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Optically controlled reconfigurable antenna for 5G future broadband cellular communication networks

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***Abstract*— This paper presents an optically controlled reconfigurable antenna for millimetre-wave frequency range. Silicon switches are used to control the optical reconfiguration, modifying the frequency response and radiation pattern of the antenna design. Therefore, the system can switch between the lightly licensed 28 GHz and 38 GHz frequency bands, useful for future mobile 5G broadband cellular communication networks. Experimental results with the reconfigurable antenna on 16-QAM and 32-QAM wireless transmission supported by photonic downconversion are successfully reported under 78 dB link budget requirement.**

***Index Terms*—** Hybrid optical-wireless architecture; optical reconfiguration; reconfigurable antennas; slotted waveguide antenna.

I. INTRODUCTION

The number of users of wireless technology has presented a continuous up growth during the last decades, pressing the development of new technologies to supply the market necessities. The dominance of smartphone in traffic web will bring on a saturation of the current network bandwidth capacity, which operates in frequencies lower than 2.7 GHz. Therefore, higher frequency bands have being investigated for high-capacity wireless systems, especially in unlicensed or lightly licensed millimeter wave (mm-wave) frequency bands, such as: the E-band (60-90GHz), W-band (75-110 GHz) and even sub-Terahertz (100-300GHz) [1-3]. To make available these efficient broadband wireless systems, operating in different frequencies, antenna is a key component to guarantee the applicability of the signal distribution. Although optical technologies can provide solutions to generate and distribute such signals, the electrical front-ends at these frequency regimes are still under development. Moreover, distributed antenna systems architectures have been shown a promising technology, due to the reduced wireless coverage in case of mm-wave links [4].

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A potential band which has been proposed for future 5G broadband cellular communication networks and satisfies bandwidth requirements is 28 GHz and 38 GHz frequency bands [5]. In such mm-wave bands, unlike at 60 GHz and above, atmospheric absorption does significantly not contribute to additional path loss [6]. Moreover, the development of front-ends capable of operating in both bands simultaneously is necessary to support large-scale deployments. Radio over Fiber (RoF) is a potential technology to enable the integration of wireless and fiber optic networks by means of taking advantages of the benefits of optical fiber with the mobility and ubiquity of wireless networks [7-8]. It is based on the transmission of RF signals by using an optical carrier through optical fiber links. RoF is an essential technology for the provision of untethered access to broadband wireless communications in a range of applications including last mile solutions, extension of existing radio coverage and capacity, indoor and outdoor cellular systems, among others.

With respect of the exploration of the underutilized mm-wave frequency spectrum be considered a potential candidate for future broadband cellular communication networks, there are several works published regarding propagation analysis of cellular mm-wave in densely populated environments [5,9-10]. T. Rappaport et al. have recently reported extensive propagation measurements campaigns at 28 GHz and 38 GHz bands for providing an insight on their applicability for indoor and outdoor environments in Austin and New York cities [5]. Moreover, narrowband wideband measurements have been performed in diverse indoor and outdoor environments in order to enable the development of reliable prediction models for 60 GHz radio channels [10].

On the other hand, another interesting and promising solution for the recent technologies of wireless communications systems is the use of reconfigurable antennas [11]. This class of antennas enables to reconfigure not only the bandwidth, but also the radiation pattern and polarization pattern. Reconfigurable antenna ensures flexibility design, once it presents frequency agile and makes use of software defined and cognitive radios to cope with extendable and reconfigurable multiservice, multistandard and multiband operation. Moreover, by using reconfiguration, an efficiently use of the spectrum and the power utilization is achieved. Our group has recently proposed the concept of an Adaptive and Cognitive Radio over Fiber (ACRoF) [12] based on the integration of an optically controlled reconfigurable antennas and RoF systems [13]. Using this new approach, it becomes possible to perform a high capacity optical backhaul with a broadband, energy- and spectrum-efficient wireless access segment, also exploiting new spectral resources.

The current work proposes the concept and reports the development of an Optically Controlled Reconfigurable Antenna (OCRAA) for mm-wave frequency range. Moreover, an application of implementation in a 16-QAM and 32-QAM wireless network system is presented. The manuscript is structured in other four sections. Section 2 reports the development of optically controlled reconfigurable antennas for 28 GHz and 38 GHz frequency bands. Section 3 describes the

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system implementation, whereas Section 4 presents the experimental results of the system performance evaluation. Finally, conclusions and future works are addressed in Section 5.

II. Reconfigurable antenna development

This section presents the development of a high-performance antenna to be applied in the 28 GHz and 38 GHz wireless experiments. In order to satisfy the requirements of the next generations of wireless networks, an optically controlled reconfigurable and multiband slotted waveguide antenna array (OCRAA) is proposed, as shown in Fig. 1. There are several mechanisms to reconfigure the antenna structure. Particularly, optically controlled antennas have been intensely exploited in the last years due to their unique advantages, such as: easy integration to optical systems, absence of bias lines, linear behavior, very fast switching and activation without producing harmonics and intermodulation [11, 14-15].

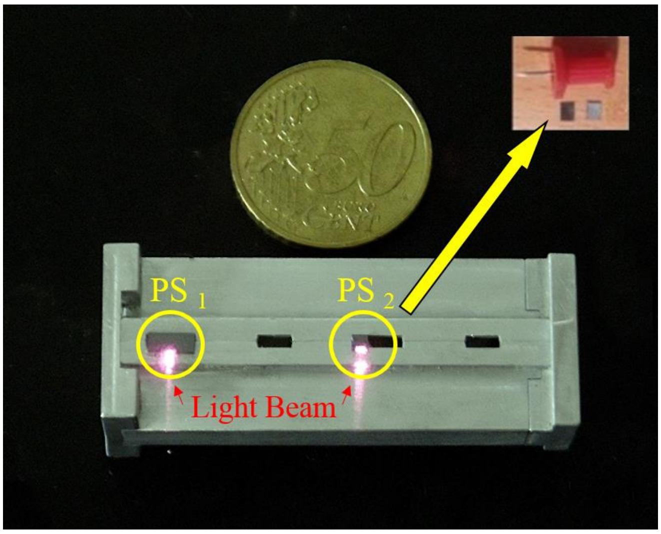

Fig. 1. Optically-controlled reconfigurable slotted-waveguide antenna developed for the experiments. In the up right corner a photoconductive switch and its integration to the reconfigurable antenna is presented

The proposed antenna is based on a Slotted Waveguide Antenna Array (SWAA) [16], composed by a metallic waveguide with proper dimensioned and disposed slots, distributed on its narrowest face, as shown in Fig. 1b. SWAAs provide the following advantages: compact, planar, high gain, low loss structure, and high power handle. However, they are typically narrow and single-band [17-18]. Unlike, this innovative structure enables a frequency response over three bands, namely: 28 GHz, 34 GHz and 38 GHz bands, shown in Fig. 2

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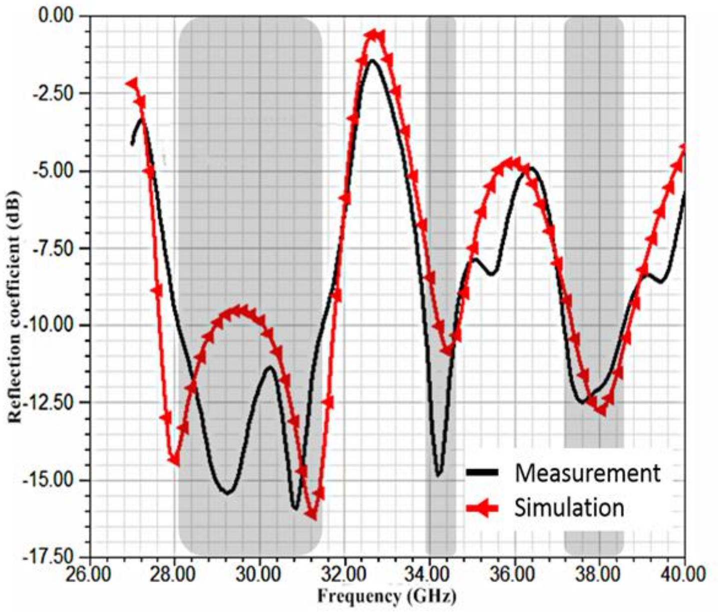

Fig. 2. Reflection coefficient with optical switch off: measured (black continuous curve) and simulated (red continuous with triangles).

In the current work, we propose to reconfigure its frequency response and radiation pattern by using a photoconductive switch illuminated via optical fiber by high-power 808 nm laser, as shown in Fig. 1. The photoconductive switch consists of a tiny piece of intrinsic silicon die (highlighted in the up right corner in Fig. 1), which can change its electrical properties when light is applied. In this way, its conductivity becomes reconfigurable as a function of the incident optical power. As soon as the photoconductive switch is illuminated, silicon semi-conductor changes for a conducting state by creating electron-hole pairs [19]. The incident photons must have enough energy to move electrons from the valence to the conduction band. Light in the near-infrared region is adequate for this process, since it strikes a balance between the absorption coefficient and the light penetration depth related to the light wavelength. In this way, it is possible to manage the switch conductivity by controlling the optical incident power. Silicon switch is strategically placed in one of the slots, making part of the antenna metallic body. In this work, the optical switch has been placed on the first and third slots. Therefore, the reconfiguration of the radiation pattern and the frequency response is obtaining according to the power delivered by the fiber. When the laser is turned on the silicon switch starts to conduct, changing the electric size of the slot. Turning on just the switch placed on the first slot, the modification on the structure removes the high frequency resonance and the antenna operates on a single widest band, as shown in Fig. 3a. Illuminating the first and the third slot, simultaneously, it is possible to reconfigure the operation band, enhancing just the 38GHz frequency, as presented in Fig. 3b.

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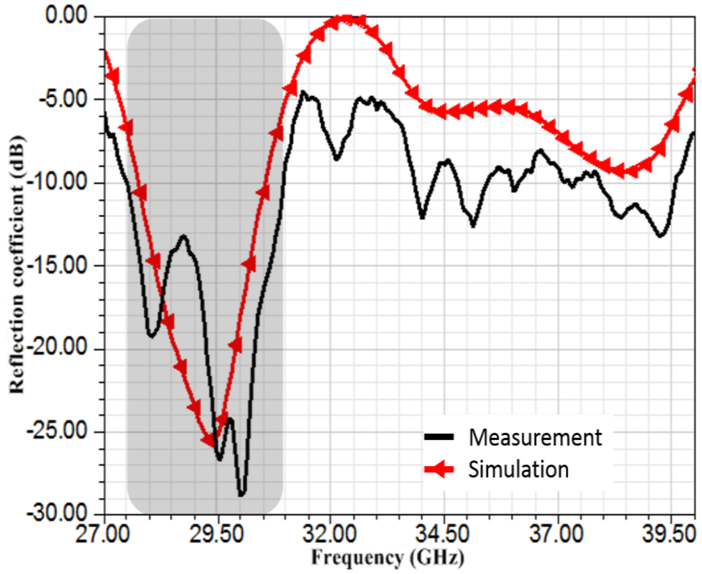
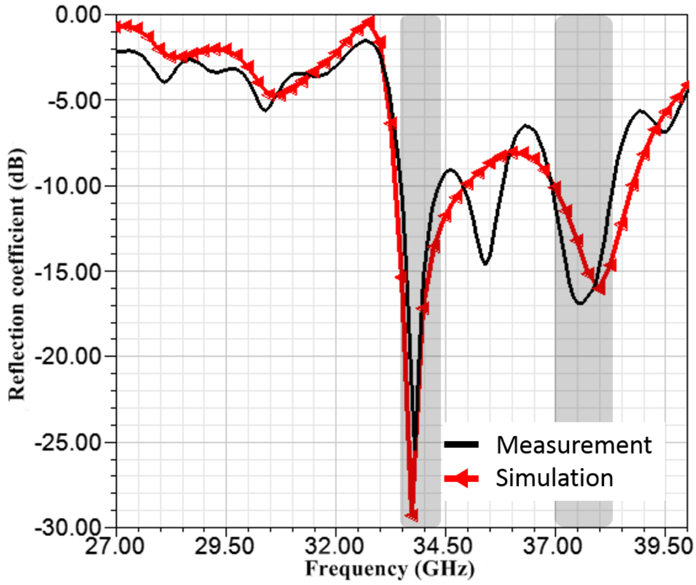


a) Reflection coefficient for the first optical switch on: measured (black continuous curve) and simulated (red continuous with triangles).



b) Reflection coefficient for the first and second optical switch on: measured (black continuous curve) and simulated (red continuous with triangles).

Fig. 3. OCRAA reconfigurable frequency response.

Since the feeding structure excites a wide range of frequencies inside the waveguide structure, other operation bands can couple with the slots. Therefore, the distance between the slots for 28 GHz and 38 GHz generates a third operation band around 34 GHz. This band can also be useful for the 5G networks, but for this work, just 28GHz and 38GHz bands are the interest regions.

Figure 4 presents full-wave simulations of antenna radiation pattern based on Finite Element Method (FEM), carried out using ANSYS HFSS. For proposed OCRAA, it is clear that incident light

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significantly modifies the antenna radiation pattern. For instance, its gain at 38 GHz increases from -3.35 dBi on the "OFF" state (green region of the main lobe from the top part) to 11.80 dBi as soon as the switch is turned to "ON" state (red region of the main lobe from the bottom part).

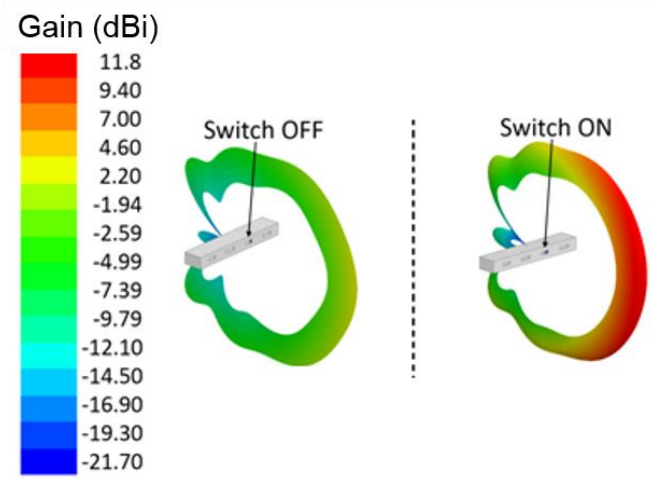

Fig. 4. Antenna radiation patterns for 38 GHz: OCRAA on "OFF" state and "ON" state.

III. System Implementation

The experimental setup is presented in Fig. 5, including the photonic downconversion stage. The Radio Frequency (RF) signal is generated using a Vector Signal Generator (VSG). It provides 40 Mbaud 16-QAM or 32-QAM at RF frequencies between 28 GHz and 39 GHz. Its output is fed into the optical controlled antenna at 5.0 dBm RF power. The RF signal is transmitted through a 5 m wireless link and received by a broadband horn antenna, and amplified using a double stage, a low noise RF amplifier (LNA) with 30 dB gain and Power Amplifier (PA) with 21 dB of gain and noise figure less than 6 dB.

To perform the downconversion for an intermediate frequency, photonic downconversion architecture was implemented [20-21]. An External Cavity Laser (ECL) is used to feed a Mach-Zehnder modulator (MZM), which is driven by a RF tone generator of 4 dBm input power. The MZM is biased at the minimum point to create three tones spaced by the Local Oscillator (LO) frequency, typically from 27 GHz to 31 GHz. Afterwards, a second MZM is used to modulate these three tones with the received and amplified wireless signal. Then, the optical signal is amplified and filtered to remove the undesired components. At the photodiode, the beating of the central carrier with the information from the upper and lower modulated tones results in the information being downconverted to an intermediate frequency, corresponding to the difference between the LO and RF signals (typically from 4 GHz to 10 GHz). An Intermediary Frequency (IF) signal after the

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photodiode is amplified and sampled using a high speed Digital Signal Oscilloscope (DSO) to perform digital demodulation and Error Vector Magnitude (EVM) measurement.

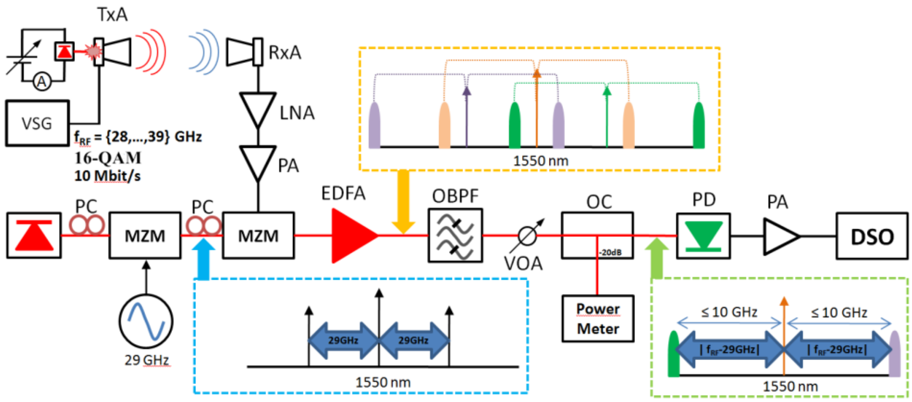

Fig. 5. Experimental setup including the photonic downconversion stage. VSG: vector signal generator, CS: Current Source, TxA: transmitting antenna, RxA: receiving antenna, PC: polarization controller, MZM: Mach-Zehnder modulator, LNA: low noise amplifier, PA: power amplifier, EDFA: Erbium doped fiber amplifier, OBPF: Optical Band Pass Filter, VOA: variable optical attenuator, PD: photo detector, DSO: digital storage oscilloscope; LO: local oscillator.

IV. RESULTS AND DISCUSSION

This section reports the experimental results for 16- and 32-QAM wireless transmission obtained using the developed antenna and photonic downconversion technique. Initially, it has been carried out experiments using OCRAA antennas for data transmission and one horn antenna for reception. Figure 6 presents the obtained results for a 16-QAM RF signal at 38 GHz propagated through 5 meters. The beating between the LO and RF signals measured was -14 dBm. The measured constellation is displayed in Fig. 6, in which the *rms* value of Error Vector Magnitude (EVM_{rms}) is only 3.09 %.

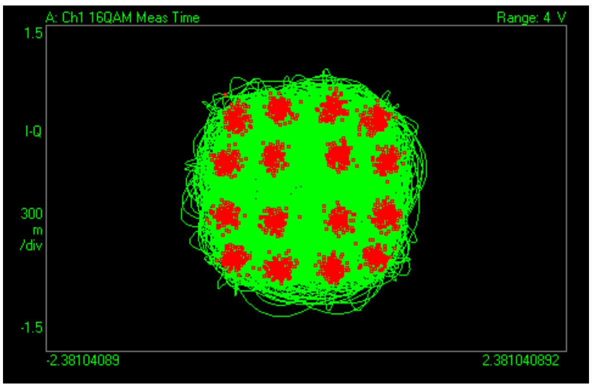

Fig. 6. Constellation of 16-QAM with EVM_{RMS} = 3.09 % for 38 GHz wireless transmission with photonic downconversion.

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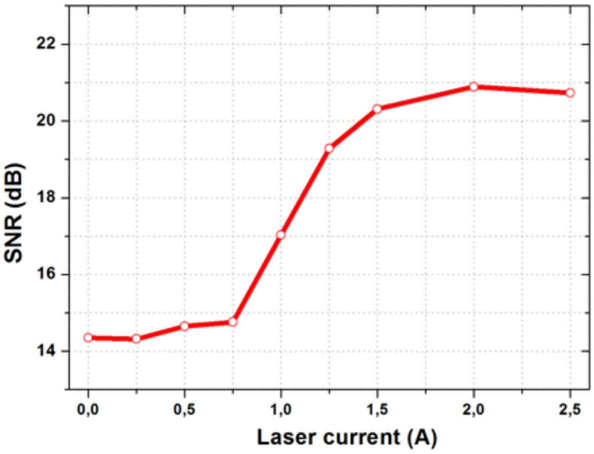
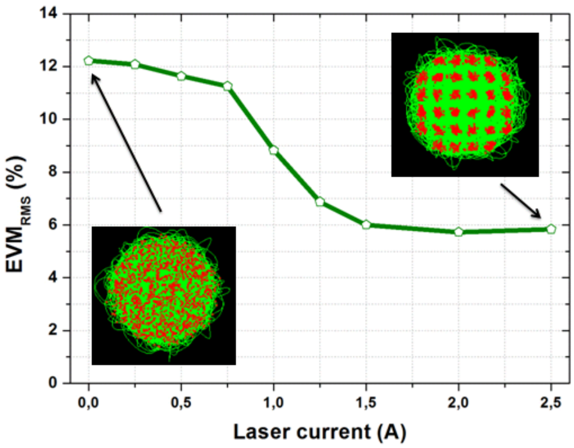
The main experiment has been focused on the implementation and applicability analysis of the optically controlled reconfigurable antenna. Once the used VSG can provide a higher output power level at the 39GHz, we decided to use the superior limit of the operation band, to obtain the best performance of the system. As described in Section 2, its bandwidth and radiation patter can be significantly managed by optimizing the incident optical power on the photoconductive switch. Mainly, its gain at 39 GHz can be significantly enhanced, from 2.62 dBi to 10.32 dBi, by illuminating the photoconductive switch, i.e. turning it to "ON" state.

Another test was performed for 32-QAM transmission pattern for 39 GHz frequency, which is the upper limit of the third bandwidth from OCRAA, as presented in Fig. 2. The free-space loss, calculated by Friis Equation [21], is 78.24 dB for 39 GHz and 5 m distance. Fig.7 reports the obtained results of the performance investigation for a 32-QAM signal as a function of the electrical Signal-to-Noise Ratio (SNR) and EVM_{RMS}. Both are plotted with respect to the applied current at the controller laser used to reconfigure the antenna properties.



a) SNR as a function of laser current



b) EVM as a function of laser currnt.

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Fig. 7. Experimental investigation of 39 GHz wireless transmission with photonic downconversion using one horn broadband antenna and an optically controlled antenna.

The constellation has been shown extremely poor for the “off” state of photoconductive switch and, consequently, the measured EVM_{RMS} was 12.2%. The higher is the laser current; the better is EVM_{RMS}, reaching 5.8% for 2.5 A. The measured constellation for “on” state is extremely better than the “off” state, as highlighted in the top-right inset of Fig. 7b. Additionally, SNR has also been significantly improved by 7 dB, as illustrated in Fig. 7a. These results demonstrate that the frequency-agile and optically steerable antenna properties can be efficiently applied to implement an adaptive wireless system in the mm-wave frequency range.

V. Conclusions

An optically controlled reconfigurable antenna for mm-wave applications was proposed, developed and implemented. Its frequency response and radiation pattern can be efficiently reconfigured by using a silicon photoconductive switch. It has been experimentally investigated by transmitting a 40 Mbaud 16-QAM and 32-QAM wireless system at 38 GHz and 39 GHz, respectively, under 78 dB link-budget requirements. Increasing the optical power on the photoconductive switch, the measured EVM_{RMS} has been gradually enhanced from 12.2 % to 5.8 %. Furthermore, the extremely poor constellation for “off” state becomes better as the switch was turned to “on” state. Moreover, the SNR also increased from 14.15 dB to 22.3dB, respectively, for “off” state to “on” state. The promising results encourage us to continue researching towards systems supporting unexploited frequency bands beyond the current commercial systems.

Acknowledgements

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