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28 GHz Switched-Beam Antenna Based on S-PIN Diodes for 5G Mobile Communications

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***Abstract*— This paper presents a 28 GHz switched five-beam antenna system based on a rectangular waveguide and a reconfigurable semiconductor circuit (RSC) with slots. Surface PIN (S-PIN) diodes are used to close or open slots in order to achieve required configuration of an aperture. The RSC with a modified WR28 waveguide compose a reconfigurable radiating structure (RRS) which provides three beams directed towards 0º, 30º, and 45º. Beam switching is achieved by reconfigurable arrangement of set of slots. Complementary RRSs connected to electromechanical RF switch is used to generate remaining −30º and −45º beams. The gain of each generated beam is similar because different number of slots is opened i.e., three, five, and nine slots for beams directed towards 0º, 30º, and 45º, respectively. Aperture of the antenna is controlled by a unit composed of high-current operational amplifiers. Measured results validate the performance of designed millimeter-wave reconfigurable antenna.**

***Index Terms*—adaptive arrays, antenna arrays, beam switching, millimeter wave technology, surface P-i-n diodes, slot antennas**

I. Introduction

5G is an emerging generation of mobile technology aiming to meet data traffic requirement for coming years. It will most likely be achieved though: ultra-densification, multiple antenna techniques (including massive MIMO), advanced waveforms, dynamic spectrum sharing, and a millimeter-wave spectrum for access and backhaul [1].

The World Radiocommunication Conference (WRC)-15 decided to locate mobile bands between 24.25 and 86 GHz for the future development of International Mobile Telecommunications (IMT) services [2]. The 28 GHz is attractive for several reasons. First, the 28 GHz band is still useful to create multipath environments compared to higher frequencies and can be used for non-line-of-sight communications. Second, the 28 GHz band is a target to first roll out of 5G services in real environment at the 2018 PyeongChang winter Olympic Games, which may push 28 GHz into consumer products before the standardization bodies finalize 5G standards [3].

The mm-wave band provides large bandwidth, however, until recently, it had been considered unsuitable for mobile communications because of unfavorable propagation conditions. Due to the high carrier frequency, mm-wave communications undergo high propagation loss, therefore beamforming is considered as an important antenna technique improving antenna's gain and a radio-link budget. Typically, beamforming is achieved by a set of antenna weights (amplitude and/or phase) applied to individual elements [4] in digital domain, analog domain, or both (a hybrid approach). Two most popular applications of beamforming are the digital beamforming and the analog phased array. Full scale implementation of digital systems is impossible due to the constraints of cost, power consumption and signal processing complexity. On the other hand, the potential of analog beamforming is limited by the unsatisfactory performance of phase shifters [5]. Therefore, a hybrid approach combining both analog and digital beamforming is more preferable [6]. Complexity, cost, and power consumption of the beamforming can be even more improved by means of the reconfigurable aperture. Such antennas provide typically few switchable beams in a given sector. Several reconfigurable antennas for high frequencies have been reported in the literature including: a planar switchable array for mobile terminal applications [7], a beam switching conformal array [8], an array based on Luneburg lens [9], and a monolithic MEMS-based reflectarray [10].

The principle of S-PIN diodes in SOI technology was described in [11]. First application of a waveguide slot antenna with reconfigurable aperture was presented in [12], however, 64 inclined slots consumed a lot of power, required complex control unit, and provided around 20% of efficiency [13]. In [14] an antenna based on a spatial multiplexing of local elements (SMILE) with only four independent slots was presented. The performance of this antenna was limited because only one radiating slot was used in each state.

This paper presents significant improvements to already published research on a reconfigurable antenna based on S-PIN diodes. Firstly, the antenna covers wide ±45º sector with five beams. All beams are available in desired frequency band and have similar gain. Secondly, the efficiency increased to 50% due to optimized dimensions, placement, and

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alignment of slots to the middle of the reconfigurable semiconductor circuit (RSC). Thirdly, power consumption and complexity of a control unit is lower because slots are grouped and connected to common DC biasing lines.

II. Reconfigurable Antenna Design and Operational Principle

A. Mechanical Structure

The designed reconfigurable antenna consists of two identical radiating reconfigurable structures (RRSs, left and right), and a commercial electromechanical radio frequency switch (ERFS) placed in between (MMT28BSL21 WR28 waveguide switch manufactured by Logus Mircowave [15]). Each RRS (left or right) is designed to generate three beams switchable in angular directions 0º, 30º and 45º. Three ports of ERFS are used: the common port (RFC) and two switchable ports (RF1 and RF2) connected to RRSs. The ERFS is used for selecting either left or right RRS, hence, providing desired sector of radiation: towards positive (ZOX plane where θ is positive) or negative (ZOX plane where θ is negative) range of angles. In this manner, two oppositely arranged structures are used to achieve five beams directed towards 0º, ±30º, and ±45º. A model of the antenna is presented in Fig. 1.

The RRS is based on a rectangular waveguide WR-28 (7.112 mm x 3.556 mm) with a slit (60 mm x 0.64 mm) etched along its narrower wall. The RSC is placed inside the waveguide under the slit. The slit is flared in the direction of the E-field and acts like a sectoral E-plane horn to improve the radiation performance of the antenna. Part of the waveguide under the RSC is filled by PTFE (Polytetrafluoroethylene). PTFE has smaller permittivity than silicon and higher permittivity than air, therefore such filling acts like a transition and is beneficial for electrical characteristics of the antenna, especially the impedance matching. A cross section and a picture of the RRS are presented in Fig. 2 and Fig. 3, respectively.

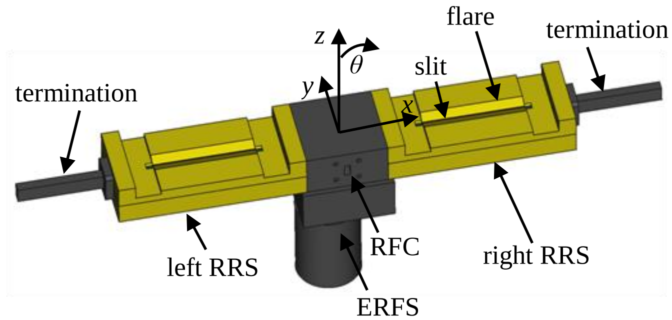

Fig. 1. Model of the reconfigurable antenna

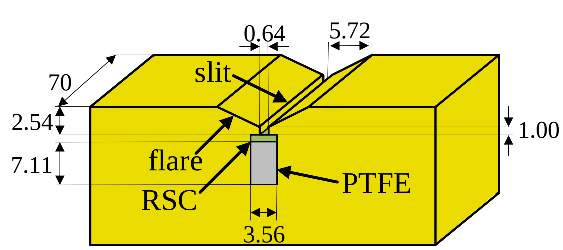

Fig. 2. Cross-sections of the RRS perpendicular to the waveguide (all dimensions in mm)

B. Reconfigurable Semiconductor Circuit

The RSC has fifteen reconfigurable slots with embedded S-PIN diodes. Slots can be reconfigured by appropriate DC biasing. When an S-PIN is reverse biased, its surface acts like a slot in the wall of the waveguide, hence, enables radiation. On the other hand, if an S-PIN is forward biased it acts like a conducting surface and blocks radiation. Polarization of a radiated wave is determined by the fundamental mode propagating inside the waveguide, therefore it is perpendicular to slots as indicated in Fig. 3.

Fig. 4 shows a schematic layout of the RSC and three configurations of the aperture. In this case a wave is propagating from left end to terminated right end exciting open slots. Remaining (non-radiated) part of wave's power is dissipated in the matched termination. Three, five, and nine slots are employed to generate beams directed towards 0º, 30º, and 45º, respectively. Number of slots is related to the effective aperture of the antenna seen from different angles, which is proportional to the cosine of a beam's direction. Therefore, to achieve the same performance of the antenna, more slots are used for beams directed away from the broadside direction. Spacing between slots influences phase-relations between fields radiated from slots, hence, determines direction of a beam. Slots are gathered into six groups controlled by separated DC bias lines. Table 1 presents detailed information on configurations of the antenna.

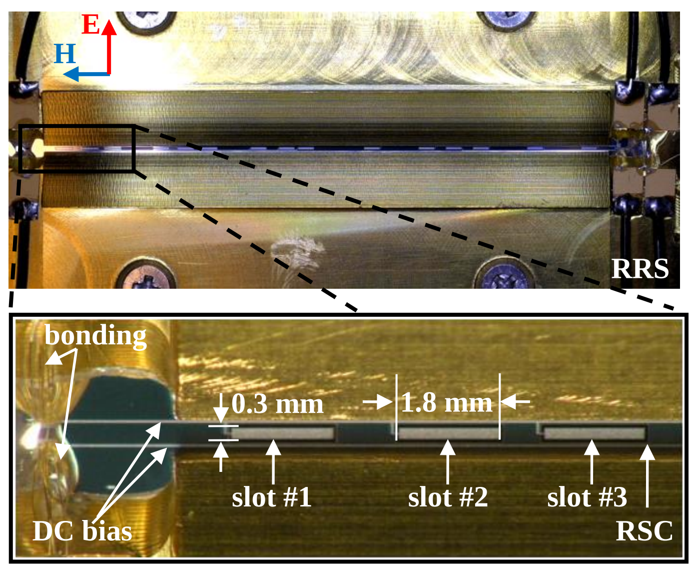

Fig. 3. Picture of the RSC mounted inside the RRS

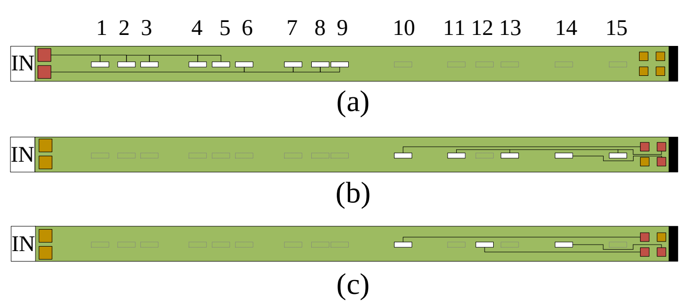

Fig. 4. The RSC with highlighted group of slots forming a beam in direction of: (a) 45º, (b) 30º, (c) 0º

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TABLE I
CONFIGURATIONS OF THE ANTENNA

Beam	Slots	ERFS position
−45º	1, 2, 3, 4, 5, 6, 7, 8, 9	RFC – RF1 (right RRS)
−30º	10, ,11, 13, 14, 15	RFC – RF1 (right RRS)
−0º	10, 12, 14	RFC – RF1 (right RRS)
+0º	10, 12, 14	RFC – RF2 (left RRS)
+30º	10, ,11, 13, 14, 15	RFC – RF2 (left RRS)
+45º	1, 2, 3, 4, 5, 6, 7, 8, 9	RFC – RF2 (left RRS)

C. *Control unit*

The control unit is used to bias S-PIN diodes and to change state of the ERFS. A diagram of the control part of the antenna is presented in Fig. 5. The control unit consists of 12 DC bias circuits (6 bias lines for each RSC) and a microcomputer. The microcomputer set appropriate levels on a LVTTL control bus. The control bus is an input for high-current operational amplifiers. Every operational amplifier operates as a voltage source with an adjustable current limit, up to 2 A. Current limits of amplifiers were set accordingly to number of S-PIN diodes connected to each bias line, assuming 100 mA per diode. The operational amplifier in a comparator circuit is used to switch the output between two voltages: 3.3 V and −1.8 V. Such voltages were selected to ensure appropriate forward and reverse bias. Positive voltage is used to forward bias a diode. Voltage drop on a conducting diode is approximately 0.7 V, thus remaining part of a positive voltage will drop on DC bias lines, DC bias wires, and an internal resistance of the amplifier. Negative voltage is used to reverse bias a diode and improve removal of carriers from the intrinsic region. Picture of the complete system placed inside the anechoic chamber is presented in Fig. 6.

III. MEASUREMENTS

Reflection coefficient (S_{11}) was measured for six states of the antenna and is presented in Fig. 7(a). The antenna's bandwidth defined as $|S_{11}|<–10$ dB in the worst case equals 600 MHz between 27.9 GHz and 28.5 GHz. If the impedance bandwidth is defined as $|S_{11}|<–6$ dB, then in the worst case it equals 2.4 GHz. Results for both RRSs are similar, although one can observe dissimilarity of the reflection coefficient for +0º and -0º. In these states the spacing between slots is for in-phase excitation. This enables broadside radiation, however, waves reflected from each slot are approximately in-phase and increase the reflection coefficient. Such interference of reflected waves is sensitive to inaccuracies of fabrication and misalignment during the assembly process, therefore the reflection coefficient may vary between RRSs. This effect is not so substantial for ±30º and ±45º states.

The gain and the radiation pattern of the antenna were measured inside an anechoic chamber. Fig. 7(b)-(d) present radiation patterns measured in H-plane in polar coordinates for most favorable frequencies. Fig. 8 shows measured realized gain versus frequency and angle θ; subfigures (a)-(c) and (d)-(f) characterize right RRS, and left RRS, respectively. Both structures are arranged oppositely, therefore plots of radiation patterns are almost identical mirror reflections, which also demonstrates repeatability of the RSC. The gain is higher than 6 dBi for all configurations. Maximum gain is slightly shifted to higher frequencies giving 28.2 GHz for 0° beam, 29 GHz for 30° beam, and 29.1 GHz for 45° beam.

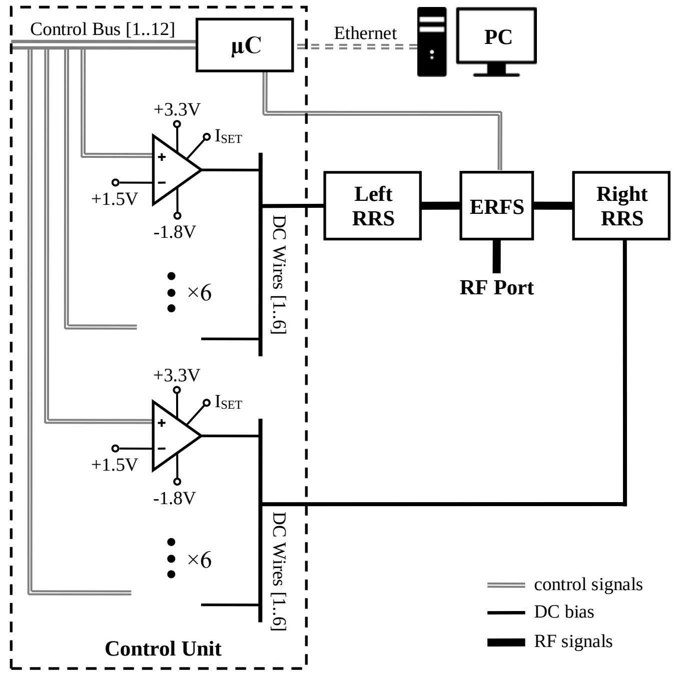

Fig. 5. Diagram of the control unit and its interfaces to the antenna and a PC

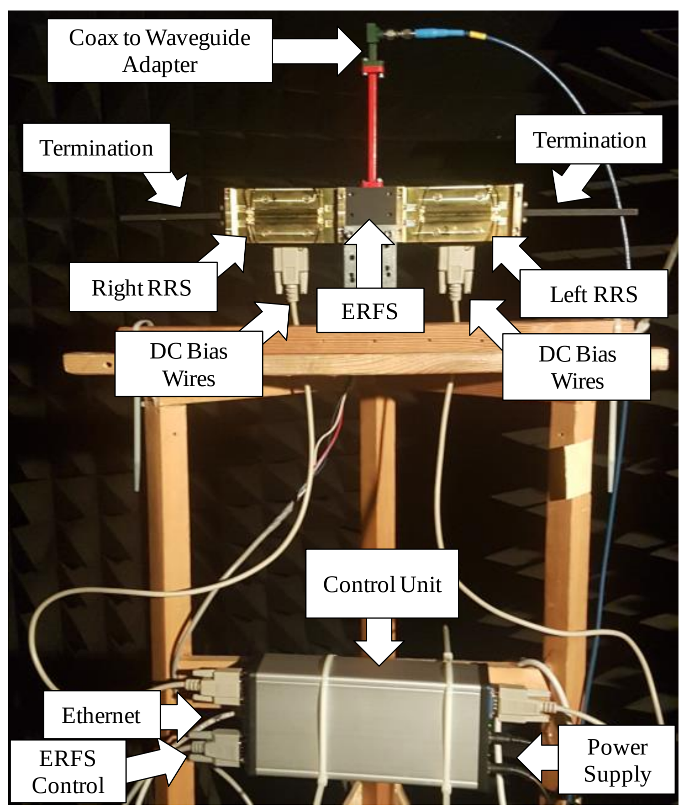

Fig. 6. Complete system composed of the antenna and the control unit

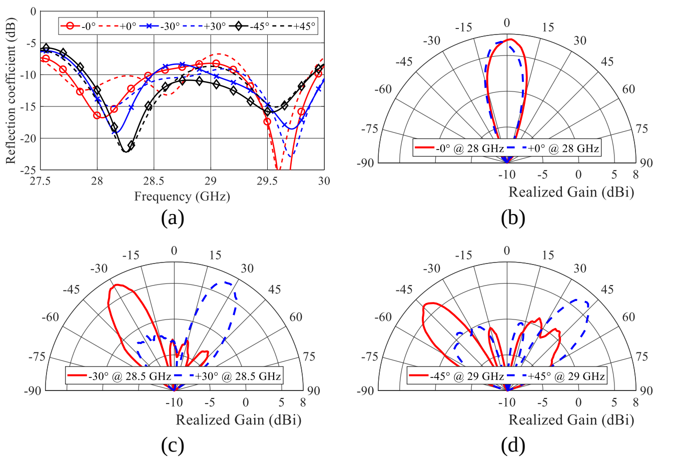

Fig. 7. Measurements of: (a) the reflection coefficient; and radiation patterns in H-plane for: (b) ±0º beams, (c) ±30º beams, (d) ±45º beams

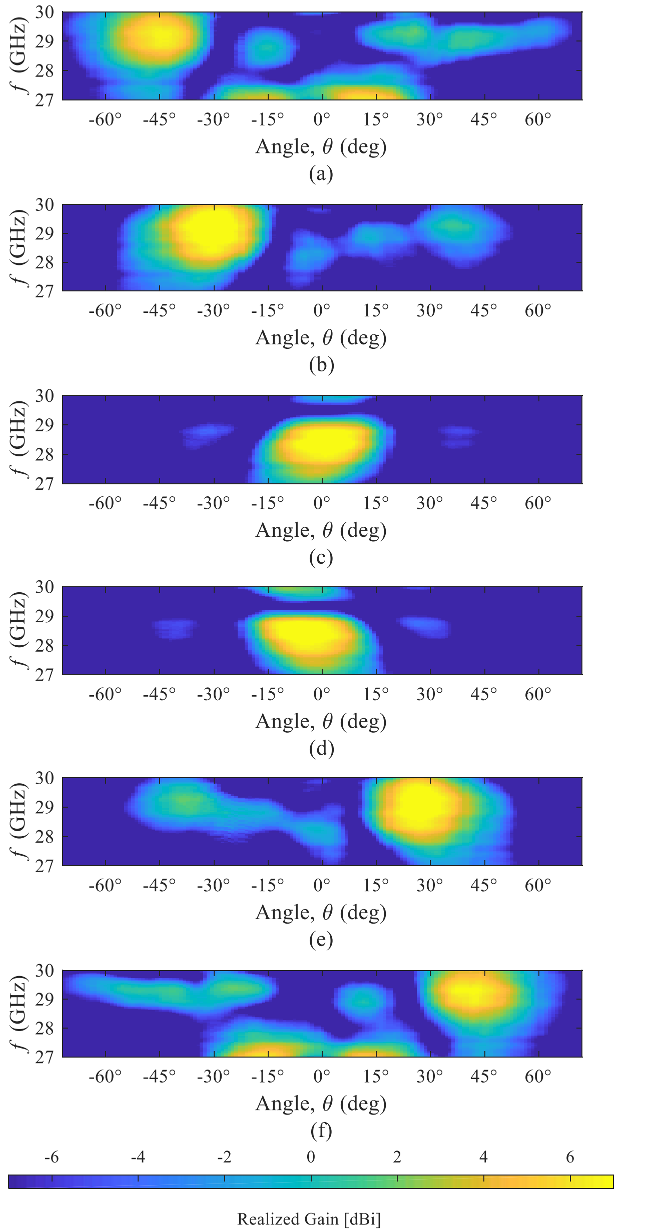

Fig. 8. Measured realized gain as a function of frequency and angle θ for main beam directed towards: (a) −45°, (b) −30°, (c) −0°, (d) +0°, (e) +30°, (f) +45°

IV. Conclusion

The beam-switching antenna for 28 GHz band is based on a reconfigurable semiconductor structure with embedded S-PIN diodes. Only three beams can be achieved with a single RRS, therefore two oppositely arranged RSSs connected to a switch are employed to obtain five beams directed towards 0º, ±30º, and ±45º. S-PINs on the RSC are grouped and connected to common DC biasing lines to simplify an interface with the control unit. Number of radiating slots increases with required beam's angle to achieve similar gain. The control unit is a voltage source with a current limit providing positive and negative voltage, hence S-PIN diodes can be forward or reverse biased. Measurements confirmed beam-switching capabilities of the antenna. The complete system demonstrates a great potential as a mm-wave base station antenna for a future 5G network.

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