Dispersion-diversity heterogeneous multicore fibres for signal processing

Sergi García, Mario Ureña, Elham Nazemosadat, and Ivana Gasulla

ITEAM Research Institute, Universitat Politècnica de València, Valencia, Spain, ivgames@iteam.upv.es

Abstract *Besides high-capacity digital communications, multicore fibres offer substantial advantages in both optical and microwave signal distributed processing. By introducing not only space but also chromatic dispersion as new degrees of freedom, we demonstrate different reconfigurable functionalities in a dispersion-diversity heterogeneous 7-core fibre. ©2023 The Authors*

Introduction

The development of multicore optical fibres (MCFs) has emerged as a solution to meet the growing demand for high-capacity digital communications, utilizing the spatial dimension [1]. Expanding upon this, by incorporating the chromatic dispersion as a new degree of freedom, MCFs can offer numerous advantages in both optical and microwave signal processing, provided that each core is customized to provide tuneable true-time delay line operation [2].

This dispersion-diversity optical fibre enables a wide range of functionalities, including parallel interference-controlled signal distribution, chromatic dispersion compensation, time differentiation and integration, Fourier transformation, multi-gigabit-per-second analog-to-digital conversion, and the exploitation of Talbot-based self-imaging phenomena. An application area where dispersion-diversity MCFs demonstrate great potential is in Beyond 5G fibre-wireless communications. Within this context, reconfigurable microwave signal processing [3], encompassing tasks such as signal filtering, radio beam-steering in phased array antennas, instantaneous frequency measurement, or arbitrary waveform generation and shaping, has been investigated (as depicted in Fig. 1 (a)-(d)).

This paper gathers the experimental demonstration of the above-mentioned signal processing functionalities. The required dispersion-diversity performance is achieved through a 5-km heterogeneous 7-core fibre, where each core presents a trench-assisted step-index profile but with totally different radial dimensions and dopant concentrations. Fig. 2 (a) illustrates the photograph of the cross-section of the fabricated fibre. The core pitch is 40 µm and the cladding diameter is 150 µm as shown in Fig. 1(a). [4]. As illustrated in Fig. 2 (b), each core possesses the required dispersion (ranging from 13.9 to 20.3 ps/(km.nm) in approximately 1-ps/(km.nm) constant increments), allowing for continuous linear group delay tunability across a 30-nm optical wavelength range.

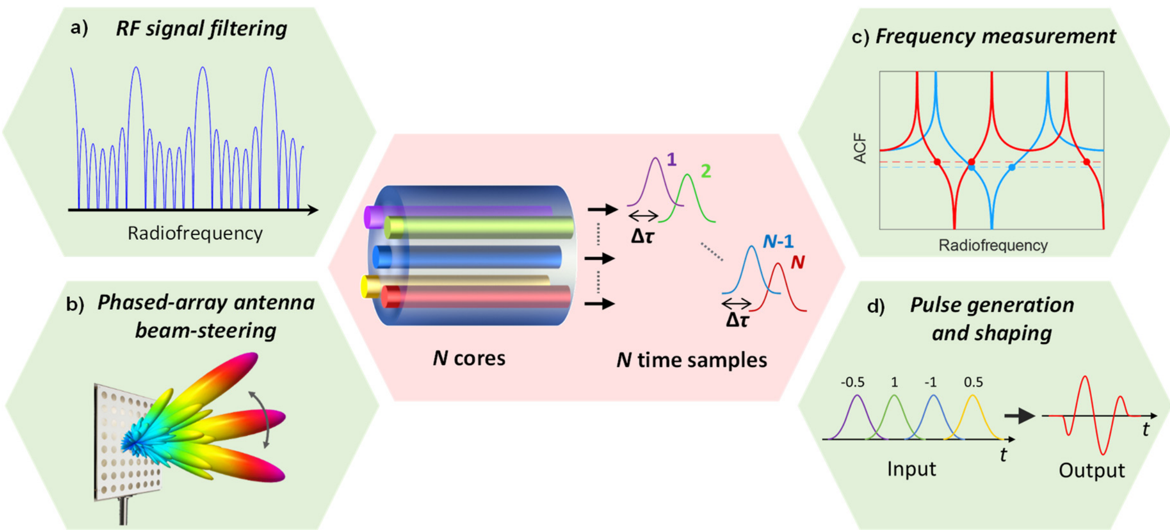

Fig. 1: Dispersion-diversity heterogeneous multicore fibre (MCF) acting as a tuneable true-time delay line with application to: (a) Radiofrequency (RF) signal filtering; (b) phased array antenna radio beamsteering; (c) microwave frequency measurement; and (d) arbitrary pulse generation and shaping.

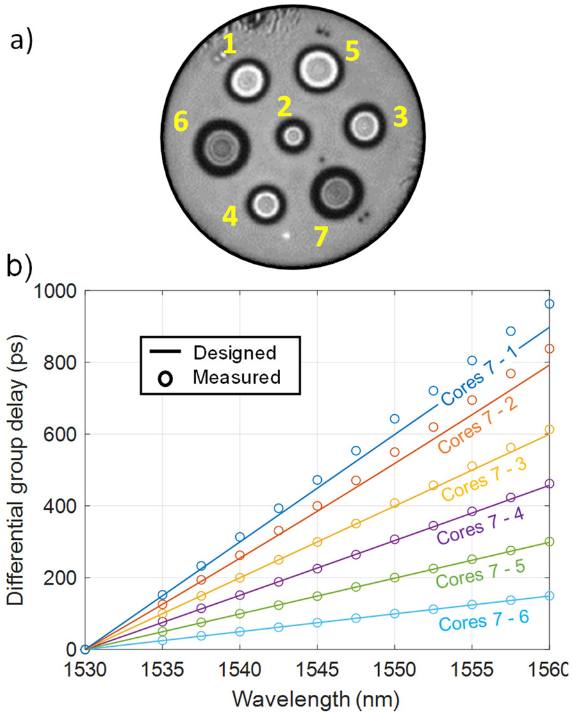

Fig. 2: Dispersion-diversity 7-core fibre: (a) Photograph of the fabricated fibre cross-section; (b) Designed and measured spectral differential group delays.

Dispersion-diversity multicore fibre signal processing applications demonstrated

Since the developed 7-core fibre acts as a tunable optical true-time delay line with good performance for most of the cores, we applied it successfully to several radiofrequency (RF) signal processing representative examples.

The first experimental demonstration relates to microwave signal filtering, exploiting both the space diversity provided by the different cores and the optical wavelength diversity provided if we use an optical source an array of lasers. Signal filtering involves the collective detection of all delayed signal samples or taps at the fibre output. The filter free spectral range, which represents the frequency periodicity, is then inversely dependent on the differential group delay ($\Delta\tau$) between the samples (as previously provided by Fig. 2 (b)). When harnessing the spatial diversity offered by the different cores, our approach enables 5-sample operation utilizing cores 3 to 7. This is due to the inability of cores 1 and 2 to fully satisfy the true-time delay line condition [4], as we can see in the measured differential groups delays shown in Fig. 2 (b). Figure 3 (a) depicts the measured filter response, with the blue dotted, orange dashed, yellow solid, purple dash-dotted, and green solid lines representing the optical wavelengths of 1540, 1545, 1550, 1555, and 1560 nm, respectively.

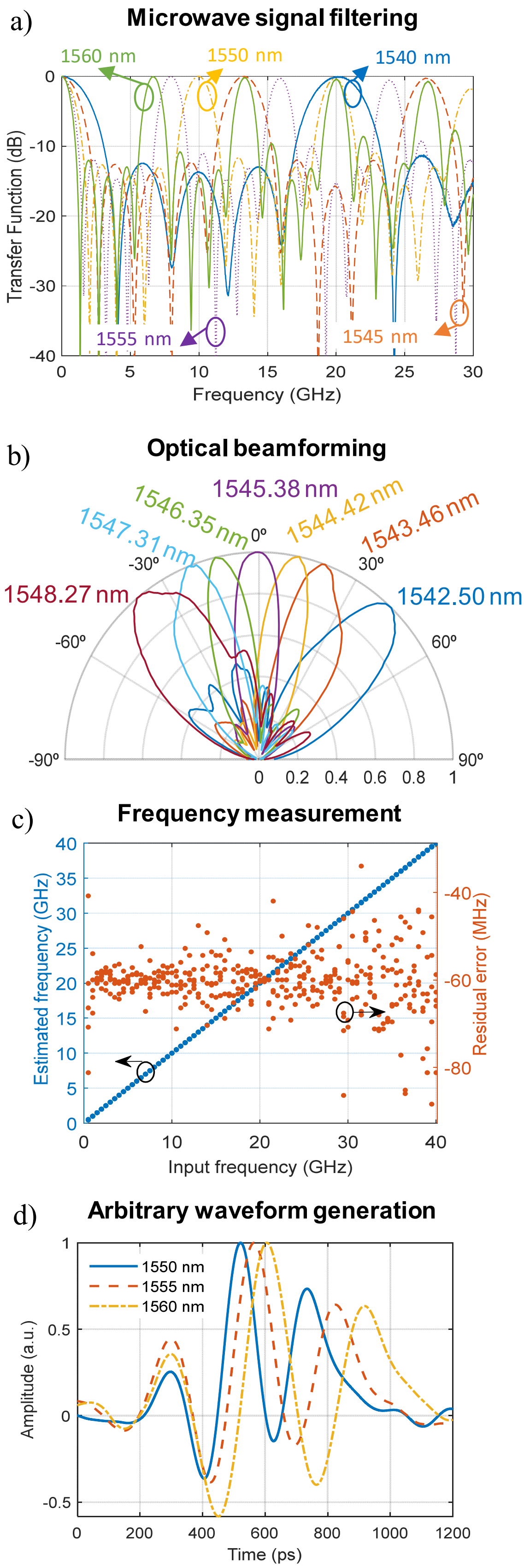

Fig. 3: Experimentally demonstrated signal processing applications: (a) microwave signal filtering; (b) optical beamforming for a phased-array antenna; (c) microwave frequency measurement; and (d) arbitrary waveform generation (quadruplet signal).

Our scheme achieves continuous tunability, ranging from a free spectral range of 20 GHz at 1540 nm to 6.7 GHz at 1560 nm, with no significant performance degradation. Furthermore, if we employ wavelength diversity (i.e., utilizing samples provided by the different wavelengths in each core), all 7 cores can be utilized. In this case, tunability is achieved by varying the separation between optical wavelengths and selecting the appropriate cores.

The second demonstrated functionality is optical beamforming for phased array antennas. Here, the output of each core feeds a given radiating element of the antenna to provide the required electrical phase shift. We have successfully demonstrated the capability of tuneable squint-free radio beam-steering in an in-house fabricated 8-element antenna operating at a radiofrequency of 26 GHz, utilizing space diversity [5]. The radiation pattern was measured in an anechoic chamber at various optical wavelengths ranging from 1542.50 to 1548.28 nm with a step size of 0.96 nm. Figure 3 (b) depicts the measured radiation pattern, exhibiting beam-pointing angles ranging from approximately -40º to 43º.

Furthermore, we have proposed and experimentally validated a method for tuneable microwave frequency measurement [6] by incorporating multiple amplitude comparison functions exploiting different cores of the 7-core fibre. This approach enables the accurate retrieval of unknown radiofrequencies with high resolution across a wide bandwidth [7]. Each comparison function is derived from the frequency responses of two distinct microwave filters implemented using fibre cores. Compared to previous methods, our solution reduces the number of required modulators and photodetectors, while achieving a more compact design. Figure 3 (c) presents the microwave frequency estimated by our approach as a function of the input frequency (blue), along with the corresponding residual measurement error (red), based on five different sets of measurements. The maximum residual error we obtained is ±71 MHz within a measurement range of 0.5-40 GHz.

In addition, we conducted experimental demonstrations of arbitrary waveform generation and shaping for ultrawideband signals. In this scenario, the complementary branches of a balanced photodetector, following MCF propagation, generate the necessary positive and negative pulses [8]. By incoherently filtering a baseband pulse with a 12.5-Gb/s input bit rate, we implemented various waveforms ranging from 2-sample (monocycle) to 7-sample combinations by using all 7 cores. As an illustrative example, Fig. 3 (d) showcases the tunability of the measured temporal waveforms for a quadruplet signal (consisting of 5 samples with weights [0.25, -0.5, 1, -0.5, 0.25]) at three different optical wavelengths.

Conclusions

In this invited paper, we have presented the experimental demonstration of a continuously tuneable microwave signal processing system utilizing a customized heterogeneous MCF. The MCF link enables simultaneous parallel dispersion-diversity signal processing and distribution, as each core is carefully designed with the appropriate chromatic dispersion characteristics. This innovative approach offers enhanced compactness, performance versatility, flexibility, and reduced power consumption. In addition to the reported applications in microwave photonics signal processing, we have recently proposed and experimentally demonstrated as well multigigabit-per-second photonic-assisted time-interleaved analog-to-digital-conversion with the same MCF, [9]. Beyond the already demonstrated applications, we envision this technology finds relevance in various fields, including high-performance computing, distributed antenna systems, physical, chemical and smart structure sensing, medical imaging, optical coherence tomography, as well as broadband electronic and radiofrequency measurement instrumentation.

Acknowledgements

ERC Consolidator Grant 724663, the Spanish Ministerio de Ciencia e Innovación Grant PID2020-118310RB-100, Generalitat Valenciana grants IDIFEDER/2018/031 and PROMETEO/2021/15, and Universitat PAID-10-21 fellowship for S. García.

References

[1] D. Richardson, J. Fini, and L. Nelson, “Space-division multiplexing in optical fibres,” *Nature Photonics*, vol. 7, pp. 354–362, 2013, DOI: 10.1038/nphoton.2013.94

[2] I. Gasulla and J. Capmany, "Microwave Photonics Applications of Multicore Fibers," *IEEE Photonics Journal*, vol. 4, no. 3, pp. 877-888, 2012, DOI: 10.1109/JPHOT.2012.2199101

[3] J. Capmany et al., “Microwave photonic signal processing,” *IEEE Journal of Lightwave Technology*, vol. 31, no. 4, pp. 571-586, 2013, DOI: 10.1109/JLT.2012.2222348

[4] S. García, M. Ureña, and I. Gasulla, “Dispersion-diversity multicore fiber signal processing”, *ACS Photonics*, vol. 9, pp. 2850–2859, 2022, DOI: 10.1021/acsphotonics.2c00910

[5] M. Ureña, S. García, J. I. Herranz, and I. Gasulla, "Experimental demonstration of dispersion-diversity multicore fiber optical beamforming," *Optics Express*, vol. 30, no. 18, pp. 32783-32790, 2022, DOI: 10.1364/OE.468436

[6] X. Zou, S. Pan, and J. Yao, "Instantaneous microwave frequency measurement with improved measurement range and resolution based on simultaneous phase modulation and intensity modulation," *IEEE Journal of Lightwave Technology*., vol. 27, pp- 5314–5320, 2009, DOI: 10.1109/JLT.2009.2030695

[7] E. Nazemosadat, S. García, and I. Gasulla, "Heterogeneous multicore fiber-based microwave frequency measurement," *Optics Express,* vol. 30, no. 15, pp. 26886-26895, 2022, DOI: 10.1364/OE.463152

[8] M. Ureña, S. García, and I. Gasulla, "Ultra-Wideband Pulse Generation Based on Dispersion-Diversity Multicore Fiber," in *Optical Fiber Communication Conference (OFC) 2023*, San Diego, United States, 2023, paper M1J.1, DOI: 10.1364/OFC.2023.M1J.1

[9] S. García, M. Ureña and I. Gasulla, "Photonic-Assisted Analog-to-Digital Conversion Based on a Dispersion-Diversity Multicore Fiber," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 6: Photonic Signal Processing, pp. 1-8, 2023, DOI: 10.1109/JSTQE.2023.3267507