# Specialty fibers exploiting spatial multiplexing for signal processing in radio access networks

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***Abstract*— The addition of the spatial dimension to the portfolio of optical multiplexing technologies, widely known as Space-Division Multiplexing, has been touted as a solution for the capacity bottleneck in digital optical communications by establishing independent light paths in one single fiber. Boosted by the benefits brought in terms of compactness, flexibility and versatility, the growing interest on these novel fibers has recently opened up new avenues for research in emerging fields of application, such as radio access network distribution and radiofrequency signal processing. We present an overview of a variety of space-division multiplexing fibers specifically engineered in terms of group delay and chromatic dispersion to provide distributed signal processing for radiofrequency signals in converged fiber-wireless communications.**

***Keywords—Space-division multiplexing, multicore fiber, few-mode fiber, photonic crystal fiber, radio access networks.***

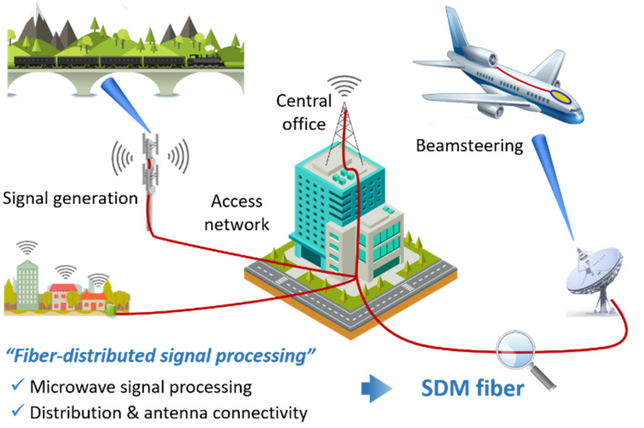

Fig. 1. Application of Space-division multiplexing fibers as fiber-distributed signal processing systems in radio access networks.

## I. INTRODUCTION

The growing interest on space-division multiplexing (SDM) fibers [1] has recently opened up new avenues for research in application areas beyond long-haul high-capacity optical communications, including radio-over-fiber distribution and microwave signal processing [2] in the context of fiber-wireless radio access networks. In this particular scenario, we have proposed a variety of SDM fiber technologies which, in addition to the distribution of parallel signals (for instance, from a central office to different remote antenna locations), operate as optical sampled true-time delay lines (TTDLs). These elements are indeed the basis of most microwave signal processing applications, such as optical beam-steering for phased array antennas, optoelectronic oscillation or signal filtering [2]. Fig. 1 illustrates a representative scenario where SDM fibers can provide what we coined as "fiber-distributed signal processing". We present in this paper an overview of different SDM fibers

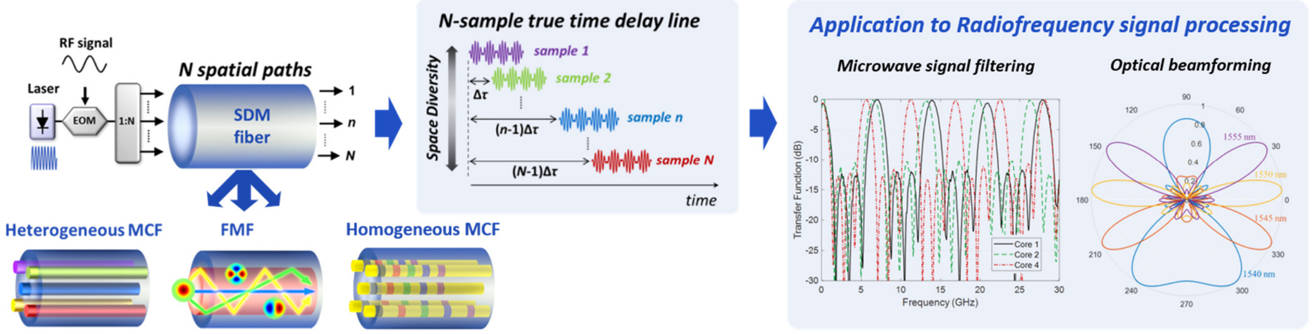

Fig. 2. General scheme of an optical true-time delay line based on a space-division multiplexing fiber with application to signal processing applications on radio access networks, such as radiofrequency signal filtering and optical beamforming for phased-array antennas.

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engineered to provide tunable microwave signal processing, including signal filtering and optical beamforming for phased-array antennas. This multidimensional approach brings advantages in terms of increased compactness, flexibility and versatility.

As illustrated in Fig. 2, the optical TTDL provides a set of $N$ time-delayed samples of the radiofrequency-modulated signal, which are characterized by a constant differential delay $\Delta\tau$ between adjacent samples. These delay taps can be provided either by modes (few-mode fiber approach) or cores (multicore fiber approach). For simplicity, Fig. 2 gathers the general case where only one optical wavelength is implicated, and all the samples are provided by the space diversity of the fiber itself (1D performance). But, if we combine the space with the optical wavelength dimension (for instance, using an array of lasers with constant separation between adjacent wavelengths), the same single SDM fiber will serve as a 2D tunable TTDL. Following this approach, up to date we have experimentally demonstrated TTDL operation using: (1) commercial homogeneous MCFs by the selective inscription of individual fiber Bragg gratings [2], (2) dispersion-engineered heterogeneous 7-core fiber [4,5], and (3) commercial FMF with inscription of long period gratings [6]. Furthermore, we have proposed and designed other custom approaches based on: (1) ring-core FMF with inscription of long period gratings [7], (2) dispersion-engineered double-clad FMF [8], and (3) dispersion-engineered 19-core photonic crystal fiber (PCF) [9].

We must keep in mind that for the MCF/FMF to operate as a tunable TTDL, we require not only a constant differential group delay between cores/modes, but also a constant differential chromatic dispersion between them to provide tunability with the optical wavelength.

## II. FEW-MODE FIBERS

Some of the FMF solutions we have developed require the inscription of several fiber gratings, [6,7]. A simpler solution comes from the design of a dispersion-engineered double-clad step-index FMF, which provides continuous broad tunability for 5 signal samples (Fig. 3 (b)) without requiring the inscription of any grating, [8]. Fig. 3 (a) depicts the refractive index profile of the designed double-clad fiber with indication of the effective refractive index of the 5 modes exploited ($LP_{01}$, $LP_{11}$, $LP_{21}$, $LP_{31}$, $LP_{41}$). To achieve a continuously tunable TTDL, the FMF is designed such that $\Delta\tau$ among adjacent samples is constant over a broad wavelength range. This mean that $\Delta\tau$ varies linearly with the optical wavelength, leading to a constant differential chromatic dispersion among adjacent samples. This unique feature, which to the best of our knowledge, has not been previously reported in any other FMF, is required for tunable operation of microwave photonics applications. The evenly spaced chromatic dispersion $D$ of the 5 spatial modes, ranges from 20.5 to 27.6 ps/nm/km, with a constant incremental step of 1.77 ps/nm/km at 1550 nm. Fig. 3 (c) shows the computed differential group delay (ps/km) between samples, after adjusting the differential delay such that $\Delta\tau = 0$ at the anchor wavelength of 1520 nm by using external delay lines. The performance of this TTDL was theoretically evaluated in the context of both microwave signal filtering and optical beamforming for phased-array antennas, [8].

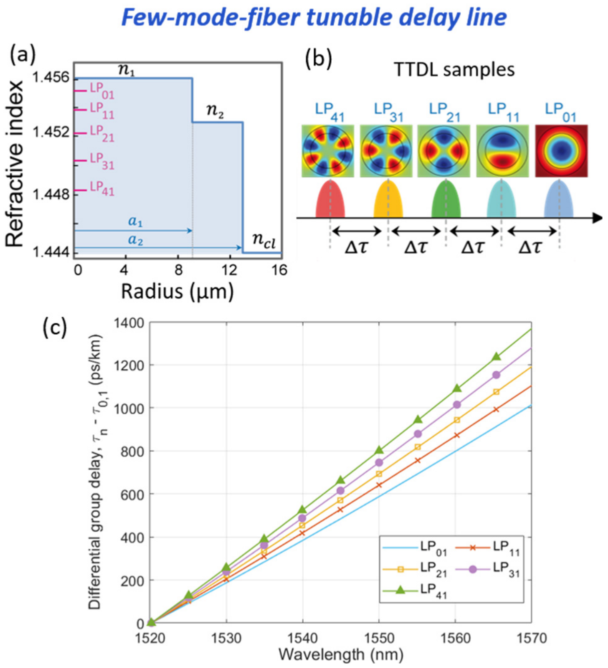

Fig. 3. True-time delay line based on a dispersion-engineered few-mode fiber: (a) Refractive index profile of the designed double-clad step-index fiber, (lines indicate the effective refractive index at 1550 nm for the 5 LP modes exploited), (b) TTDL samples provided by the different mode groups, (c) Spectral differential group delay (in ps/km) between the TTDL samples with respect to the first sample carried by the $LP_{01}$ mode.

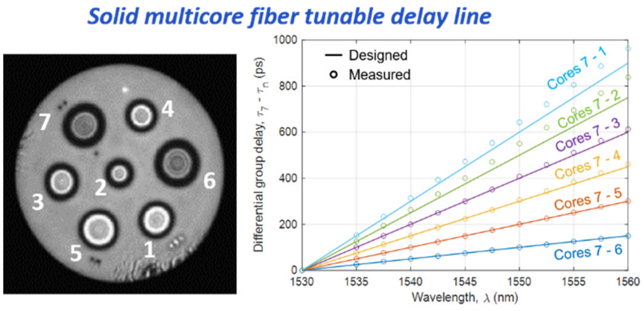

Fig. 4. True-time delay line based on a heterogeneous solid 19-core fiber: (a) Fiber cross-section image, (b) Measured (markers) and computed (lines) spectral differential group delays in ps for a 5-km link.

## III. HETEROGENEOUS SOLID MULTICORE FIBERS

The use of different cores to provide the required set of group velocities implies the custom design of a heterogeneous fiber where every core provides a different group delay and chromatic dispersion [4]. In the line of solid doped-core multicore fibers, we developed a 7-core fiber where each core features a different refractive index profile: $GeO_2$-doped silica core (with a different core radius and core-to-cladding relative index difference), silica inner cladding (with a different core-to-trench distance) and a 1%-Fluorine-doped trench (with a different width), [5]. With the proper radial dimensions and doping concentrations, the fiber provides a range of chromatic dispersion $D$ from 14.3 up to 20.3 ps/(km·nm), with a constant incremental step of approximately 1 ps/nm/km at 1550 nm and a common group delay at an anchor wavelength of 1530 nm.

Fig. 4 (a) illustrates the photograph of the cross-section area of the 7-core fiber manufactured by YOFC using 7 different doped preforms with a cladding diameter of 150 µm and a core pitch of 40 µm. We can see in Fig. 4 (b) the spectral differential group delay for every core (ps) for a 5-km link, where markers correspond to the experimental values and lines to the theoretical simulations. This tunable TTDL was experimentally applied with success to microwave signal filtering [5] and radio beam-steering in phased-array antennas exploiting 2D operability.

## IV. HETEROGENEOUS MULTICORE PHOTONIC CRYSTAL FIBERS

Scaling up the number of samples in solid MCFs implies a considerable challenge since it is difficult to get a wide dispersion range with a low dispersion slope by only changing dopant concentrations and dimensions. Therefore, we proposed to replace the solid doped cores with pure silica PCF cores, since these can offer better control over chromatic dispersion. This way, we designed a heterogeneous 19-core PCF that extends the dispersion range from 1.5 up to 31.2 ps/nm/km, with an incremental step of 1.65 ps/nm/km, [9]. When we exploit the space diversity, it is possible to get a theoretical radiofrequency signal processing range (given by the inverse of $\Delta\tau$) from 24 up to 1210 GHz.km in a wavelength window of ±50 nm around the anchor wavelength. If we exploit the wavelength diversity instead, the radiofrequency signal processing range goes from 64 to 1333.3 GHz.km.

Fig. 5(a) shows the cross-section layout for the designed 19-core PCF with a core pitch of 36 µm and a cladding diameter of 250 µm. Each hexagon represents a silica glass PCF surrounded by 5 rings of airholes, shown up-close in Fig. 5(b), where $d_i$ is the diameter of the 3 inner rings, $d_o$ is the diameter of the 2 outer rings and $\Lambda$ is the airhole pitch, which is constant. To get the required 19 evenly spaced chromatic dispersion values, we varied $\Lambda$ and $d/\Lambda$ while keeping $d_i = 0.36d_o$. Fig. 5 (c) shows the group delay difference (ps/km) for every core as a function of operation wavelength, where we can appreciate ideal TTDL tunable functionality up to 1600 nm. The performance of this TTDL was theoretically evaluated in the context of microwave signal filtering, [9].

## V. CONCLUSIONS

Beyond traditional high-capacity digital communications, space-division multiplexing fibers are called to bring important advantages to emergent scenarios, such as radio access networks for 5G (and Beyond) communications. The addition of the space dimension translates into the capability of providing parallel microwave signal processing functionalities while the signals are being distributed in the access network infrastructure. Depending on the particular characteristics of the final application and the fiber link length required, a variety of SDM approaches can be exploited to perform fiber-distributed providing fiber-distributed signal processing with increased compactness as well as performance versatility and flexibility.

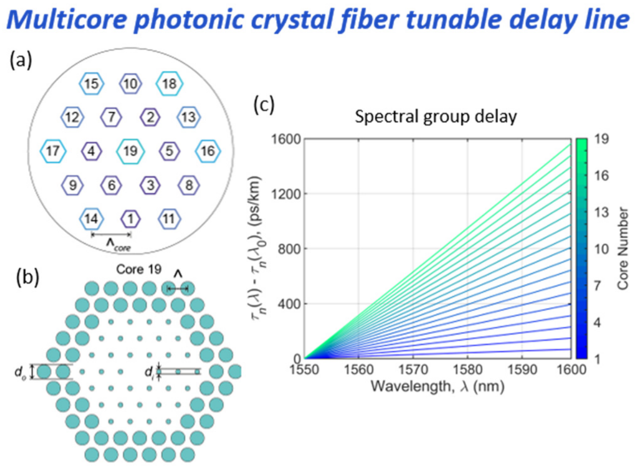

Fig. 5. True-time delay line based on a heterogeneous 19-core photonic crystal fiber: (a) Schematic cross-section where cores are represented by numbered hexagons, (b) close-up of core 19, (c) computed spectral group delay difference (in ps/km) for every core.

We have presented an overview of SDM technologies we have recently proposed and/or experimentally demonstrated exploiting dispersion-engineered few-mode fibers, heterogeneous solid doped-core MCFs and heterogeneous multicore PCFs. By properly tailoring the group delay and chromatic dispersion of every core/mode, tunable sampled TTDL operation is achieved what translates into tunable functionalities such as microwave signal filtering or radio beam-steering in phased-array antennas.

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