DEMONSTRATION OF DISTRIBUTED RADIOFREQUENCY SIGNAL PROCESSING ON HETEROGENEOUS MULTICORE FIBRES

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Abstract

We experimentally demonstrate for the first-time to our knowledge distributed radiofrequency signal processing performed by a heterogeneous multicore fibre link. A trench-assisted 7-core fibre, where each core presents a different chromatic dispersion behaviour, is custom-engineered to operate as a 2D sampled true time delay line.

1 Introduction

Up to date, multicore fibres (MCFs) have amply demonstrated their capability as a compact solution for high-capacity digital communications, [1]. They exhibit great potential not only to distribute parallel channels but also to process the signal while it is being distributed. This is particularly interesting for next-generation fibre-wireless communications scenarios, as 5G and the Internet of Things, which demand on higher degrees of capacity, connectivity, flexibility and compactness, [2]. In this context, we have previously proposed the exploitation of heterogeneous MCFs as compact "fibre-distributed signal processing" elements, that is, implementing simultaneously both radiofrequency (RF) access distribution (including multiple antenna connectivity) and broadband microwave photonics (MWP) signal processing [3], [4]. The core concept lies in the custom design of MCFs to act as tuneable sampled true time delay lines (TTDLs), which are the basis of many MWP signal processing functionalities, such as signal filtering, radio beam-steering, multi-cavity optoelectronic oscillation and arbitrary signal generation, [5].

A TTDL provides a set of different time-delayed signal samples that are characterized by a constant differential delay $\Delta\tau$ between them. Therefore, a TTDL built upon a heterogeneous MCF implies that each core *n* features an independent group delay. The group delay can be expanded in 2nd-order Taylor series around an anchor wavelength λ_0 as $\tau_n(\lambda) = \tau_n(\lambda_0) + D_n (\lambda-\lambda_0) + S_n/2 (\lambda-\lambda_0)^2$, where D_n is the chromatic dispersion and S_n the dispersion slope of core *n* at λ_0. In [4], we showed that TTDL operation requires D_n to increase linearly with the core number while guaranteeing a linear behaviour of the differential group delays within our tuning optical wavelength range. We provided different MCF designs for tuneable 2-dimensional (both spatial and wavelength) TTDL performance while keeping a low crosstalk and robustness against fibre curvatures.

In this paper we report, for the first time to our knowledge, the experimental demonstration of tuneable sampled TTDL operation on a 5-km heterogeneous 7-core fibre link. Each core is fabricated to have a different refractive index profile in terms of both core dimensions and dopant concentrations. The TTDL is experimentally validated by implementing reconfigurable 2-dimensional RF signal filtering.

2 Multicore fibre true time delay line: design and fabrication

We designed a dispersion-engineered heterogeneous MCF to behave as a group-index-variable delay line. It comprises 7 trench-assisted cores placed in a hexagonal disposition (core pitch of 40 μm) inside a 150-μm cladding. The core refractive index profiles consist of a GeO_2-doped core (core radius a_1 and core-to-cladding relative index difference Δ_1) surrounded by a pure silica inner cladding (core-to-trench distance a_2) and a 1%-Fluorine-doped trench (trench width a_3).

We designed the MCF using the numerical software *Fimmwave* from Photon Design. The fibre core parameters were properly chosen to fulfil the TTDL requirements, [4]. The crosstalk robustness was managed by designing neighbouring cores as different as possible in terms of effective index, [6]. By properly tailoring the design parameters a_1, a_2, a_3 and Δ_1, we set a common group delay to all cores at an anchor wavelength λ_0 = 1530 nm and a range of chromatic dispersion D_n values from 14.3 up to 20.3 ps/km/nm with a 1-ps/km/nm incremental dispersion at λ_0, respectively for cores 1 up to 7. The cladding-to-trench relative index difference is 0.321%. The minimum effective index difference between adjacent cores resulted in $7\cdot10^{-4}$, leading to a threshold bending radius of 80 mm (i.e., the minimum bending radius that ensures no phase matching between any pair of adjacent cores, [6]). Table 1 gathers the fibre core design parameters.

Table 1 Core design parameters of the MCF-based TTDL.

Core *n*	1	2	3	4	5	6	7
a_1 (μm)	3.3	3.2	3.5	3.7	4.8	5.0	5.3
a_2 (μm)	5.8	2.4	4.5	3.7	5.8	4.6	3.3
a_3 (μm)	3.2	4.1	4.0	3.6	3.0	6.0	6.0
Δ_1 (%)	0.335	0.300	0.315	0.301	0.293	0.287	0.279

The fabrication of the MCF was carried out by YOFC company. Figure 1(a) shows the fabricated preform for the 6th core, in which the dimensions were properly scaled according to the design requirements. The inset on the upper right part shows the SEM image of that core once the MCF was fabricated. Fig. 1(b) illustrates the SEM image of the fabricated MCF. The fibre cores can be distinguished by their different dimensions according to Table 1 parameters. The 5-km MCF is spliced to a couple of fan-in/fan-out devices to inject/extract the light to/from the cores.

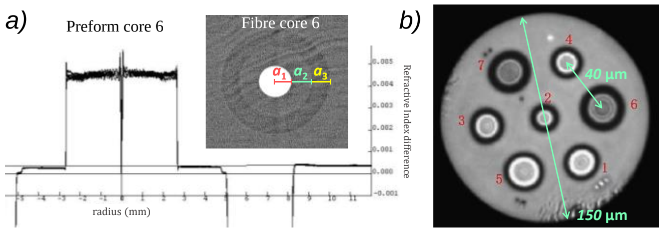

Fig. 1 (a) Preform refractive index profile and core SEM image for core #6; (b) SEM image of the fabricated MCF.

3 Experimental characterization of the TTDL performance

The characterization of the TTDL performance requires the evaluation of the core differential group delays behaviour with the optical wavelength. We measured the differential group delays between cores via an optical interferometric based technique, [7]. First, we compensated slight mismatches between the group delays at the anchor wavelength λ_0 with variable optical delay lines (VDLs). These mismatches might have been caused by small discrepancies between either the design and the fabricated fibre parameters, or the different path lengths of the fan-in/fan-out devices.

Then, we measured the differential group delays between cores for different optical wavelengths ranging from 1535 up to 1560 nm. Fig. 2 shows the measured differential delays between core 7 and the rest of cores. Circle markers represent the experimental values while solid lines correspond to the computed differential delays for the designed MCF. We see that the measured differential delays of cores 3 to 7 match mostly the designed values up to a 30-nm wavelength range. Nonetheless, cores 1 and 2, which are the smallest ones, do not satisfy plenty the incremental group delay slope requirement (i.e., incremental chromatic dispersion values) since they were affected more intensely by fabrication errors. These cores can however be devoted to distribute 2 additional signal channels or to implement other applications that do not require space-diversity signal processing.

We measured the chromatic dispersion of each core at the anchor wavelength λ_0 by evaluating the carrier suppression effect (CSE) that affects the RF response of the 5-km link, [8]. The inset of Fig. 2 depicts the received RF power as a function of the modulation frequency for each core at the wavelength of λ_0 = 1530 nm. The estimated chromatic dispersion values are 14.4, 15.2, 16.6, 17.6, 18.6, 19.6 and 20.6 ps/km/nm, respectively for cores 1 up to 7. We thus see that the fabricated cores 3 - 7 preserve the 1-ps/km/nm incremental dispersion values, while cores 1 and 2 diverge from the rest.

The fabricated MCF based TTDL can operate in two different regimes whether we exploit the spatial or the optical wavelength diversities, what translates into different delay line possibilities within the same fibre link [3],[4]. For the spatial diversity regime, a 5-sample TTDL can be implemented by using cores 3 - 7, since they preserve similar differential group delays. The linear evolution of these 5 core differential delays between 1530 and 1560 nm wavelength allows us to continuously tune the basic differential delay of the TTDL between 0 and 150 ps. On the other hand, all 7 cores are applicable to work in the wavelength diversity regime, where the differential delay comes by the propagation difference created between two adjacent wavelengths in a given core.

The average intercore crosstalk at the 5-km MCF output (including the fan-in/fan-out devices) is below -40 dB, which allows independent signal transmission, while the average insertion losses are 5.8 dB.

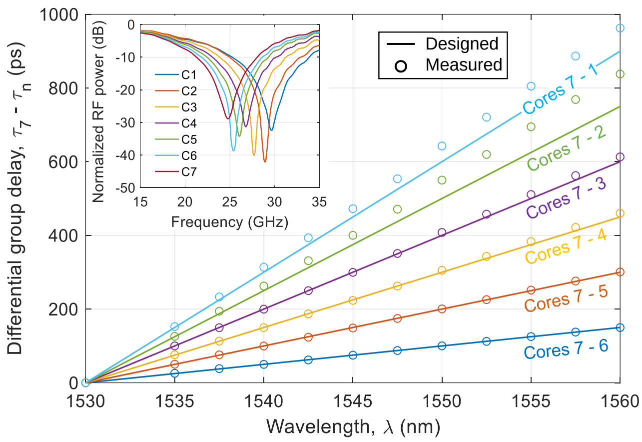

Fig. 2 Measured differential group delays for all the cores with respect to core #7. Inset: Carrier suppression effect in the RF response for each core at λ = 1530 nm.

4 Experimental demonstration of distributed radiofrequency signal filtering

We have experimentally demonstrated the performance of the fabricated MCF-based TTDL when it is applied to microwave signal filtering. Two different experiments are carried out depending on the diversity regime exploited. For the space dimension, a single optical carrier is modulated and injected in all the cores, so that the different path delays come from the combination of the cores at the MCF output. For the wavelength dimension, an array of lasers operating at different wavelengths are modulated and injected to one of the cores. In this case, the sample time delays are created by the different propagation velocities experienced at each wavelength.

Figure 3 shows the experimental setup used to measure the RF filtering response. The optical signal is generated by: (a) a broadband source (BS) (required to avoid optical coherent interference) followed by a 0.1-nm-bandwidth optical filter (needed to avoid high frequency fading effects due to the

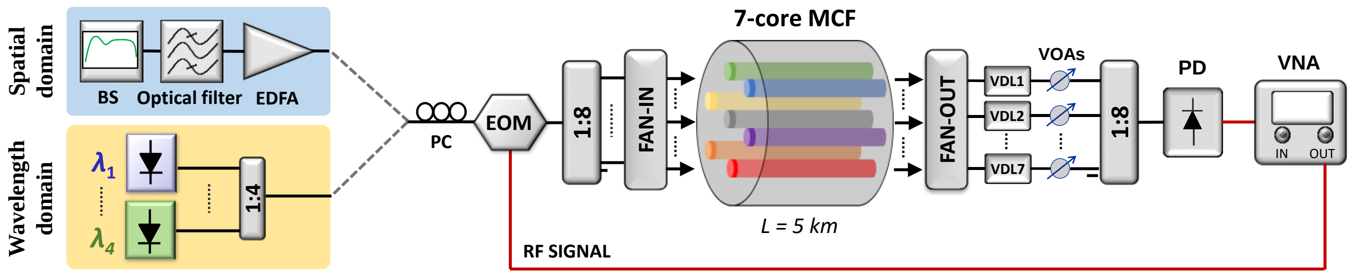

Fig. 3 Experimental setup of the RF filter transfer function measurement for the spatial and wavelength diversity domains.

broadband source, [9]) for the spatial diversity domain; (b) a 4-tuneable-laser array for the wavelength diversity domain. An electro-optical modulator (EOM) modulates the optical signal with the RF signal generated by the Vector Network Analyser (VNA). Single sideband modulation was used to avoid the carrier suppression effect. The signal is then split and injected into all MCF cores. After 5-km MCF propagation, the signals are treated differently depending on the operation regime. In the spatial diversity domain, all cores are combined at the fibre output and variable optical attenuators (VOAs) finely equalize the output power of the samples for uniform amplitude distribution. In the wavelength diversity domain, a single core is chosen to create the RF filtering functionality. VDLs were used to compensate the core group delay fabrication mismatches at the anchor wavelength.

In a first experiment, we evaluate the 5-tap filter built by cores 3 - 7 in the space diversity domain. Figure 4(a) shows the measured RF filter transfer function up to a frequency of 30 GHz for different operation wavelengths. We see that varying the operation wavelength changes the filter free spectral range (FSR), which depends on the inverse of the TTDL basic differential delay, from 13.3 GHz at 1545 nm (black solid line) down to 10 GHz at 1550 nm (green dashed line) and 8 GHz at 1555 nm (red dash-dotted line) without any significant degradation on the filter response. Thus, Fig 2 shows that we can continuously reconfigure the filter FSR from 6.7 GHz up to the mm-wave band by properly tuning the operation wavelength from 1560 down to 1530 nm.

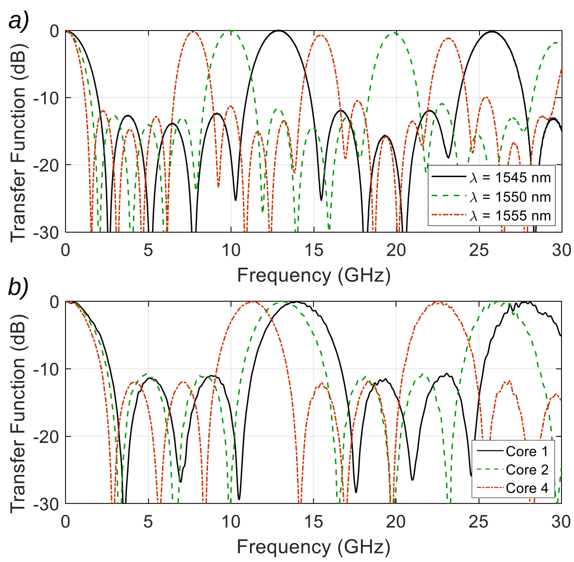

Fig. 4 RF signal filtering responses when we operate the TTDL on (a) spatial diversity and (b) wavelength diversity domains.

In the second experiment, we use an array of 4 lasers operating at optical wavelengths ranging from 1540 up to 1543 nm with 1-nm separation to exploit the wavelength diversity regime. Figure 4(b) shows the measured transfer functions of the 4-tap filters created in 3 of the MCF cores. Black solid, green dashed and red dash-dotted lines represent the filter responses for cores 1, 2 and 4, respectively. In this case, the FSR of the filter depends inversely on the chromatic dispersion of the core we select. The resulting FSRs are 14, 13.2 and 11.3 GHz for cores 1, 2 and 4, respectively. For each core, the filter FSR reconfigurability in this regime is given by the wavelength separation of the optical sources.

5 Conclusions

We have experimentally demonstrated a new approach for tuneable sampled TTDL operation, basis among others of many MWP signal processing functionalities, which is built upon a 7-core heterogeneous MCF. Each trench-assisted core was dispersion-engineered to feature a different chromatic dispersion behaviour. This is, for the first time to our knowledge, the first MCF fabricated with these dispersion characteristics. Although the 2 smallest cores were affected by fabrication errors, the MCF provides successful 5-sample delay line operation up to a 30-nm range, allowing us to tune the basic differential delay up to 150 ps. Moreover, since all 7 cores can also work in the wavelength diversity domain, the MCF provides 2-dimensional sampled delay line operation, what translates into different delay line possibilities within the same fibre link. We successfully demonstrated reconfigurable RF signal filtering in both spatial and wavelength diversity domains. Other RF signal processing applications, such as optical beamforming for phased array antennas or multicavity optoelectronic oscillation, can also be implemented by this approach. All in all, this is a compact and versatile solution to provide, in a single optical fibre, both signal distribution and signal processing. It can be applied in addition to a wide range of optical or RF signal processing systems that require to modify/compensate the chromatic dispersion or group delay in both analogue or digital communications.

6 Acknowledgements

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