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Antenna Phased Array Beamforming at 26 GHz Using Optical True Time-Delay

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***Abstract*— Multi-element antenna beam steering in free-licence higher frequency bands is one of the crucial features of 5G networks enabling better tracking of the users. In this paper, we present an experimental microwave photonics transmission system operating at 26 GHz where beamforming is fully realized in the optical domain. The system is designed to be deployed as a part of the mobile fronthaul network with an optical fiber span of 15 km. As a proof of concept, a planar 3-element antenna array has been developed and radiation patterns were measured in an anechoic chamber with high agreement between experimental and simulation results.**

Keywords*— *Optical fiber, microwave photonics, beamforming.

I. INTRODUCTION

As mobile data consumption has been continuously growing worldwide, especially because of high-quality video streaming, the 5th generation (5G) mobile networks gradually substitute commonly used 4G networks. The transition to the new mobile network architecture brings indisputable advance compared to 4G in terms of data rate (10-100 times), lower latency (1ms), availability (99.999 %), longer battery life (10 times), higher mobile data volume (1000 times), network management operational expenses (5 times less) or energy consumption (10 times less) [1]. However, since the biggest challenge is related to the significantly increased data rate, new frequency bands need to be adopted to fulfill such demands. For this purpose, frequency bands above 6 GHz are considered to cover micro-, pico-, or femtocells in urban areas with a dense population. The first frequency band above 6 GHz in 5G, providing sufficient bandwidth, falls within the range approximately between 24 – 27 GHz [2].

There is another important challenge coming with 5G networks, which is the use of multi-element antenna arrays enabling beam steering to effectively reach the users in spite of the individual element characteristics [3]. Besides the microwave progress in developing standards to fully reach 5G capacities, the optical infrastructure has attracted attention for replacing electrical fronthaul network in centralized architectures [4], [5]. The principle of the radio frequency (RF) transmission over optical fiber is known as radio over fiber (RoF) technology [6]. The millimeter-wave (mmw) signal is then delivered to a remote antenna site, which can be located up to 50 km away. The remote site does not carry out any processing since it just amplifies and radiates the signal [7]. The technologies convergence made possible the beamforming and also processing in the optical domain leading to simpler base stations in the mobile network. When considering RoF fronthaul network, the antenna beam can be optically steered in several different ways [8]. For example, optical true time-delay (TTD) was used for phased array radar operating at 10 GHz [9]. The TTD was realized by a combination of optical sources at different wavelengths, wavelength division multiplexers (WDMs) and optical fiber delay lines, with optical 2x2 switches activating variable optical fibers paths to introduce phase difference between particular branches. The effect of chromatic dispersion was used in [10] where a tunable dispersion medium served as TTD was used for beamforming up to ± 90° at 5 GHz using a 4-element antenna array. A 38-GHz mmw beam steered fiber and wireless system has been proposed in [11] based on an arrayed waveguide grating feedback loop. Up to 8 Gb/s bit rates were realized with 2-element antenna array over the distance of 26 cm. In [12], TTD was implemented by the combination of tunable lasers and chromatic dispersion in variable delay lines (VDL) for 4-element patch antenna array at 2 GHz band and for 2-element patch antenna array at 20 GHz band. The use of VDL was also presented in [13] to perform optical beamforming with 2-element antenna array transmitting 1 Gb/s on-off-keying data on the 19 GHz RF carrier. However, only 2-element antenna array in such a high frequency band for mmw system does not enable enough scanning angle for antenna beam steering. In this paper, we present optical beamforming with TTD based on VDLs at a frequency of 26 GHz with 3-element antenna array to provide enough accuracy of beampointing angle. The experimental campaign with results is described in section 2 and the conclusion is provided in section 3.

II. EXPERIMENTAL SETUP & RESULTS

The principle of beamforming of a linear N–element antenna array is shown in Fig. 1 for $N=3$ corresponding to our experimental configuration. Note that $n=N-1$. The equal distance between antenna elements is denoted as Λ, requested steered angle is θ. The time delay difference between two adjacent elements is obtained as follows [8]:

$$\Delta t = \frac{\Lambda \cdot sin\theta}{c}, \tag{1}$$

where c is the speed of the light in the air. Based on eq. 1, the time delays, necessary to point the wave front to angle θ in three-element antenna array are 0, $(\Lambda \cdot sin\ \theta)/c$ and $2(\Lambda \cdot sin\ \theta)/c$, respectively. The desired time delay is realized by using variable delay lines (VDL), which are capable of changing the delay between 0 and 130 ps. The antenna array based on the planar dipole antennas has been designed using the CST Studio Suite to operate in the frequency range between 24 and 28 GHz as depicted in Fig. 2, and it has been manufactured. Note that the elements spacing is 6 mm. The particular antenna element in the array is connected to the signal source by a coaxial connector. Furthermore, the complete microwave photonic link including optical beamforming is shown in Fig. 3. The optical transmitter part consists of an optical source, a continuous-wave laser (ID Photonics CoBrite-DX4) at the wavelength of 1550 nm and optical power of 16 dBm, and a polarization controller to adjust the polarization state at the input of a Mach-Zehnder intensity modulator (MZM, Fujitsu FTM7938EZ/201) biased at quadrature transmission point. A single-tone radio signal at the frequency of 26 GHz is modulated on the optical carrier. The 15 km long single-mode optical fiber emulates an optical fiber infrastructure leading to a remote antenna system e.g. as part of the fronthaul network. The optical signal is further divided by a 1:3 power splitter to separate the signal for the particular antenna element. Each branch contains a single mode fiber pigtailed VDL providing optical TTD to introduce distinctive phase delay in the signal feeding the antenna elements.

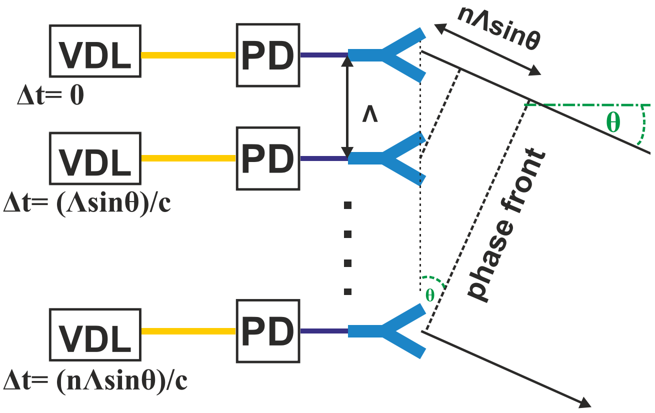

Fig. 1 Principle of optical beam steering using VDL with 3-element antenna array.

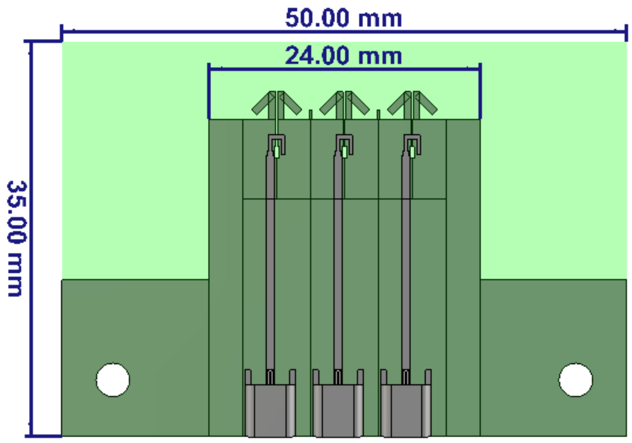

Fig. 2 Antenna array design.

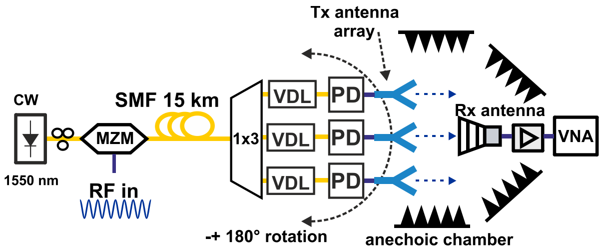

Fig. 3 Optical beamforming setup.

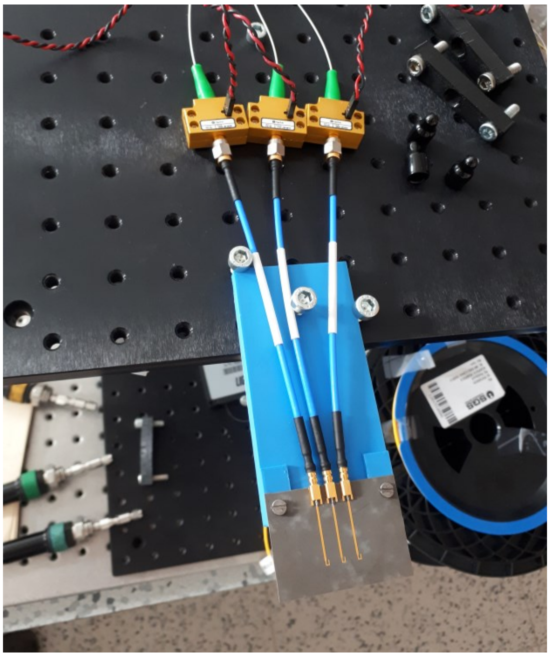

Fig. 4 Antenna terminal in optical true time delay beamforming system.

Finally, high-speed photodetectors (Optilab - PD40) are used for converting the signal back from the optical to the electrical domain. The photodetectors are connected with the antenna array by 10-cm long coaxial cables, which have been chosen according to the phase stability requirements in the given frequency band. The picture of the antenna array with photodiodes is shown in Fig. 4. The proposed system with antenna array has been tested in anechoic chamber with the use of a vector network analyzer (R&S ZVA67) and double ridged waveguide horn antenna (RF Spin DRH40), placed in far-field distance of 3 m, to receive the wireless signal. The receiving antenna has beam width approx. ±15°.Note that the tested antenna array with photodetectors are placed on ± 180° rotating board for measuring radiation patterns. In order to compensate for the losses caused by wireless transmission and cable connection from receiving antenna to the vector network analyzer, an RF amplifier is used. In the experiment, three beam steering directions have been selected with the main lobe direction of 0 and ± 22.5° – see in Fig. 5, corresponding to a phase difference of 80° in RF domain between signals at 26 GHz feeding adjacent elements. Accordingly, Δt was set to 7.7 ps between the neighbor elements to achieve demanded phase difference. Finally, the antenna radiation pattern has been measured and compared with simulation results obtained during the design. Whereas fade colors denote simulation patterns, rich colors stand for measured magnitudes. High level of agreement between simulated and measured data was achieved. The only marginal difference between the measured and simulated results is observed for rear lobes, which has, however, insignificant impact on the radiating characteristics. Note that the radiating paterns are not identical for various steering angle, especially in terms of the main lobe width and the shape of side and rear lobes what, however, originates from the phased array design. The main to side lobe ratio (MSLR) is about 10 dB as can be seen in Fig. 5. Finally, we verified that the system is capable to provide beam steering with better resolution than 1°.

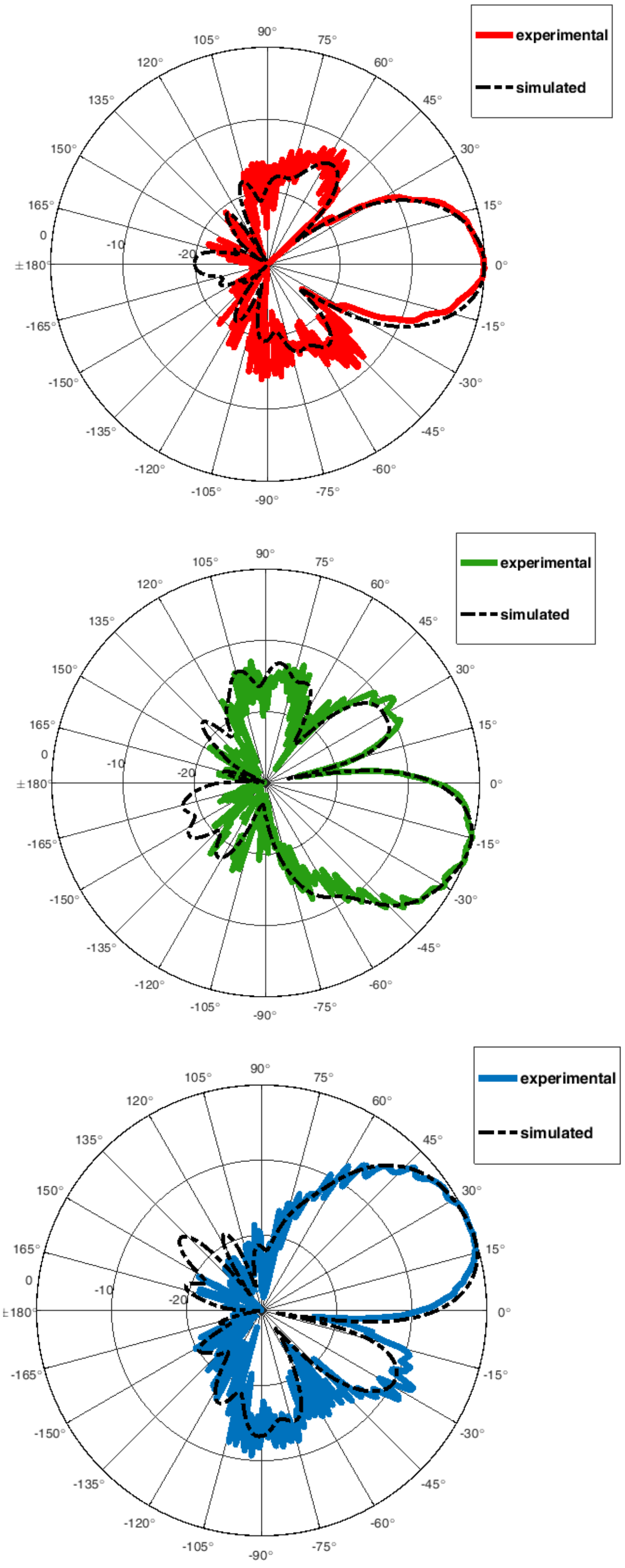

Fig. 5 Radiation patterns for proposed optical beamforming system with a steering angle a) $\theta = 0°$, b) $\theta = -22.5$ ° and c) $\theta = 22.5°$. The relative intensity is given in dBs.

III. CONCLUSION

The fully optical beamforming for microwave photonics link has been successfully demonstrated with the radio signal, i.e. single carrier at the frequency of 26 GHz, transmitted through RoF system including 15 km of single-mode fiber as a part of the fronthaul network. The combination of optical VDLs and in-house built 3-element antenna array using planar dipoles has been used to realize the fully optical beam steering with MSLR of 10 dB and range of ± 22.5°, which can be further extended if needed. Moreover, we show that simulated results correspond well with experimental measurements carried out in the anechoic chamber.

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