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Experimental Demonstration of Reconfigurable Microwave Signal Processing Using a Dispersion-Tailored Few-Mode Fiber

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Abstract

We experimentally demonstrate, for the first-time to our knowledge, reconfigurable radiofrequency signal processing in a few-mode fiber link. The modes of the double-clad step-index few-mode fiber exhibit relatively constant incremental chromatic dispersion values, enabling its operation as a tunable 2D sampled true-time delay line. ©2022 The Authors

Introduction

The growing interest in space-division multiplexing (SDM)[1] has led to the development of novel multicore and few-mode fibers (FMF) in recent years[2]–[4]. In addition to optical communications, these fibers have found applications in some emerging fields, including amongst others, microwave photonics (MWP) signal processing[5]–[11]. In this particular field, SDM fibers provide a compact platform for sampled true-time delay line (TTDL) operation, which is the building block of most MWP signal processing applications, such as signal filtering, arbitrary waveform generation and optical beam-steering for phased-array antennas[12]. A TTDL consists of a set of time-delayed samples of a radiofrequency (RF) signal that have a constant differential time delay $\Delta\tau$ between them. In SDM fibers, each spatially multiplexed path, with its distinct group delay and dispersion, could be designed to provide one of the time-delayed samples. While all SDM-based TTDLs are advantageous in terms of their increased compactness, low weight and performance versatility (as they provide sample diversity in both space and optical wavelength dimensions), FMF-based solutions provide an additional advantage as compared to those offered by MCFs, thanks to their easier and more cost-effective fabrication process.

To date, the TTDLs experimentally realized over commercial FMFs[7]–[9], all fail to provide tunability with the optical wavelength. Here, we experimentally demonstrate, for the first time to our knowledge, continuously tunable TTDL operation over a 1-km dispersion-engineered FMF, while exploiting both space and wavelength diversities.

FMF-Based TTDL: Theory and Fabrication

In a FMF, the group delay for spatial mode n, can be expanded in a 1-st order Taylor series around an anchor wavelength λ_0, as:

$$\tau_n(\lambda) = [\tau_{0,n} + D_n(\lambda - \lambda_0)]L \qquad (1)$$

where $\tau_{0,n}$ is the group delay per unit length and D_n is the chromatic dispersion, of mode n at λ_0, and L is the fiber length. A continuously tunable TTDL, requires the basic differential group delay (DGD) between neighboring samples ($\Delta\tau$) to be constant not only at one single wavelength, but over the entire tuning range. This translates into a linear behavior of the DGD with the optical wavelength and a constant differential chromatic dispersion ΔD between neighboring modes[13].

Accordingly, in an earlier work[13], we designed a novel double-clad step-index FMF, in which 5 spatial modes (LP_{01}, LP_{11}, LP_{21}, LP_{31} and LP_{41}) fulfilled the aforementioned requirements and were theoretically capable of providing continuously tunable TTDL operation. To carry out further studies, we recently fabricated the designed FMF through the manufacturer YOFC. The measured refractive index profile of the fabricated 1-km long FMF at 633 nm, is shown in blue in

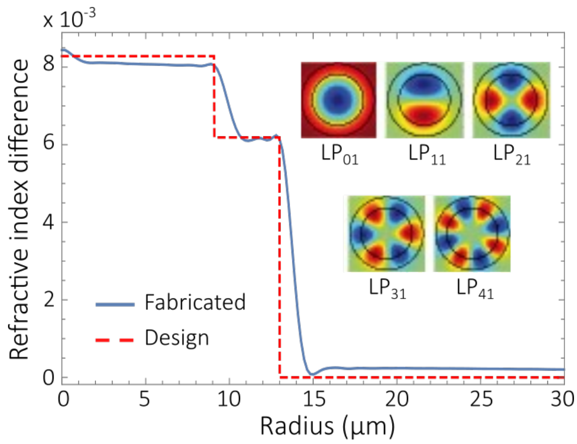

Fig. 1: Refractive index profile of the fabricated (solid blue) and designed (dashed red) double-clad step-index FMF at 633 nm. The mode profiles of the 5 spatial modes suitable for tunable TTDL operation are also shown.

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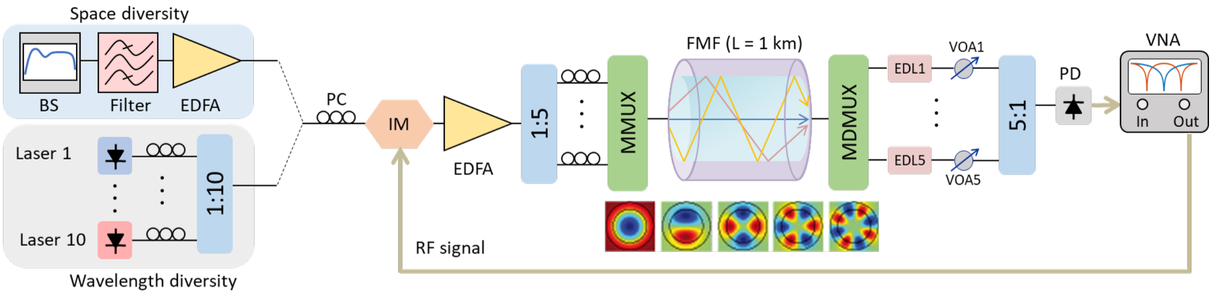

Fig. 2: Experimental setup used for the FMF characterization and measurement of the RF filter transfer function in both space and wavelength diversity domains. BS: broadband source, EDFA: erbium-doped fiber amplifier, PC: polarization controller, IM: intensity modulator, MMUX: mode multiplexer, MDMUX: mode demultiplexer, EDL: external delay line, VOA: variable optical attenuator, PD: photodetector, VNA: vector network analyser.

Fig. 1, while the designed profile is depicted in dashed red. As observed, due to fabrication imperfections, the refractive index profile of the fabricated fiber is slightly different from that of the designed FMF. The silica core has around 7.79 mol% GeO_2 doping concentration with a radius of 9.1 µm. The inner and outer claddings are doped with 5.93 mol% and 0.22 mol% GeO_2, while their radii are 13 µm and 62.5 µm, respectively.

Characterization of the Fabricated FMF

Performance evaluation of the FMF-based TTDL requires the measurement of the DGD among the modes as a function of the optical wavelength. We used the setup shown in Fig. 2 to characterize the FMF and afterwards measure its RF filtering response in both the spatial and wavelength diversities. The input optical carrier is either generated by (a) a broadband source followed by a 0.1-nm-bandwidth optical filter to avoid optical interference between the fiber modes, in the spatial diversity domain or (b) an array of lasers operating at evenly-spaced wavelengths, in the wavelength diversity domain. After amplification, the signal is intensity modulated by a frequency-swept microwave signal generated by a Vector Network Analyser (VNA), where the RF power is 5 dBm and the RF frequency varies from 10 MHz up to 40 GHz. The modulated signal is then launched into the desired modes using a mode multiplexer fabricated by Cailabs. After demultiplexing the modes at the FMF output, appropriate short lengths of single-mode fiber, referred to as external delay lines (EDLs), are added to the optical path of each mode to compensate the mismatches between the group delays of the modes at the anchor wavelength $\lambda_0 = 1503$ nm, so that $\Delta\tau = 0$ is obtained at this wavelength. Given that the required single-mode fiber lengths are short ($<$ 2.5 m), their effect on the overall chromatic dispersion behavior of the fiber link is negligible.

For uniform amplitude distribution, the mode powers are then equalized using variable optical attenuators (VOAs). Depending on the operation regime, either (a) all modes are combined and detected together (space diversity) or (b) only a single mode is detected (wavelength diversity). Regarding the degenerate modes, it should be noted that we only detect one out of every two degenerate modes. By employing polarization controllers at the multiplexer input, the power in the degenerate mode that is to be detected is maximized.

To measure the DGD behavior of the 5 modes of interest with the optical wavelength, the space diversity setup of Fig. 2 was employed. After propagation through the FMF, the microwave signals modulated on the modes interfere with each other in the photodetector. The interference pattern measured by the VNA was used to extract the DGDs among the modes[14]. The results are shown in Fig. 3, where the DGD between LP_{01} and the other four modes were measured from 1530 to 1565 nm. The average value of the measured $\Delta\tau$ at each wavelength (red dots) along with its associated standard deviation (error bar) is displayed in the inset, showing that the time delay can be continuously tuned from 46.3 to 105.6 ps within the C-band. While ideally, at each wavelength, a constant $\Delta\tau$ is desirable for TTDL operation, the error bars show that in practice, $\Delta\tau$ values are not exactly the same among different neighboring modes. However, our results in the next section demonstrate that these small amounts of error do not have a considerable effect on the microwave filter response.

The differential dispersion ΔD among the modes was extracted from the DGD values of Fig. 3, using $\Delta D = d(\Delta\tau)/d\lambda$. The slopes of the fitted lines in Fig. 3 show that the modal dispersion increases with the mode number, in relatively constant steps of $\Delta D = 1.7$ ps/nm/km, satisfying the required condition for TTDL operation.

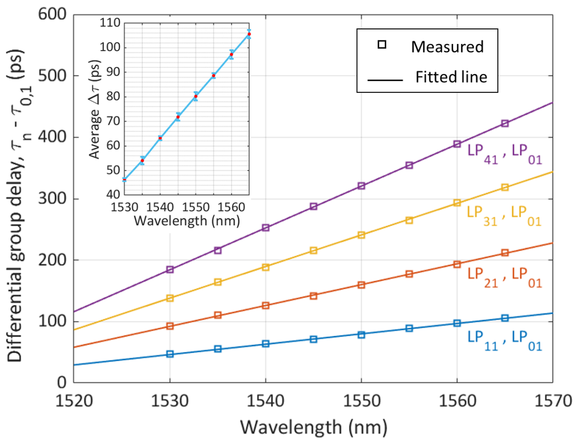

Fig. 3: Measured differential group delays of different modes with respect to LP_{01}. The inset shows the mean $\Delta\tau$ values (red dots) and their corresponding error bars at different wavelengths.

Experimental Demonstration of RF Signal Filtering

To assess the performance of the fabricated FMF-based TTDL, we applied it to microwave signal filtering in two separate experiments, exploiting the space and wavelength diversity regimes individually. In the space dimension, the sample time delays are provided by the distinct group delays of the modes, while in the wavelength dimension, the time delays are due to the different group delays experienced by different wavelengths.

In the space diversity regime, a 5-tap filter was realized using the 5 modes of interest (LP_{01}, LP_{11}, LP_{21}, LP_{31} and LP_{41}). The transfer functions of the RF filters measured at three different wavelengths are shown in Fig. 4(a). When the optical source is swept from 1530 nm to 1565 nm, $\Delta\tau$ is continuously tuned over a wide range, from 46.3 to 105.6 ps (see inset of Fig. 3), corresponding to continuous tuning of the RF filter's free spectral range (FSR $= 1/\Delta\tau$) from 21.6 down to 9.5 GHz. These results confirm the tunability of the fabricated TTDL, leading to reconfigurable microwave filters.

In the wavelength diversity regime, 10-tap filters were obtained by feeding each of the FMF modes with an array of 10 lasers, whose wavelengths ranged from 1531 to 1549 nm, with 2-nm separations. As an example, Fig. 4(b) depicts the measured transfer functions of the RF filters realized in three different modes. The FSR varies from 27.1 GHz for LP_{01} down to 19.8 GHz for LP_{41}. In this regime, the FSR of the filter constructed in each mode is inversely proportional to the chromatic dispersion of that mode. Apart from selecting another mode, the filter FSR can be reconfigured by changing the wavelength separation between the lasers. Further filter reconfigurability can be obtained by modifying the number of lasers (number of taps) as required.

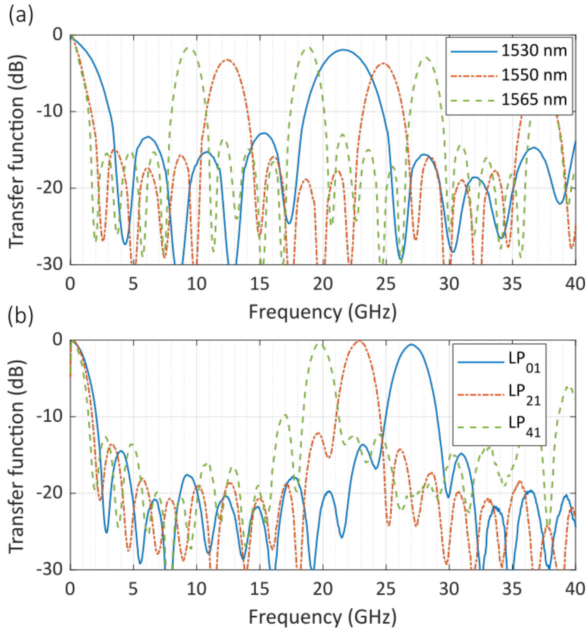

Fig. 4: Measured RF signal filtering responses for TTDL operation in the (a) space and (b) wavelength diversity domains.

Conclusions

We experimentally demonstrate, for the first time to our knowledge, a FMF-based sampled TTDL that exhibits continuous tunability in space and wavelength diversity regimes, offering different delay line configurations within the same fiber. This has become possible thanks to the particular design of our 1-km double-clad step-index FMF, which features relatively evenly-spaced incremental modal chromatic dispersion values close to 1.7 ps/nm/km. The performance of this delay line for RF signal filtering in both diversity regimes is evaluated and a variety of 5-tap and 10-tap filters with tunable FSRs ranging from 9.5 up to 27.1 GHz are experimentally demonstrated. Furthermore, this TTDL can also be applied to realize other microwave signal processing functionalities, such as arbitrary waveform generation or optical beamforming for phased array antennas.

Acknowledgements

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