Dual-Wavelength Integrated K-band Multi-Beamformer operating over 1-km 7-core Multicore Fiber

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Abstract: A dual-wavelength broadband photonic integrated beamformer over 1-km MCF provides independent angles with up to 350 ps increment to 3-GHz or 260 ps to 4-GHz BW signals over two different wavelengths and K-band frequencies.

1. Introduction

Beamforming plays an important role to fulfill the capacity and data transmission targets of 5G wireless cellular networks [1], in particular considering K-band operation as in 5G *new radio* (5G-NR) specification [2] and also for next-generation beyond-5G (B5G) network systems, which are also expected to operate in the K-band (and possibly extending to the complete mm-wave band [3]). Due to the increased atmospheric transmission attenuation at mm-wave frequencies, combined with line-of-sight blocking expected in mm-wave cells, the introduction of beamforming techniques has been indicated to increase the antenna directivity (gain) in 5G-NR and B5G cellular networks. Moreover, future B5G networks are expected to further rely on beamforming techniques for mm-wave cell discovery [1]. Current 5G smaller cells using higher frequencies can be served with phased array antennas (PAAs). Optical true time delay (TTD) systems applied to PAAs have been appointed as a suitable solution for providing high bandwidth (BW), continuous tuning and multi-beam capabilities [4]. The proposed photonic TTD integrated system provides continuous delay tuning based on optical ring resonators (ORRs). Previous TTD beamformer implementations have demonstrated multi-beam operation taking advantage of the cyclic response of the ORRs that provides different delays to different RF frequencies [4] but without the possibility of independently tuning each wavelength. Recently, a dual-wavelength version of a photonic TTD integrated beamformer was presented [5]. As a step further in the optical network integration, the combination of this novel dual-wavelength TTD beamformer with multi-core fiber (MCF) as depicted in Fig. 1(a) is proposed and evaluated experimentally in this work. Implementing spatial division multiplexing (SDM) over MCF to connect the beamformer to each antenna element (AE) of the PAA makes possible the transmission of different data signals at the same electrical frequencies and optical wavelengths in all the cores [6], all of them experiencing similar response in terms of optical losses, chromatic dispersion, etc. The use of multiple wavelengths also enables multiplexing and processing multiple RF frequency bands in the same system. In this paper, we present the experimental demonstration and the complete characterization of a dual-wavelength TTD integrated beamformer system operating over 1-km 7-core MCF.

2. Multi-beamformer over 1-km 7-core MCF characterization: transmission, phase, delay and stability

Fig. 1(b) shows the experimental setup and block diagram of the proposed dual-wavelength photonic TTD integrated beamformer operating over 1 km of 7-core MCF. The integrated chip includes first a multiplexer (Mux) that combines the two input wavelengths (λ_1 and λ_2). In order to relax the delay bandwidth requirement, an optical sideband filter (OSBF) is integrated into the beamforming chip [5].

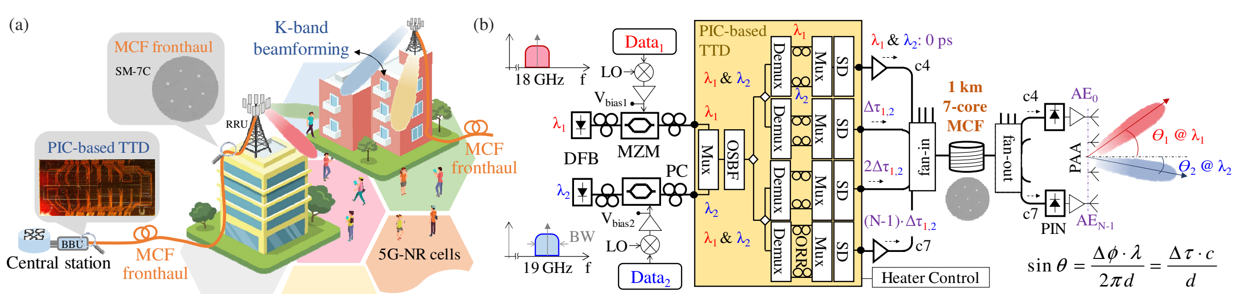

Fig. 1. (a) Multibeamformer application scenario in 5G-NR cells operating over MCF. (b) Experimental setup and block diagram of the dual-wavelength beamformer employing 1 km of 7-core MCF, providing independent tuning to each wavelength to steer the beam to Θ_1 and Θ_2

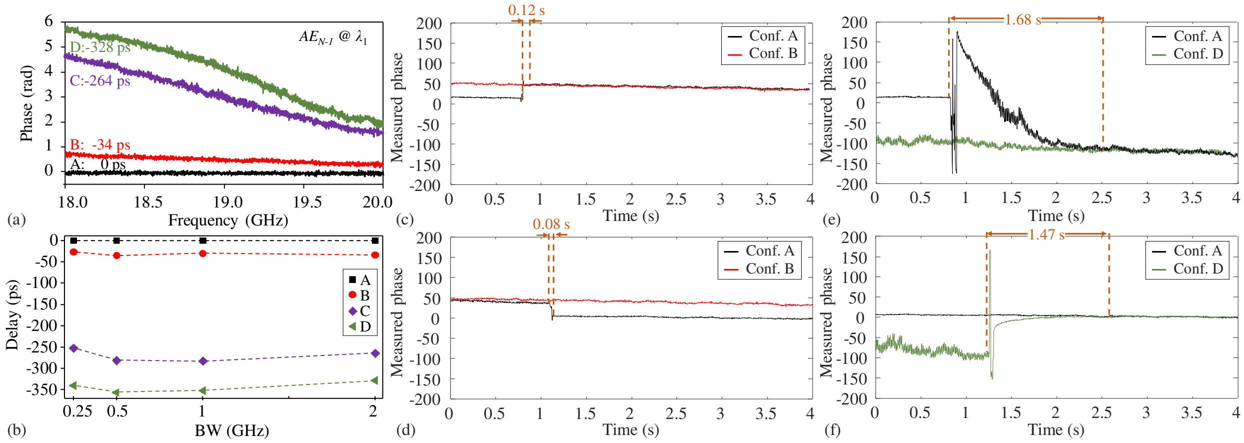

Fig. 2. (a) Measured phase from 18 to 20 GHz and estimated delay for different configurations at AE_{N-1} at λ_2=1551.116 nm. (b) Delay vs. signal BW for different heaters' configurations obtaining $\Delta\tau_A \approx 0$ ps, $\Delta\tau_B \approx 40$ ps, $\Delta\tau_C \approx 260$ ps and $\Delta\tau_D \approx 350$ ps. Measured phase and time needed for stabilization when changing from conf.: (c) A→B, (d) B→A, (e) A→D and (f) D→A.

The induced optical delay is configured by thermo-optically tuning each ORRs, which changes the coupling ratio of the rings [5]. Low coupling ratios induce higher delays at the resonance but at the expense of higher losses and a steep delay profile [5]. At higher coupling ratios, the delay profile is less steep (smaller delay), allowing a wider BW. The optical signals coming out the integrated TTD beamformer chip are transmitted over 1 km of a commercially available 7-core MCF with 35 µm nominal core spacing –Fibercore SM-7C1500(6.1/125)–. For simplicity, two optical paths are characterized for four different heaters' configurations. As depicted in Fig. 1(b), the optical signal containing both λ_1 and λ_2 configured to obtain ≈ 0 ps delay (conf. A) is used as reference signal to feed the PAA AE_0 and transmitted over core 4 of the MCF. The ORRs for signal at λ_1=1548.469 nm are configured with low voltage to provide a 0˚ steering angle in all cases. In the case of operation at λ_2=1551.116 nm, the other optical paths are configured to provide an incremental delay $\Delta\tau$ to each AE in order to steer the beam to $\sin\Theta = (\Delta\tau \cdot c)/d$, where d is the distance between adjacent AEs of the PAA (half of the operating wavelength) and c is the velocity of light in vacuum. Considering a PAA with N elements, the last AE requires a time delay of $(N\text{-}1)\cdot\Delta\tau$. The signal to be connected to $AE_{N\text{-}1}$ is transmitted over core 7 of the MCF.

Fig. 2(a) shows the phase measured with HP8703A network signal analyzer from 18 to 20 GHz for AE_{N-1} operating at λ_2=1551.116 nm for different heater configurations (A to D), where conf. A corresponds to a low voltage applied to the ORRs to provide a flat response (reference AE_0 with ≈ 0 ps). In the other configurations, higher voltage is applied, obtaining a delay of B≈ -40 ps, C≈ -260 ps and D≈ -350 ps. Fig. 2(b) shows the delay measured for different BWs. Steady operation is confirmed as the induced delay remains almost constant with the signal BW for all configurations. A maximum time delay increment of $\Delta\tau_D \approx 350$ ps is achieved with conf. D, which covers the full ±90˚ scan at 19 GHz K-band with a 4-element PAA (as current 5G arrangements assemble in groups of 4 AEs [3]) or can provide a 65˚, 25˚ or 12˚ steering with a 16-, 32- or 64-element PAA, respectively.

In Fig. 2(c-f) we evaluate the time needed for stabilization when changing the voltage applied to the ORRs. The minimum stabilization time is measured to be of 0.08 s when changing from conf. B to conf. A –Fig. 2(d)–. A maximum time of 1.68 s is needed when changing from the minimum delay (conf. A: $\Delta\tau_A \approx 0$ ps) to the maximum delay (conf. D: $\Delta\tau_D \approx 350$ ps) –Fig. 2(e)–. The time requirement is more relaxed when changing from high voltage to low voltage configurations (33% lower when changing B→A compared to A→B –Fig. 2(d)–, and 23% lower when changing from D→A –Fig. 2(f)– compared to A→D).

3. Signal performance evaluation after 1 km of 7-core MCF with different beamformer configurations

Dual-wavelength performance when transmitting orthogonal frequency division multiplexing (OFDM) and single-carrier signals is also evaluated over 1 km of 7-core MCF using different beamforming configurations. Different electrical data signals –$Data_1$ and $Data_2$ in Fig. 1(b)– employing 16QAM modulation are generated with an arbitrary waveform generator (Tektronix AWG7122B) and are upconverted to 18 GHz RF for λ_1 and to 19 GHz for λ_2. As depicted in Fig. 1(b), external Mach-Zehnder modulation (MZM) is employed and polarization controllers (PC) are included before the PIC-based TTD beamformer system to ensure optimum operation. Due to the insertion losses of the chip, optical amplification is used before the MCF, always ensuring operation in the linear regime. After 1 km of 7-core MCF transmission, the signals are photodetected (PIN) and amplified.

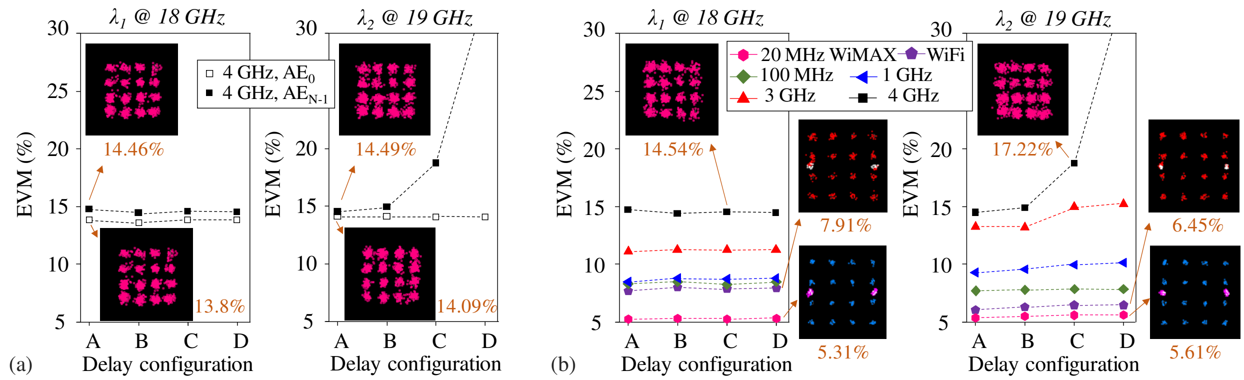

Fig. 3. (a) Measured EVM for 4-GHz BW signals comparing AE_0 and AE_{N-1} performance in both wavelengths for different delay configurations corresponding to $\Delta\tau_A \approx 0$ ps, $\Delta\tau_B \approx 40$ ps, $\Delta\tau_C \approx 260$ ps and $\Delta\tau_D \approx 350$ ps. (b) Measured EVM for different delay configurations for AE_{N-1} in both wavelengths. Example of received 16QAM constellations and EVM values included as insets.

The quality of the signals is measured in terms of error vector magnitude (EVM): single-carrier signals are sampled with Tektronix DPO 72304DX oscilloscope and analyzed with SignalVu software, while full-standard IEEE 802.16 WiMAX and IEEE 802.11a WiFi OFDM signals are sampled with Keysight PXA N9030A and analyzed with 89600 VSA software. Fig. 3 (a) shows the measured EVM for both wavelengths and RF frequencies for 4-GHz BW signals measured in both AE_0 and AE_{N-1} for different delay configurations. It can be observed that the performance for 4-GHz BW reference signals in AE_0 maintains the EVM around 13.8% for λ_1 at 18 GHz and around 14% for λ_2 at 19 GHz. AE_{N-1} operation with 4-GHz BW signals at λ_2 (19 GHz RF) shows that for low-voltage configurations (A and B) the EVM remains below 15%. But the EVM of 4-GHz BW signals is degraded to 17.22% for conf. C ($\Delta\tau_C \approx 260$ ps) and to above 30% for conf. D ($\Delta\tau_D \approx 350$ ps). Fig. 3(b) confirms that delays up to 350 ps can be achieved with 3-GHz BW signals obtaining an EVM < 17.4% (error-free recommendation for 16QAM signals [7]). Fig. 3(b) also shows the performance of 20-MHz signals following WiMAX and WiFi standards, confirming also the operation of the multi-beamformer system with OFDM signals. Observing at the results included in Fig. 3(b), it can be seen that for signal BW $\leq$ 3GHz, the EVM is kept almost constant for all delay configurations (and consequently for all the resulting beam-steering angles). This confirms the suitability of the proposed beamformer system as changing the beam-steering angle does not impact on the signal quality.

4. Conclusion

We propose and fully characterize a dual-wavelength broadband photonic TTD integrated beamformer using MCF suitable for K-band 5G and B5G wireless cellular networks. The different AEs of a PAA are remotely connected by 1-km 7-core fiber. The TTD beamformer chip based on ORRs enables continuous tuning of time delays higher than 350 ps. A maximum stabilization time of 1.68 s is needed when changing the heaters' configuration from 0 to 350 ps delay. The stabilization time is smaller when changing from high to low voltage configurations. Operation with OFDM and single-carrier signals is confirmed experimentally. A 350 ps delay increment is provided to $\leq$ 3 GHz BW signals obtaining a constant EVM for each BW, where changing the beam-steering angle does not affect the quality of the signal. For 4-GHz BW signals, up to 260 ps increment is achieved with appropriate EVM quality.

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