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Photonic integrated circuits employing multi-core fiber for broadband radio beamsteering

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Abstract

This paper presents an optical beamforming network based on a photonic integrated circuit employing a weakly-coupled multi-core fiber to connect the different antenna elements. The proposed beamformer enables a centralized control of the resulting steering angle. By means of wavelength tuning, fast and dynamic configuration of the induced delay (and associated beam steering angle) is achieved remotely. The experimental results confirm high throughput transmission (> 10 Gbps) with electrical data signals with up to 3GHz bandwidth in the 24 GHz RF band (K-band). Wireless transmission of 16QAM-modulated, 1.5 GHz-wide signals is demonstrated in the laboratory from –26˚ to 33˚ providing a scanning range of 59°.

1 Introduction

5G and beyond-5G (B5G) are the next generation of cellular wireless network technology designed to deliver high-data rates to a large number of devices. One of the key enablers for 5G is the availability of suitable radio spectrum including high frequencies above 24 GHz (mm-wave) with very large bandwidths (BW), providing ultra-high capacity and supporting critical services requiring very low latency [1].

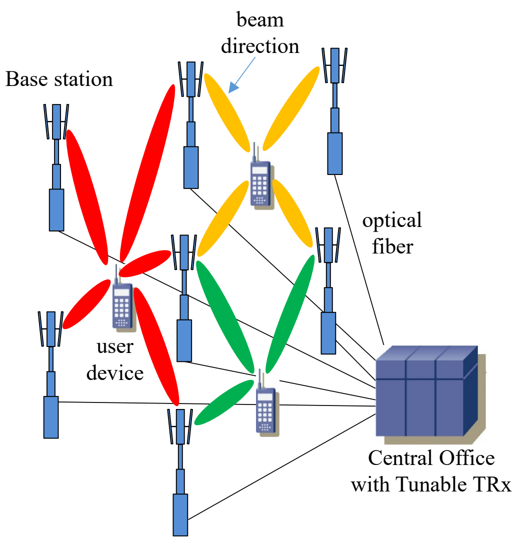

Figure 1. Multi-beam steering functions for serving a mobile user from different base stations. Multi-core single mode fiber are employed to connect base stations to a single processing unit.

The main limitation associated with mm-wave communications are the transmission losses and, for this reason, high antenna directivities and multibeam-steering are important requirements for (B)5G systems to obtain high-throughput and adequate transmission distances [2]. A mobile user can be serviced by several base stations which are connected with optical fibers to a central office where baseband units and electro-optical tunable transceivers are located. The network coverage and the capacity per user can be increased by applying multiple-input multiple-output (MIMO) techniques from these base stations, like depicted in Figure 1. To realize wide-band, large beamsteering angles and multibeam capability, a Silicon Nitride (Si_3N_4) photonic integrated circuit (PIC) has recently been proposed for two-dimensional radio beamforming for satellite communications [3] using thermo-optic delay tuning [4]. A photonic integrated true time delay (TTD) device based on thermo-optic phase shifters in 2-port optical ring resonators (ORRs) provides a linear phase shift over a large frequency range with the advantage of reduced weight and size together with immunity to electromagnetic interference. In order to further reduce the size of the beamformer, we propose to use multi-core fiber (MCF) to feed the different antenna elements of a phase antenna array as depicted in Figure 2.

The equivalent optical paths of the cores in the MCF are exploited to carry the beamformed signals from a central location to the remote antenna elements maintaining the critical delay difference between signals. With this approach, the remote antenna unit is simplified as each antenna element is fed by a dedicated core of the MCF media. The optical signals are only photodetected, amplified and ready to be radiated with the desired beamsteering angle provided by the delay difference between the antenna elements.

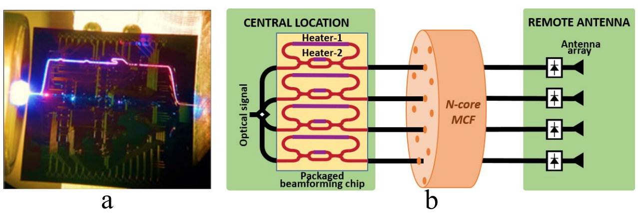

Figure 2. Proposed on-chip optical TTD beamformer using ORRs and MCF: (a) Fabricated 16×16 mm^2 chip incl. test structure (visible light for testing input-output connection) and (b) Schematic diagram of the TTD chip assisted by MCF, example connecting 4 antenna elements.

In this work, compared to previous implementations [4, 5], we use wavelength tuning of the ORRs and MCF optical feeding to assist our TTD chip in order to obtain a fast and significantly compact beamformer network for K-band applications. The chip is tested with large throughputs (> 10 Gbps) and it can be expanded to feed larger antenna arrays while keeping the size approximately constant.

2 Beamformer and tuning methodology

The beamforming chip fabricated on Si_3N_4 platform is shown in Figure 2(a). Optical true-time delay is achieved through tunable ORRs. Thermo-optic phase shifters are used to enable delay tuning of the beamformer. As labelled in Figure 2(b), the ORRs include two heaters, where heater-1 is used to control the coupling into the ring, while wavelength tuning is achieved through heater-2 used to align the resonances across the rings. Taking advantage of the wavelength-dependent delay of the ORRs, an electrical signal at 24 GHz RF frequency modulated over an optical carrier is delayed as determined by the delay profile. This profile is dependent on the coupling ratio of the ORR. The optical transmission response of ORRs with dissimilar coupling ratios is shown in Figure 3(a).

Low coupling ratios induce higher delays at the resonance but at the expense of higher optical loss and a steep delay profile [3]. At higher coupling ratios, the delay profile is less steep and thereby the variation in delay can be smaller, allowing a wider TTD BW.

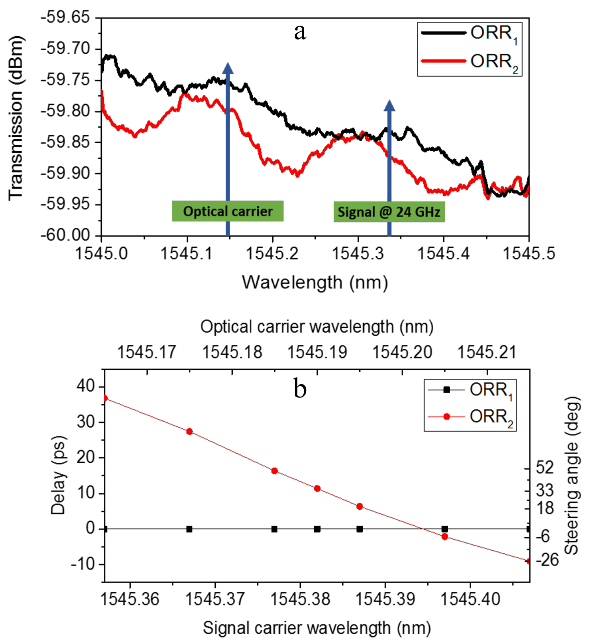

Figure 3. ORR response depending on the location of the optical and signal carriers at 24 GHz and corresponding measured delay for both ORRs: (a) Optical transmission response, (b) Normalized delay and the corresponding steering angle.

To measure the delay, a vector network analyser (VNA) is used to sweep an RF signal from 23 to 25 GHz. From the measured unwrapped phase, we calculate the induced delay through the relation:

$$\Delta\tau = \frac{\Delta\varphi}{2\pi\cdot\Delta f} \tag{1}$$

where $\Delta\varphi$ and Δf denote the phase and frequency difference between the measured and stimulus signal, respectively. With wavelength delay tuning, the optical carrier is moved, shifting also the position of the data signal carrier along the ORR delay profile. Using this method, the TTD device needs to be thermo-optically tuned only once at the start of operation and then the delay is adjusted by changing the optical carrier wavelength. This enables remote and dynamic configuration of the steering angle with tuning speed limited only by the switching speed of the laser and without having to continuously set the on-chip heaters.

The measured delays and their corresponding steering angles are reported in Figure 3(b) for different wavelengths for both ORR configurations (being ORR_1 dedicated to the reference antenna element with induced delay ~0 ps and ORR_2 configured with an incremental delay $\Delta\tau$ in order to steer the beam an angle θ). In a 1×2 beamformer application, a delay of 21 ps is required to steer a 24 GHz RF signal to 90°, calculated from the relation:

$$\Delta\tau = \frac{\sin\theta\cdot d}{c} \tag{2}$$

where d is the spacing between antenna elements (in this case, defined as half of the operating wavelength) and c is the velocity of light in vacuum. The delay profile can be tuned to obtain longer delays depending on the required delay and bandwidth requirements. In previous works, delays up to 250 ps have been demonstrated [3]. However, this setting is sufficient for a 1×2 beamformer system at 24-GHz.

3 Performance evaluation

Figure 4 shows the experimental setup employed to evaluate the performance of the 1×2 beamformer system. In a central location, single carrier signals with different BWs (1.5 to 3 GHz) and modulation formats (from 16QAM to 128QAM) are generated via an arbitrary waveform generator (AWG) with center frequency of f_c=3 GHz. The data signal is upconverted to the 24-GHz 5G band through electrical mixing with a local oscillator at f_{LO}=21 GHz. The 24-GHz signals are modulated onto the optical carrier via a Mach-Zehnder modulator (MZM). An external optical filter removes one of the optical sidebands generating a single sideband signal in order to relax the delay BW requirement of the ORRs. After optical pre-amplification the signal is split into two optical paths and fed into the beamformer chip. The heater voltages are controlled from a central computer. A commercial 4-core MCF Fibercore SM-4C1500(8.0/125) acts as the transmission channel between the central office and the antennas elements of the phase array antenna, ensuring low loss and equivalent delays in each core. The small difference in delay length per channel due to the fan-in/out SMF pigtails can be compensated by the ORRs. A simplified system is deployed at the remote antenna location consisting only of photodetectors (PIN), electrical amplifiers and the antenna array. The received signal prior to wireless transmission is sampled by a digital phosphor oscilloscope (DPO) and its error vector magnitude (EVM) is evaluated with SignalVu software.

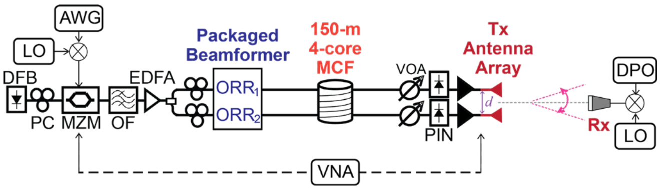

Figure 4. Experimental set-up of an optical beamformer controlling a 1×2 antenna array employing MCF.

Figure 5 shows the measured EVM for 16QAM- and 128QAM-modulated single-carrier signals at various steering angles with electrical signal BWs ranging from 1.5 to 3 GHz. The calculated EVM threshold for error-free transmission with bit error rates BER ≤ 3.8E^{-3} is calculated as 17.4% for 16QAM and 6.33% for 128QAM-modulated signals [6]. A more conservative EVM recommendation could be taken into account as defined by 3GPP 5G NR standard (Release 15) with 12.5% for 16QAM signals [7]. 128QAM modulation is specified but should be between 8% and 3.5%.

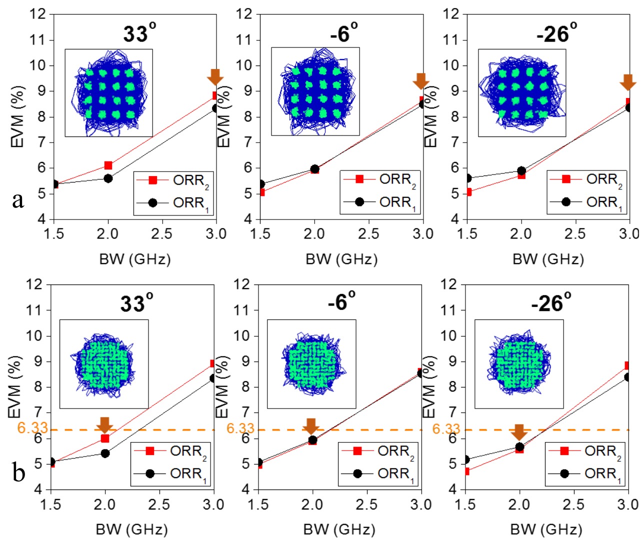

Figure 5. Measured EVM vs. signal BW for different steering angles and modulation formats including insets of received constellations marked with an arrow for: (a) 16QAM single-carrier signals –which always meets the EVM recommendation–, and (b) 128QAM signals, with EVM recommendation in dashed horizontal line.

With the different delay settings evaluated (and resulting steering angles of +33°, -6° and -26°) and using 16QAM modulation, error-free transmission with single carrier signals with up to 3-GHz BW can be achieved, attaining a data rate of 12 Gbps. Increasing the modulation order increases the achieved data rate at the cost of the attainable BW. With 128QAM modulation, up to 2-GHz BW can be transmitted error-free providing 14 Gbps data rate. Examples of the received constellation diagrams are included as insets in Figure 5.

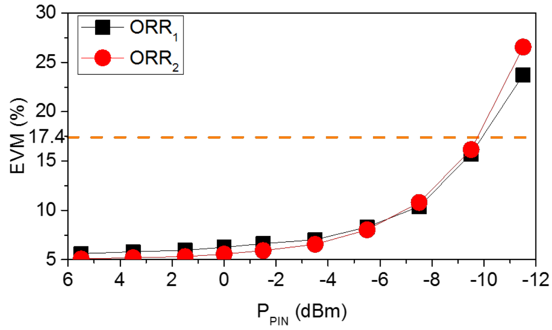

Figure 6. Measured EVM vs received optical power at the photodiode (PPIN) of a 1.5 GHz-wide 16QAM-modulated signal at 0° steering angle.

Next, as depicted in Figure 4, a variable optical attenuator (VOA) is included at the receiver in order to assess the effect of optical loss on the performance of the system. The performance is evaluated for a 1.5 GHz-BW 16QAM-modulated signal with different received optical power levels at the photodiode (P_{PIN}). From Figure 6, it can be observed that a receiver power level $P_{PIN} \geq$ -10 dBm is needed to achieve error-free transmission in both optical paths.

The wireless transmission is evaluated using an array of bow-tie antennas as transmitter (with a pitch *d*=6 mm designed for K-band communications) and a horn antenna as receiver. Figure 7 shows the performance of the wireless transmission of a 1.5 GHz-BW 16QAM-modulated signal. Error-free wireless transmission is demonstrated in a laboratory environment from –26° to 33° providing a 59° steering range.

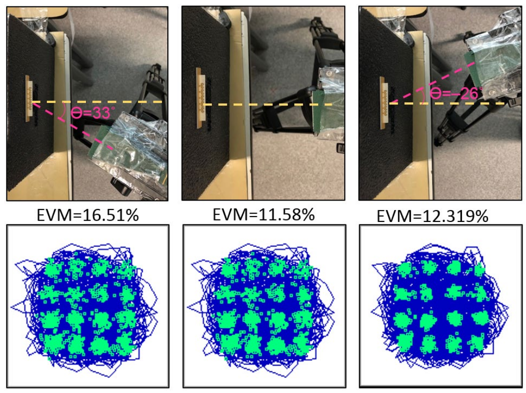

Figure 7. Measured EVM after wireless transmission of 1.5 GHz-BW 16QAM-modulated signals at 33°, 0°, and -26° steering angles.

As new integration platforms with high-index contrast become available, the same concept can be applied to further reduce the size or further increase the number of phase shifters for much larger antenna arrays.

In addition to the Si_3N_4 PIC platform, we have designed and manufactured TTD chips on the Indium-Phosphide Membranes on Silicon (IMOS) for TTDs. Due mainly to the high index contrast, the IMOS platform has resulted in much compact devices with performances comparable to other membrane devices (propagation loss < 7 dB/cm, negligible bending loss for micron size radii, 50/50 splitter with 0.6 dB excess loss).

Moreover, due to the use of active InP materials, lasers and semiconductor optical amplifiers can be integrated to locally generate light and to compensate for optical losses induced by the many power splitters in a TTD chip, respectively. By shrinking the TTD size and by integrating amplifiers we will now be able to manufacture a compact optical beamformer chip that can control large-size antenna arrays. Such a chip for these large arrays would be larger than ours if it is made on the passive integration platforms such as Si_3N_4 and SiO_2. At the time of writing, we are still conducting device and system characterization on the optical and RF performance of one of our realized small-size IMOS chips and the results of this work will be shown if they are available.

4 Conclusion

In this work, we have demonstrated the feasibility of a wavelength-tunable photonic integrated circuit for K-band radio beamsteering applications. Optical true-time delays have been built in the chip to realize broadband and wide angle steering. Moreover, a weakly-coupled, commercial MCF is used to assist the beamforming chip, further reducing the size and making the system more compact. Furthermore, successful transmission of >10 Gbps throughput in a Si_3N_4 chip has been achieved with a 59° steering range, demonstrating the suitability of this compact optical solution to be deployed for high-capacity 5G and B5G applications. We are currently assessing passive and active integration technologies for reducing footprints and power consumption in one side and for scalability in the other side since most smart antenna applications require the use of large antenna arrays.

5 Acknowledgements

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