Space-Division Multiplexing fibers for radiofrequency signal processing

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***Abstract*— Beyond high-capacity transmission, space-division multiplexing fibers can be engineered to provide distributed signal processing for microwave signals. We present an overview of different fiber technologies where the incorporation of the space dimension brings advantages in terms of compactness as well as operation flexibility and versatility.**

Keywords—Space-division multiplexing, multicore fibers, few-mode fibers, long period gratings, true time delay line, Microwave Photonics, signal processing.

I. Introduction

Over the past few decades, research on optical communications has focused on developing new optical fibers and multiplexing technologies to relentlessly increase the capacity offered by optical networks. In particular, the addition of the spatial dimension to the portfolio of optical multiplexing technologies, known as Space-Division Multiplexing (SDM), boosted the development of novel fiber solutions such as multicore (MCFs) and few-mode fibers (FMFs). The growing interest on these novel fibers has recently opened up new avenues for research in emerging fields of application beyond long-haul optical communications, including in particular radiofrequency (RF) wireless access network distribution [1] and signal processing [2].

In this paper, we present an overview of different SDM fiber technologies in the context of radiofrequency signal processing where the incorporation of the space dimension brings advantages in terms of compactness as well as operation flexibility and versatility, offering what we call as "fiber-distributed signal processing". The majority of microwave signal processing applications, such as reconfigurable signal filtering, squint-free beam-steering for phased-array antennas and multi-cavity optoelectronic oscillation [3], are based on time-discrete approaches built upon an optical true-time delay line (TTDL). As illustrated in Fig. 1, this core element provides a set of time-delayed samples of the RF-modulated signal, where all pairs of adjacent samples feature the same differential delay (basic differential delay, $\Delta\tau$), [2]. If only one optical wavelength is implicated, as we can see in Fig. 1, the TTDL features 1D performance where all the samples result from exploiting the space diversity. If we combine the space diversity with the optical wavelength diversity (for instance, injecting an array of optical lasers), we can offer 2D operation within the same single fiber. Following this approach, we have demonstrated sampled TTDL operation using custom heterogeneous MCFs [4], commercial homogeneous MCFs [5] as well as FMFs [6,7].

II. Heterogeneous Multicore Fiber Approach

The use of different cores to provide the required set of group velocities implies the custom design of a heterogeneous structure where every core provides at its output a different time-delayed version of the RF- modulated signal. For the MCF to operate as a tunable sampled TTDL, we need not only a constant differential group delay between consecutive cores, but also a constant differential chromatic dispersion between consecutive cores to enable tunability with the optical wavelength, [4]. With those requirements in mind, we have developed different heterogeneous MCF links comprising up to 7 trench-assisted cores with a length up to 5 km.

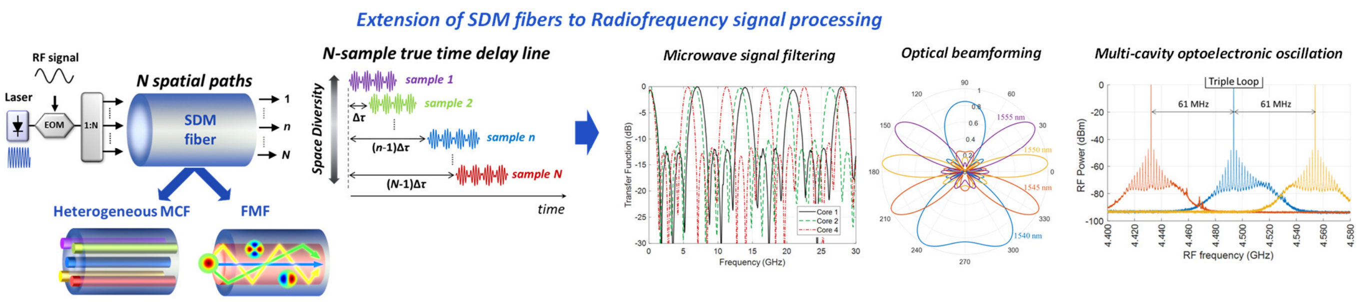

Fig 1. Optical true-time delay line based on a Space-division multiplexing fiber with application to different radiofrequency signal processing applications, such as microwave signal filtering, optical beamforming for phased-array antennas and multi-cavity optoelectronic oscillation.

This research was supported by the ERC Consolidator Grant ERC-COG-2016 InnoSpace 724663, Spanish MINECO Project TEC2016-80150-R, Generalitat Valenciana (PROMETEO 2017/017 research excellency award); Spanish MINECO scholarship BES-2015-073359 for S. García and Spanish MINECO fellowship RYC-2014-16247 for I. Gasulla.

For instance, we designed a 7-core fiber where the refractive index profile of each core consists of a GeO_2-doped core (with a different core radius and core-to-cladding relative index difference) surrounded by a silica inner cladding (with a different core-to-trench distance) and a 1%-Fluorine-doped trench (with a different width). By adjusting these parameters, we provide chromatic dispersions D ranging from 14.3 up to 20.3 ps/(km·nm) (1 ps/(km·nm) incremental step), respectively for cores 1 up to 7, and a common group delay at an anchor wavelength of 1530 nm. Fig. 2 (left) shows the photograph of the cross-section area of the MCF manufactured by the company YOFC using 7 different preforms. Fig. 2 (right) shows the spectral differential group delays where markers correspond to the experimental values and lines to the theoretical simulations. This tuneable TTDL was experimentally applied to microwave signal filtering and radio beam-steering in phased-array antennas using both space- and wavelength-diversity domains, as shown in the right part of Fig. 1.

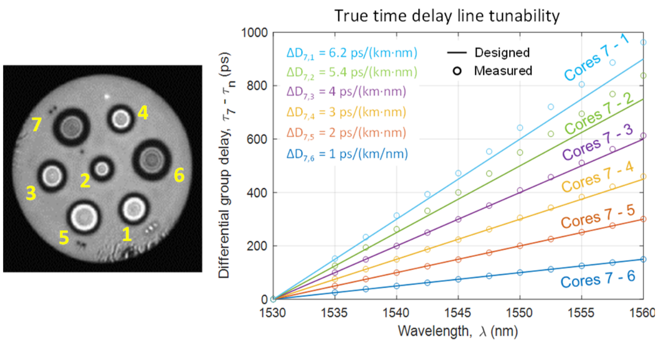

Fig. 2. (Left) Dispersion-engineered heterogeneous 7-core fiber MCF. (Right) Measured (markers) and computed (lines) spectral differential group delays.

III. Few-Mode Fiber Approach

Similarly, we can implement a sampled TTDL over the different modes (or group of modes) propagated through a FMF if we engineer our system so that we obtain a constant basic differential delay and a constant incremental dispersion between the samples received at the output of the FMF link. In addition, one must ensure low coupling between groups of modes, what calls for step-index profiles and short distances combined with direct detection. We have previously demonstrated different configurations for FMF-based TTDLs that work only in the 1D diversity regime by exploiting the spatial diversity at a single optical wavelength. For instance, in [7] we demonstrated a 4-sample TTDL on a 4-LP-mode fiber where the inscription of 3 long period gratings (LPGs) at specific locations allowed the excitation of the 3 higher-order modes while adjusting the individual sample group delays and amplitudes. However, TTDL tunability with the optical wavelength was not possible with that approach, since the chromatic dispersion corresponding to each sample was not customized as required.

To overcome that limitation, we proposed an approach where we combined the custom design of a 7-LP-mode ring-core fiber and the inscription of 5 LPGs at the appropriate locations to achieve both constant differential time delay and differential chromatic dispersion, as illustrated in Fig. 3, [6]. We can see there how the modes are combined through the different LPGs to generate the output samples. This scheme provides at the fiber output equivalent sample differential group delays ($\tau_{eq,i}$ - τ_{01}, normalized with respect to the LP_{01} mode) of 7.882, 7.982, 8.082 and 8.182 ns/km and equivalent chromatic dispersions of 12.1, 17.2, 22.3 and 27.4 ps/(km·nm), respectively for samples 1 to 4. The performance of the designed tunable TTDL was theoretically evaluated when applied to reconfigurable microwave signal filtering and radio beam-steering in phased array antennas.

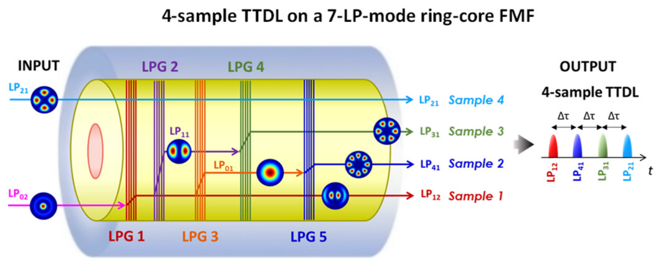

Fig. 3. (Left) TTDL based on a ring-core FMF with long period gratings inscribed at specific longitudinal positions. (Right) Output TTDL time samples characterized by a constant basic differential delay $\Delta\tau$.

IV. Conclusions

SDM optical fibers, usually focused on high-capacity digital communications, can bring many advantages as well to fiber-wireless communications providing fiber-distributed signal processing with increased compactness and performance versatility as compared to bundles of parallel standard singlemode fibers. We showed here an overview of the design, fabrication and experimental demonstration of microwave signal processing based on dispersion-engineered heterogeneous MCFs and FMFs combined with inscribed gratings for mode conversion and group delay adjustment. This approach can be extended to perform additional microwave or optical signal processing applications that require different values of the group delay and/or chromatic dispersion.

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