Mode-division multiplexing for microwave signal processing

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***Abstract*—We present an overview of different mode-division multiplexing fiber technologies engineered to provide tunable microwave signal processing, including signal filtering and optical beamforming for phased-array antennas. The exploitation of both the space and wavelength dimensions brings advantages in terms of increased compactness, flexibility and versatility.**

***Keywords*—Few-mode fibers, space-division multiplexing, mode-division multiplexing true time delay line, Microwave Photonics, signal processing.**

I. Introduction

The addition of the spatial dimension to the portfolio of optical multiplexing technologies, known as space-division multiplexing (SDM) [1], boosted the development of novel optical fibers, including multicore (MCF) and few-mode fiber (FMF) solutions. The growing interest on these novel fibers has recently opened up new avenues for research in emerging fields of application beyond high-capacity digital optical communications, including among others, radio access networks and microwave photonics signal processing [2]. In these scenarios, we have proposed the use of different SDM technologies as compact media for sampled true-time delay line (TTDL) operation, basis of most microwave signal processing applications, such as optical beam-steering networks for phased array antennas or signal filtering [2]. In addition to the advantages brought by SDM-based TTDLs in terms of compactness, weight and performance versatility (given by the exploitation of both optical wavelength and space diversity dimensions of operation), mode-division multiplexing (MDM) in FMFs allows a simpler and more cost-effective fabrication process as compared to solutions built upon MCFs.

To date, different SDM-based TTDLs have been proposed, including homogeneous MCFs with inscription of selective fiber Bragg gratings (FBGs) [3], dispersion-engineered heterogeneous MCFs [4], multicore photonic crystal fibers and a variety of MDM solutions [5-8]. We experimentally demonstrated TTDL operation over a commercial step-index FMF in [5], where the inscription of long period gratings (LPGs) allowed for the excitation of higher-order modes as well as the control of the group delay of the output samples. However, that scheme cannot provide time delay tunability, what requires the design of a customized FMF such as the ring-core fiber approach we proposed in [6], where the inscription of 5 LPGs was required to implement a tunable 4-sample TTDL. A much simpler solution comes from the dispersion-engineered double-clad step-index FMF we presented in [7], which does not require the inscription of any external grating element and provides continuous broad tunability for 5 signal samples. In this paper, we concentrate on the review of this latest approach, as it enables a simple and compact platform for implementing reconfigurable RF signal processing functionalities along short-reach (in the order of 1-km) links, such as those encountered in 5G (and Beyond) fiber-wireless access networks.

II. Mode-Division Multiplexed Microwave Signal Processing

Sampled TTDLs provide a set of time-delayed versions of the input signal featuring a constant time delay difference $\Delta\tau$ between adjacent samples. Fig. 1 (a) shows the conceptual scheme for the proposed 5-sample TTDL when using spatial diversity in a FMF (the 5 samples are provided by 5 spatial modes), while Fig. 1 (b) depicts the refractive index profile of the designed double-clad FMF 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 not only at a single optical wavelength, but over a broad wavelength range. This mean that $\Delta\tau$ varies linearly with the optical wavelength, consequently leading to a

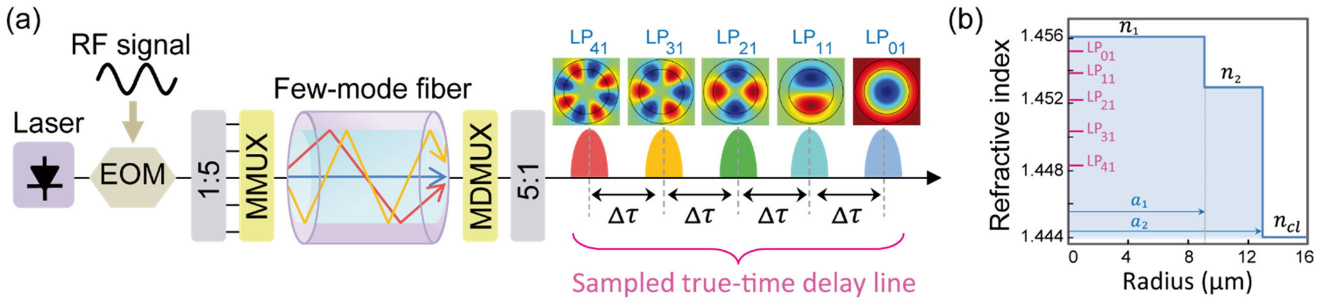

Fig 1. (a) Optical true-time delay line based on mode-division multiplexing over a dispersion-engineered few-mode fiber, EOM: electro-optic modulator, MMUX: mode multiplexer, MDMUX: mode demultiplexer; (b) Refractive index profile of the designed double-clad step-index few-mode fiber. The lines indicate the effective refractive index of the 5 LP modes exploited for TTDL operation, at 1550 nm.

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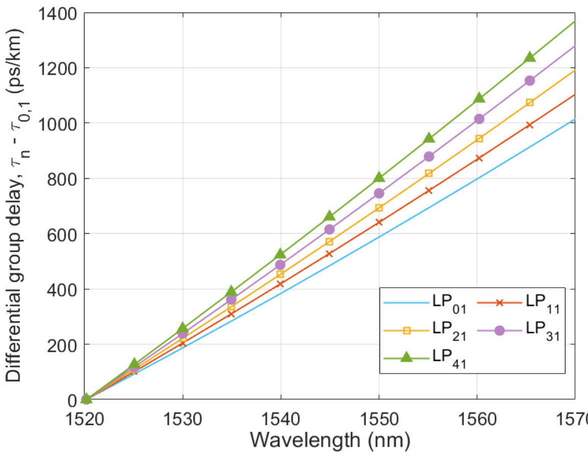

Fig. 2. Spectral differential group delay (per unit length) between the TTDL samples with respect to the first sample carried by the LP_{01} mode.

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 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. Using external delay lines, the differential delay among adjacent modes could be adjusted such that $\Delta\tau = 0$ is obtained at an anchor wavelength (1520 nm in our case), as depicted in Fig. 2.

We theoretically studied the performance of the designed tunable TTDL in the context of microwave signal filtering and radio beam-steering for phased-array antennas, over a FMF link of 1-km. The calculated transfer function of the microwave filter operating in the space diversity is presented in Fig. 3(a), for two different operation wavelengths, while Fig. 3(b) depicts the filter response when wavelength diversity is exploited in the same FMF, for two different modes. The results verify that the free spectral range (FSR) of the microwave filter can be continuously tuned over a broad RF range, in both space and wavelength diversities. The applicability of the TTDL in optical beam-steering, while operating in the spatial diversity, is illustrated in Fig. 3(c), where the array factor of the phased array antenna is calculated as a function of the beam-pointing angle, for different operating wavelengths. As observed, the beam-pointing angle of the antenna can be continuously tuned over a wide range by simply tuning the optical wavelength.

III. Conclusions

Beyond high-capacity digital fiber optic communications, mode-division multiplexing can bring many advantages to fiber-wireless communications providing fiber-distributed signal processing with increased compactness and performance versatility. In this paper, we have focused on the design of a double-clad few-mode fiber customized to provide evenly spaced chromatic dispersion values among adjacent groups of modes with the aim of acting as a sampled tunable true time delay line for RF signals. We have shown wide operation tunability when applying the TTDL to microwave signal filtering and radio beam-steering in phased array antennas over a 1-km FMF link.

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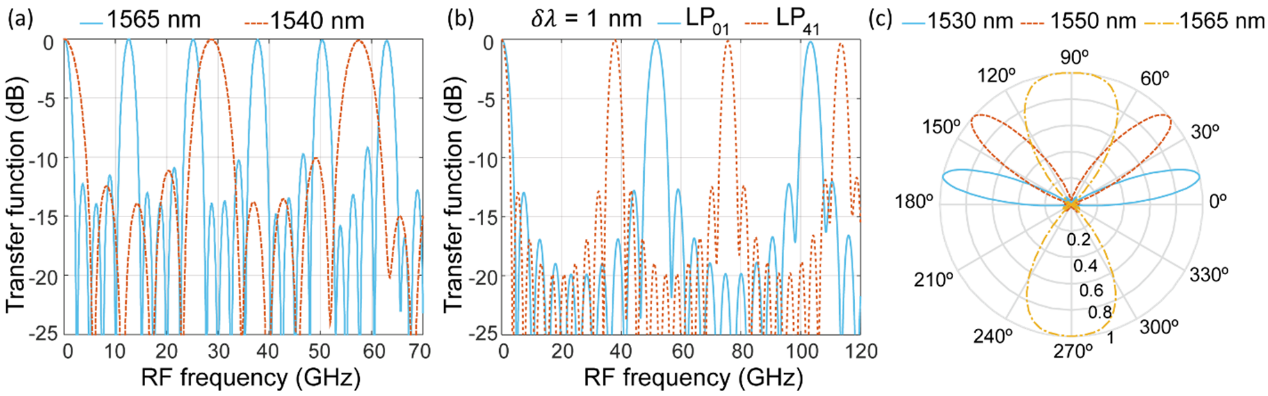

Fig. 3. (a) Application of the MDM-based TTDL to microwave signal processing: Computed transfer function of the 5-tap microwave signal for a 1-km FMF link when (a) operating in the spatial diversity domain, at 1565 nm and 1540 nm; (b) operating in the wavelength diversity domain, for LP_{01} and LP_{41} modes. An array of 10 lasers with an initial wavelength of 1530 nm, separated by 1-nm, is considered; (c) Computed array factor of the 5-element phased array antenna for different operation wavelengths, for an RF frequency of 6.2 GHz and antenna element spacing of 2.4 cm.