upper arm at the FMF input in Fig. 3 shows. The optical signal coming from a broadband source (BS) followed by a 0.1-nm-bandwith optical filter is amplified by an Erbium-doped fiber amplifier (EDFA) and then modulated in single-sideband by an electro-optical intensity modulator (EOM) with the RF signal generated by a vector network analyzer (VNA). The broadband source is required to avoid optical coherent interference between the different signal samples. An additional polarization controller at the TTDL input sets the optimum polarization required for the subsequent LPG mode conversions. The optical signal coming from the singlemode fiber is then injected to the FMF fundamental mode, which properly distributes the signal to the rest of modes through the LPGs. After the TTDL device, all 4 output modes are demultiplexed and coupled together before detection. We must note that, since we are using direct detection without Multiple Input Multiple Output (MIMO) signal processing, there is a strong coupling between the degenerate modes that cannot be avoided and, therefore, it is preferable to select the degenerate mode that carries most of the optical power associated to that sample. In our work, the majority of the power was received in LP_{11a} and LP_{21a} modes with a low level of losses. In a real application scenario, optical or electrical diversity combining techniques could be introduced to combine the degenerate modes properly [11].

We include variable optical delay lines (VDLs) at the TTDL output to compensate any small inference to the desired DGDs that is not produced by the TTDL itself but by external mismatches (as, for instance, those produced by inevitable differences in the fiber lengths of the coupler arms or multiplexers). We use variable optical attenuators (VOAs) to finely equalize the sample output powers to achieve uniform windowing.

In the second scenario, we included just before the TTDL device, 1 km of additional FMF as a distribution link that may be required in a real MWP scenario, such as radio access networks for wireless communications. This is depicted by the lower arm at the FMF input in Fig. 3. At the TTDL operation wavelength (in this case 1558 nm), this additional link propagates only the fundamental mode LP_{01}, what allows to preserve the TTDL performance. We must note that at any other wavelength outside operation spectrum of the set of LPGs, all LP modes can behave as mere distribution channel media (i.e., avoiding any signal processing) without any significant degradation caused by the LPGs.

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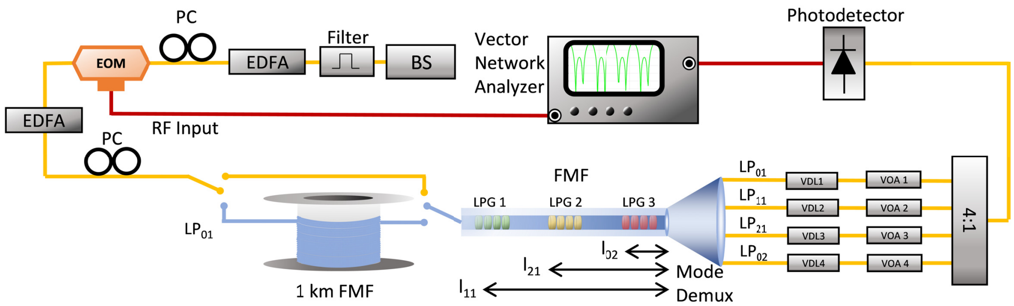

Fig. 3. Experimental setup for MWP signal filtering based on the 4-sample FMF TTDL. BS: broadband source; EDFA: Erbium-doped fiber amplifier; EOM: electrooptic modulator; PC: polarization controller; VDL: variable delay line; VOA: variable optical attenuator.

Figure 4 depicts the measured RF 4-tap filter transfer functions for both scenarios as compared to the theoretical transfer function. Here, the black dotted line corresponds to the computed ideal response with uniform sample distribution; the green-dashed line corresponds to the experimental response when only the 44.4-m TTDL segment is considered (first scenario); and the red-solid line corresponds to the experimental response when we added the 1-km FMF link (second scenario). We see that the experimental results in both scenarios are in a good agreement with the theoretical ones up to a RF frequency of 40 GHz. Slight discrepancies in the main-to-sidelobe levels come as a consequence of random variations in the TTDL sample amplitudes 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 fiber coating; and (2) low intermodal crosstalk between the LP groups of modes, which is more significant (as expected) when we introduce the 1-km FMF link.

In the second scenario, we appreciate some distortion at frequencies approximately above 27 GHz that are caused by frequency limitations of some of the RF components employed, such as cables, transitions and a 90° 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 [12].

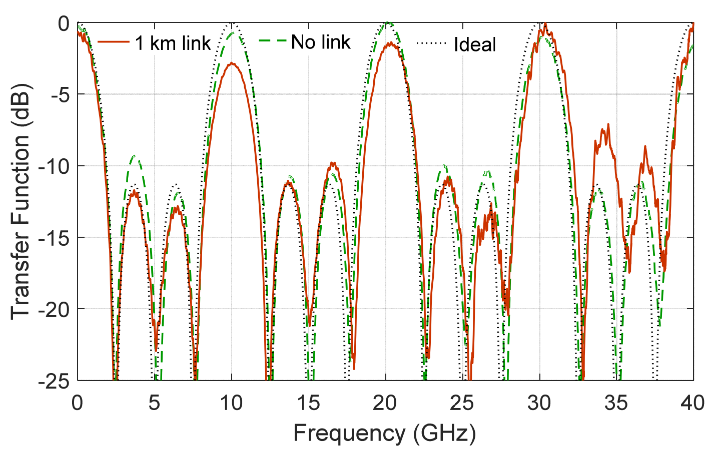

Fig. 4. Measured MWP filter transfer function for both scenarios. Black dotted line: theoretical response; green-dashed line: measured response for the TDDL segment (first scenario); red-solid line: measured response for 1-km FMF link + TTDL segment (second scenario).

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5. Conclusions

Within the framework of fiber-distributed MWP signal processing, we have proposed and experimentally demonstrated an FMF-based sampled TTDL for RF frequencies around 10 GHz. Three LPGs conveniently inscribed along the 44.4-m FMF link provide 2 fundamental functionalities: (1) in-fiber excitement of the 3 higher-order modes and (2) tailoring of both amplitude and group delay of the signal samples as to accomplish TTDL operation. Among the variety of discrete-time signal processing applications that can be built by means of this TTDL, we demonstrated here a 4-tap periodic RF filter with an FSR of 10 GHz. We demonstrated as well that the 44.4-m processing device can coexist in short-reach radio-over-fiber scenarios, such as a radio access networks, where an additional distribution link may be required, showing no significant degradation over the TTDL performance.

We would like to point out that the rationale beyond the use of a single FMF instead of N parallel SMFs for N-sample TTDL operation lies in the reduction of size and weight by a factor N. This is an important feature for network deployment in next-generation fiber-wireless communications systems where, for instance, optical beamforming networks for phased array antennas will cope with a high number of radiating elements featuring smaller sizes. Although we have demonstrated here a 4-sample TTDL, the gain in compactness will grow more significant if we scale up the number of samples.

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