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Abstract—This paper presents a single bit millimeter wave (mmWave) intelligent reflective surface (IRS) unit cell for use in 5G communication enhancement. A PIN diode switch is used to introduce a 180° phase shift in reflection mode between ON and OFF state. The geometry of the top layer of the unit cell allows for transverse electric (TE) polarized reflection with an angular stability of 30°, both in azimuth and elevation plane. The design is intended for use in the n257 FR-2 band for 5G applications with the center frequency at 28 GHz. The proposed unit cell design covers a bandwidth of 3 GHz while achieving the required phase difference of 180° ± 20°. The magnitude of reflection is greater than 78.5% throughout the band. These performance characteristics allow the proposed unit cell to be useful in digitally programmable metasurface applications with features such as beam focusing, beam steering and beam scattering.

Keywords- metasurface, mmWave, unit cell, 5G, IRS.

I. INTRODUCTION

With the revolution in modern communication technologies, the world has experienced a shift of era. The very lifestyle of human beings has been completely transformed with the advancement of fast and reliable wireless communications, along with great upgradations in every industry imaginable. The scientific community, looking to further push these advancements, has shown interest in pursuing the use of mmWave bands. With expected data rates of greater than 100 Gbps, the mmWave technology aims to fulfil the requirements of extremely high data using applications [1]. A lot of work has been done on optimization of modulation and coding schemes for highest possible data rates [2]-[4]. The 5G and 6G (already offering ultra-wide bandwiths), have been coupled with the use of massive MIMO antennas, which use spatial multiplexing to allow very high data rates [5]-[7]. One of the uncontrollable variables has been the properties of the wireless channel (from transmitter to receiver) and has a drastic effect on the performance of mmWave signals. The mmWave frequencies suffer from disintegration, while coming across humans or objects (non-metallic) in their path [8].

Over the past one decade, a lot of research has been conducted in an effort to increase the spectral efficiency of the wireless propagation channel through use of reconfigurable intelligent surfaces (RIS) [9]. Metasurfaces have been widely used to achieve a wide array of electromagnetic (EM) wave manipulation functions through their structure and geometry such as filtering (bandpass/band stop) [10], [11], cross polarization reflection/transmission [12], [13], linear-to-circular polarization conversion [14], and absorbers [15], [16]. The RIS is a programmable class of metasurfaces, which have widely gained interest due to their ability to reconfigure and manipulate EM waves [17]. The IRS (a reflective RIS) is capable of anomalous reflection and reflects incoming EM waves at a desired angle, as opposed to specular reflection by a simple reflector [18]. Through use of IRS, secondary line of sight (LOS) is created in outdoor scenarios where blockages exist in direct path of transmitters and receivers. The IRS helps in the establishment of a dense and passive point to point communication network and would help eliminate the need for excessive base stations, which are costly and power consuming [19]. The IRS usually consists of a reflective metasurface which alters the behavior of the incident EM waves and assist in functions such as beam focusing, beam steering, filtering, scattering and absorption [17]. The concept of digital and programmable metasurfaces [20] enabled assigning digital codes to individual metasurface unit cells, allowing a programmable sequence to alter the surface properties and, hence, functionality. The tuning of these N-bit metasurface unit cells has been implemented via switching elements such as varactors [18], diodes [20], and liquid crystal [21]. The quantization of the phase difference of the N-bit unit cells assigns them their respective codes, which can be altered in a complete metasurface to achieve the required function (such as beam focusing, steering). Among the switching techniques, the most popular one is the PIN diode due to its low loss and utilizes a biasing network with low complexity. Although the varactors possess a continuous tuning ability and better phase resolution, they generate higher losses in ON state [22].
Currently, sub-6GHz bands are actively being utilized for wireless communications with most of the literature in RIS or IRS in the sub-6GHz band [23]. In [24], a novel and simple 1-bit unit cell design of metasurface is presented at sub-6GHz which exhibited reflection phase difference performance as required by IRS, over a band of 200 MHz. A multibit unit cell was presented in [25] using a combination of 3 PIN diodes and a capacitor and yielded a bandwidth of 1.5 GHz.

There is limited literature for the IRS at mmWave bands. In [26], a mmWave IRS was first presented using a combination of inductive chokes and two diodes per unit cell, one for each independent polarization. With a bandwidth of 2 GHz, the design showed an amplitude reflection of 5 dB in the operating band. In [27], a 1-bit unit cell which showed wideband characteristics for the IRS application with a 2.8 dB reflection magnitude loss is presented.

In this paper, we present a simple metasurface unit cell design for the RIS for the n257 band. The 1-bit design uses the PIN diodes for switching between the states. The low loss cell design is a suitable candidate for low cost, low complexity and easy to implement IRS for the mmWave applications.

II. UNIT CELL DESIGN

In general, the first step in RIS design methodology is the construction of a unit cell, which is a small part of a larger array. The array consists of tunable devices (resonators) which control the characteristics of the metasurface at cell level, thereby allowing phase response control throughout the metasurface.

The proposed metasurface unit cell is designed and simulated on CST Design Studio with periodic boundary conditions, thereby creating conditions for an infinite array simulation. The unit cell proposed is a three-layered model with two dielectrics in between them as depicted in Fig. 1. A rectangular patch of copper split into two by a vertical gap through the center, forms the upper layer of the unit cell design. Fig. 1 shows the top layer geometry and dimensions of the unit cell.

Layer 1 is responsible for the reflected electromagnetic (EM) behavior of the incident wave. The patches are etched on Rogers RT5880 substrate (ε_r=2.2 and tanδ=0.0009 at 10 GHz). The values of the unit cell dimensions are Lg=Wg=3.8 mm, Wp=1.45 mm, and Lp=2.7 mm.

Because it is intended to be a reflective metasurface, the second layer is a solid ground of 3.8 x 3.8 mm² and is also referred to as the RF ground. The third layer (bottom layer), also referred as the control layer, consists of the DC biasing circuit and the RF diode switches. The switch used in this design is the Aluminum-Gallium-Arsenide (AlGaAs) beam lead PIN Diode by MACOM and is suitable for applications up to 40 GHz. The RF ground and the control layer are separated by a dielectric sheet of the commonly used FR-4 substrate (ε_r=4.3 and tanδ=0.025). The vias indicated in Fig. 2 are used to short the patch to the RF ground in the switch ON state. The via location is optimized for achieving the required phase response.

III. RESULTS AND DISCUSSION

The IRS unit cell model is simulated in CST Design Studio using periodic boundary conditions. The reflection amplitude of the proposed unit cell design is shown in Fig. 3. The ON and OFF states are achieved by switching the state of the RF PIN diode. The amplitude loss of the y-incident wave in reflection mode is less than 2.1 dB throughout the n257 band.

Fig. 2. Unit cell model with implementation of PIN diode with vias

Fig. 3. Simulated reflection coefficient of the proposed unit cell for a TE-incident wave

Fig. 4. Simulated phase difference between ON and OFF states up to azimuth incidence of 30°
The unit cell is excited at varying azimuth and elevation incident angles to see the effect of incoming signals from different directions, as is expected to be in a real outdoor communication network scenario. Fig. 4 shows the phase difference of the unit cell with varying azimuth incidence angle $\theta$. The operational requirement of the 1-bit IRS is satisfied as long as the phase difference remains in the $180^\circ \pm 20^\circ$ region. It is noteworthy that the $180^\circ \pm 20^\circ$ phase quantization condition is for the 1-bit unit cell only. For an N-bit unit cell, the phase difference would have to be quantized in $2^N$ parts.

The phase difference between ON and OFF state is within the region of acceptance up to an incident angle of $30^\circ$. This shows angular stability of $30^\circ$, which allows a field of view (FOV) of $60^\circ$ in azimuth plane when used in RIS application. A bandwidth of $3$ GHz is achieved which covers the complete n257 band.

A similar case is shown is shown in Fig. 5, where the angular stability is shown by varying the elevation angle $\phi$. The unit cell simulation shows that design is angularly stable in elevation plane up to $30^\circ$. This study is one of its kind, as it shows the FOV of operation in both azimuth and elevation planes, which is an important aspect in the placement of an IRS system for enhancement of network coverage for maximum data throughput.

IV. Conclusion

A metasurface unit cell is designed and simulated on CST Design Studio for mmWave RIS application. The design operates from $26.5$ GHz to $29.5$ GHz with center frequency at $28$ GHz, covering the n257 $5$G band. The phase difference of $180^\circ$ is introduced by shorting one patch to the RF ground, thereby satisfying the phase difference requirement for 1-bit digital metasurface. The cell state is switched OFF and ON by use of PIN diode at the bottom layer of the design to prevent any interference in EM wave manipulation. The design has a reflection amplitude loss of less than $2$ dB and an angular stability of $30^\circ$. The proposed design can be used in RIS for mmWave communication enhancement.

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