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Reconfigurable reflectarrays for 5/6G wireless systems with linear polarization

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Abstract. Numerous studies on wireless technologies for the fifth and sixth generation networks are widely conducted at the moment. They are driven by potential opportunities of digitalization in the information society era. Further enlargement of data transfer rates is required to enhance virtual interactions in various public areas via appearance of new services and applications. In this work, we report on the development of a reconfigurable reflectarray for 5/6G wireless communication systems with linear polarization. The proposed reflectarray utilizes current controlling diodes in a metallic screen inserted in between of front and rear metallizations of a planar patch antenna array. This makes it capable of a digital beam steering on a microsecond scale. Performance of the reflectarray designed for operation at 15 GHz is described in terms of numerical simulations and prototyping. We also discuss prospects and technological challenges of fabricating a scaled-down version of the reflectarray for 150 GHz operation.

Keywords: reconfigurable reflectarray, 5/6G network, wireless channel, sub-terahertz communication

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Реконфигурируемые антенные решетки отражательного типа для беспроводных систем 6/5G с линейной поляризацией

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Аннотация. В настоящее время активно проводятся многочисленные исследования беспроводных технологий для сетей связи пятого и шестого поколений. Они обусловлены возрастающим потенциалом цифровизации в эпоху информационного общества. Для улучшения виртуального взаимодействия в различных общественных сферах за счет появления новых сервисов и приложений требуется дальнейшее увеличение скоростей передачи данных. В данной работе мы сообщаем о разработке реконфигурируемой антенной решетки отражательного типа для беспроводных систем 6/5G с линейной поляризацией. Предлагаемая конструкция антенной решетки основана на использовании управляющих током диодов в металлическом экране между лицевой и тыльной металлизацией двумерной решетки патч-антенн. Это обеспечивает дискретное диаграммообразование в отраженном свете с микросекундным быстродействием. Представленные в работе характеристики антенной решетки с рабочей частотой 15 ГГц получены как в рамках численного моделирования, так и прототипирования. Обсуждение перспектив и технологических сложностей изготовления масштабированной версии антенной решетки с рабочей частотой 150 ГГц также представлено в работе

Ключевые слова: реконфигурируемая антенная решетка отражательного типа, сеть 6/5G, беспроводной канал, суб-терагерцовая связь

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Introduction

The studies on wireless technologies for the fifth and sixth generation (5/6G) networks are of current interest. They are driven not only by a potential enlargement of data transfer rates, but by the prospects of appearance of new services and applications as well [1]. Ultra-directional transceivers are proposed to improve connection quality in sub-terahertz (sub-THz) communication channels. This makes them less vulnerable to propagation losses and fading, but more vulnerable to blockages [2]. The issue can be resolved if reconfigurable reflectarrays are used for beam routing in sub-THz data links. The reflectarrays together with a transmitter and receiver in a wireless channel should utilize optics capable of fast beam steering [3]. In this work, we report on the development of a reconfigurable reflectarray for 5/6G networks. It makes use of a diode-based design of each cell ensuring a sub-THz beam steering on a microsecond scale or faster.

Materials and Methods

Fig. 1 illustrates schematic of a 15 GHz reconfigurable reflectarray (RRA). RRA utilizes current controlling diode switches (DSs) in a metallic screen (MS) inserted in between of front and rear metallizations of a planar patch antenna array. The latter is based on a 0.338 mm thick low-loss dielectric substrate with relative permittivity $\varepsilon_r = 3.5$ [4]. This makes the design compatible with the use of a fused quartz if operation at sub-THz frequencies is considered.

Referring to Fig. 1, Gaussian beam (GB) of a linearly polarized light incident along normal to the RRA surface is reflected at angle θ determined by the configuration of up to 3 DSs. Quantities $\mathbf{k}$ and $\mathbf{E}_0$ denote wavevector and electric field strength of incident GB. The design ensures a multidirectional beam steering by rearranging currents in MS. For turned on DSs 2–3 all over RRA and tuned on/off DS 1 in even/odd rows (or vice versa) oriented along $\mathbf{E}_0$, in-reflection phase shift between neighboring rows is approximately 180°. Thus, bidirectional beam steering is implemented. Calculated θ swings from −15° to +15° if DSs act as ideal switches. These findings are further experimentally justified.

To measure reflective properties of the developed RRA, we designed transmitting (T*x*) and receiving (R*x*) planar patch antenna arrays. Using classic literature [5–7] as guidelines, we developed a first-run geometry of the antenna arrays comprising 8×8 elements. Given that desired operating frequency was in the range of 13–16 GHz, we chose a relatively thin substrate with low

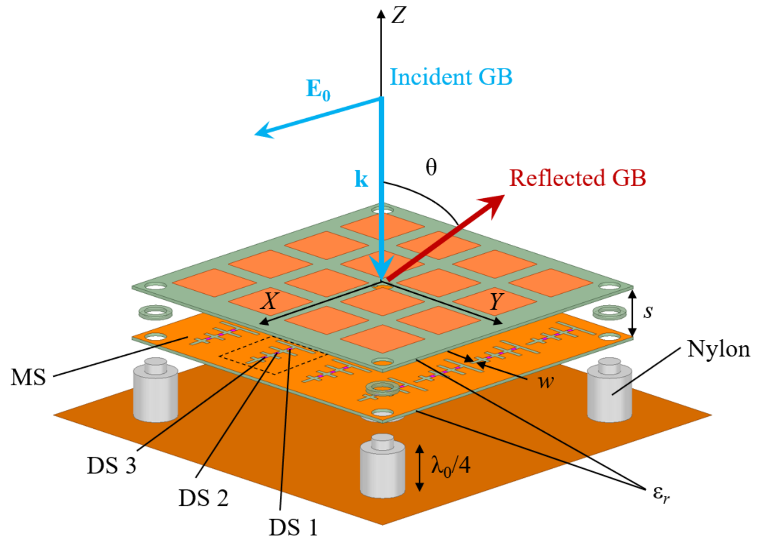

Fig. 1. Schematic of a 15 GHz RRA in action

permittivity and small loss tangent (namely, FSD255G series PCB laminate with a thickness of 1 mm [8]). This allowed us to implement a feeding network with a microstrip line significantly narrower than the patch and to achieve efficient distribution of a microwave power in the array. In accordance with equations (14–6) and (14–7) from [5], linear dimensions of patch antennas were calculated in the computer algebra system (CAS) Maxima. The distance between them of $3\lambda_0/4$ was chosen with λ_0 denoting a free space wavelength. For an 8×8 elements patch antenna array, we calculated beam profiles in E- and H-planes with the aid of CAS Maxima.

The developed pattern of patch antennas was further equipped with a feeding network. Due to the pattern compactness, we decided not to rely on regular quarter-wave matching impedance transformers, but to implement a constant width microstrip line with multiple T-junctions. Such a geometry potentially suffers from excessive input return losses but lacks noticeable distortion of beam parameters as compared to classic patch antenna array designs. Electrical lengths of the microstrip lines from each antenna in the array to the common microwave input port were kept identical.

Results and Discussion

Fig. 2,*a* provides resulting drawing of the developed pattern of a ready-to-use T*x*/R*x* antenna array. This drawing was used as an input for a computer numeric control (CNC) machining with the aid of a MITS Eleven Lab milling machine.

To measure beam profiles of the fabricated antenna array prototypes, we developed an experimental setup including a microwave vector network analyzer (VNA) and 3D-printed holders. Two prototypes of the antenna array under study were connected to the VNA ports 1 and 2 through coax cables. The array planes were set parallel such that their optical axes were coaligned. Sweeping the scan angle of the receiving antenna array from −90° to +90°, we measured the magnitude of S21-parameter at carrier frequency of 15 GHz. The developed antenna arrays demonstrated consistent performance in both simulations and performance tests. Moreover, the achieved beamwidths of 10° were suitable for using the arrays as remote probes in evaluation of RRA prototypes developed by us.

When prototyping RRA, all DSs 2–3 were replaced by bridges and DS 1 was replaced by a bridge/gap in even/odd rows oriented along $\mathbf{E}_0$ in the dendriform slots of MS (see Fig. 1). Fabrication tolerances for the slot width, w, and the spacing between the top substrate of RRA and MS, s, were found to be the most crucial. We measured relative fabrication errors $\delta w = 7.2\%$ and $\delta s = 9.5\%$, and used these values to predict margins for parameters of reflected GB. We numerically observed relative errors $\delta\theta = 5.9\%$ and $\delta I = 7.6\%$ for the angle of reflection and the intensity of the reflected beam, respectively. In the numerical simulations, the spacing between the substrate with MS and the ground plane was fixed to $\lambda_0/4$. This was consistent with our experimental findings.

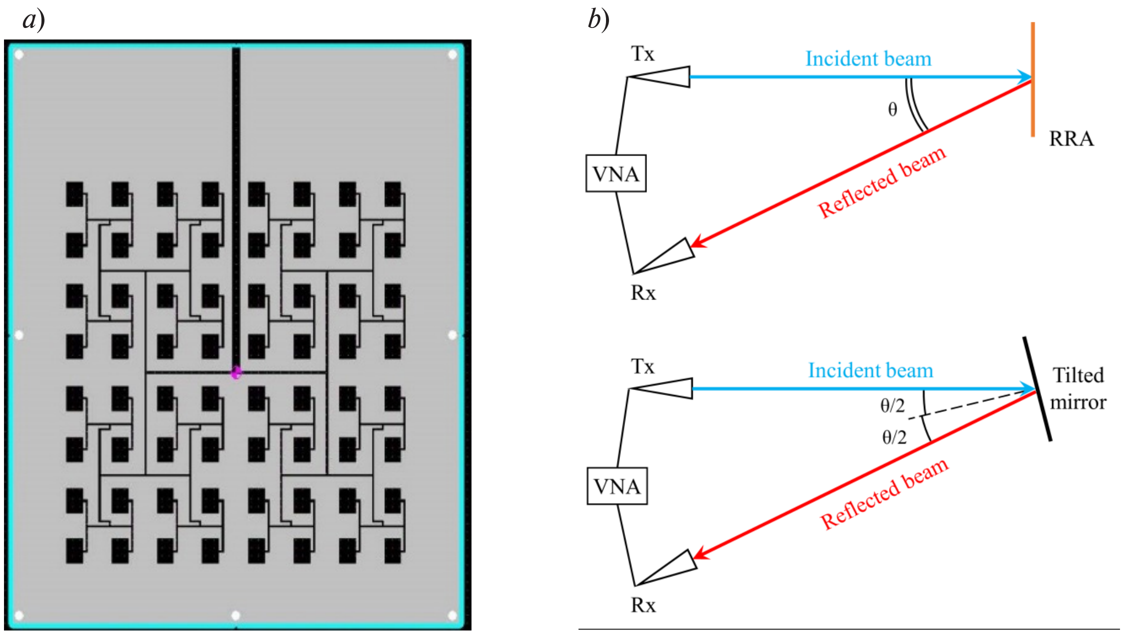

Fig. 2. Developed pattern of a ready-to-use T*x*/R*x* antenna array (*a*). Experimental setup for measuring H-plane profiles of T*x* beam after reflection from tilted mirror or RRA (*b*)

Fig. 3 demonstrates measured H-plane profile of T*x* beam after reflection from RRA. The profile was compared with that reflected from tilted mirror replacing RRA, when rays in the beam obey the geometrical-optics law of reflection. The beam profiles were measured at 15 GHz in accordance with experimental setup presented in Fig. 2,*b*. As one can clearly see, behavior of main and side lobes in the beam profiles agree well. We also observed identical main lobe levels within the measurement uncertainty of 0.5 dB. The profiles of the main lobes are quantitively consistent down to −12 dB. It is also worth noting that RRA outperforms tilted mirror in terms of side lobe levels, whose peak values are correspondingly equal to −10.5 dB and −6 dB. Angle θ was fixed to 15° in all the measurements.

We believe that obtained experimental results are quite promising for further development of a miniaturized version of RRA. Thus, we expect reduction of δw and δs down to 1–2% leading to significant decrease in $\delta\theta$ and δI, when fabricating a 150 GHz RRA with the chosen form factor. This is to be achieved upon use of photo-, e-beam lithographies for deposition and patterning of thin-film metallic surfaces and precise computer-aided machining for packaging. Additionally, our simulations of RRA with different impedances of DSs in on/off states confirm usability of Schottky diodes with feasible parasitic parameters. We believe that all together proves technological robustness and suitability of the developed RRA for 5/6G wireless communication systems.

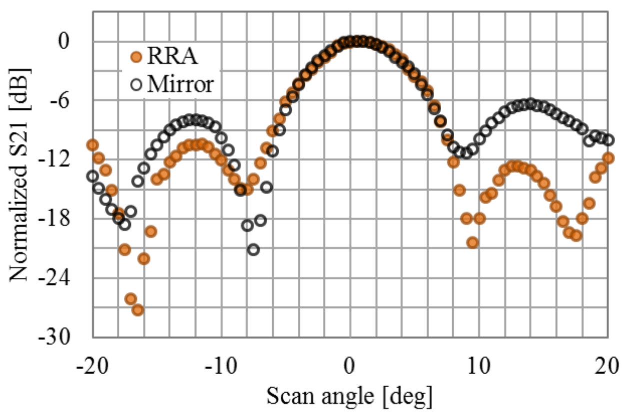

Fig. 3. H-plane profiles of T*x* beam after reflection from tilted mirror or RRA

Conclusion

We developed and prototyped RRA operational at 15 GHz. The RRA design relies on a low-loss PCB substrate with relative permittivity of 3.5. This makes it a quartz-compatible and easily scalable for operation in the sub-THz band. The proposed design utilizes current controlling diodes in a metallic screen inserted in between of front and rear metallizations of a planar patch antenna array. To simplify prototyping, the fabricated RRA has 1-bit elements, the pattern of phase shift upon reflection from them is fixed such that the deflection angle equals 15°. We observe agreement between calculated and experimentally measured profiles of reflected from RRA beams. The profiles are also compared with that reflected from tilted mirror replacing RRA in position, when rays in the routed beam obey the geometrical-optics law of reflection. Behavior of main and side lobes in the beam profiles agree well. We also observed identical main lobe levels within the measurement uncertainty of 0.5 dB. The profiles of the main lobes are quantitively consistent down to −12 dB. It is also worth mentioning that RRA outperforms tilted mirror in terms of side lobe levels, whose peak values are correspondingly equal to −10.5 dB and −6 dB. The developed RRA design potentially ensures up to a 3-bit resolution of the elements. This, in turn, significantly increases number of available states upon digital beamforming in reflected light. Use of Schottky diodes for in-reflection phase shift in the RRA elements enables sweep time on a microsecond scale. We believe that all together suggests suitability of the proposed RRA for beam routing in 5/6G wireless communication systems.

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