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RESEARCH ARTICLE

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Reconfigurable Metasurface-Based Antenna for Beam Steering in Next-Generation Wireless Communication Systems

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Abstract

A reconfigurable reflector element utilizing Metasurfaces (MS) with a lower feature and diminished weight is proposed for inside and outside 5G transmission techniques to surmount barriers, facilitating wireless quasi-line of sight communications at 38 GHz. Incorporating variations with MS unit cells (UC) facilitates tunability and adaptability. This methodology has been documented in numerous research studies, with frequency extending to the K-band. Currently, elevated frequencies are predominantly utilized, particularly in communications. This study introduces the layout of a reconfigurable MS reflector operating at Ka-bands, using an innovative resonant UC that provides uniform reflection across a broad range of incident angles, along with a straightforward DC bias stimulation for every UC, enabling two-dimensional (2D) ongoing manipulation of the reflecting stage. The UCs have a variable reflecting phase range exceeding 320° across a broad capacity. Results of one-dimensional (1D) and 2D systems at 38 GHz are shown. A steering rate of up to +48° was achieved for azimuths or elevations. A concurrent separate 2D beam steering (BS) capability of up to 15° in azimuths and +5° in elevations is demonstrated, enabling the circumvention of obstructions within a feasible angular geographic cone of 25° and 15°.

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Introduction

The desire for enhanced data communication rates necessitates the utilization of higher frequencies, shown by the advancement of fifth generations (5G) cellular interactions, which employ Millimeter-Waves (MMW) (30-300 GHz) for both indoor shorter-range connections and outside points-to-points connectivity.[1,12]. The characteristics of wave-propagation in MMW irradiation closely resemble the ray-traced theory.[2] Surroundings, specular reflections, multipath effects, and the directivity of broadcasters and recipients influence it.[14] Tuning reflections in 5G communications facilitates quasi-lines-of-sight pathways and enhances the channel quality.[3, 16] Exterior connection necessitates circumventing impediments such as edifices and other structures in metropolitan environments and mountainous terrains in rural regions.[4]

Indoor communications necessitate adjustable reflectors to navigate walls and corners. Deploying a 5G cellular connection necessitates constantly monitoring the user's position and the precise alignment of the MMW beam .[15, 20] The monitoring technique is now conducted via the existing 4 G. Determining the consumer's exact position allows the Ground Station (GS) to choose the optimal path utilizing adjustable reflectors around itself and the user.[13, 21]

Network capacity and component quantity necessitate cost-effectiveness, lower-profile, lightweight, remotely-operated, and efficient technologies. This work presents a Metasurface (MS) system that can be controlled by the GS to optimally direct the beam to the consumer, characterized by lower weight, lower complexity, and lower cost. MSs, particularly programmable MSs, generate significant interest in the scientific community.[18]

Numerous transdisciplinary applications significantly involve MS. An MMW MS ideal absorber was created to identify micropoisons in potable water, and a parabolic layer was employed in W-band transmission.[5]. These MS are predicated on resonating unit cells (UC) and are constrained to a shorter bandwidth centered around a specific operational rate.[17]

Incorporating tunability into each UC facilitates a programmable MS and enhances the capabilities and possibilities of MS applications.[19] Integrated electrical devices or tunable substances attain adaptability for the MS. Examples include Positive-Intrinsic-Negative (PIN) toggles, Micro-Electro-Mechanical Systems (MEMS) toggles, liquid crystal substances, piezoelectric components, and varactor detectors.[6]

Reconfigurable MSs were utilized for many applications, including reconfigurable reflect arrays, programmable antennas, leaky-wave antennas, tunable filtering and absorbents, parabola mirrors with adjustable focus, and polarized rotators with tuning capabilities. A reconfigurable MS with varactor diodes was developed for the X-band and lower frequencies. Only simulation studies have been reported for Ku-band frequency. Modifying the MS element by creating a suitable single UC for the new utilized frequencies is necessary.

Producing MS at elevated frequency bands, such as K-bands and Ka-bands, necessitates reducing the UC size. The varactor dimensions significantly influence the front MS region, resulting in greater absorption and dispersion.[7] The model and evaluation of novel reconfigurable MS reflectors in K-band are discussed. This MS reflector facilitates autonomous two-dimensional continuous Beem Steering (BS) of reflected radiation.[11] It is appropriate for inside and outside 5G transmission techniques, effectively addressing barriers including buildings, walls, and corners. In contrast to the intermittent reflective phase technique utilizing switches, the continuous reflection phase technique mitigates BS quantized loss by as much as 3 dB. To the understanding, a 2D continuous adjustable MS for K-band frequency ranges has not been developed or reported.[10]

Metamaterial-based Antennas

Metamaterial (MM) based antennas utilize meta-surfaces to converge Electromagnetic (EM) impulses. MMs are artificially manufactured substances designed to possess distinctive features that do not exist in nature. MMs acquire characteristics due to the unique configuration of sub-wavelength features. The precise geometry and placement of sub-wavelength structures allow MMs to control Electromagnetic (EM) waves by obstructing, deflecting, or absorbing the Radio Frequency (RF) signal. MMs possess distinctive properties whereby their relative permeability and conductivity can assume negative and positive values. Diodes, capacitors, or RF switching can regulate their refractive coefficient. Thus, MMs can direct the antenna pattern of radiation without the necessity for intricate structures or phase shifters. Due to their innovative features and design effectiveness, MMs are currently experiencing significant growth.

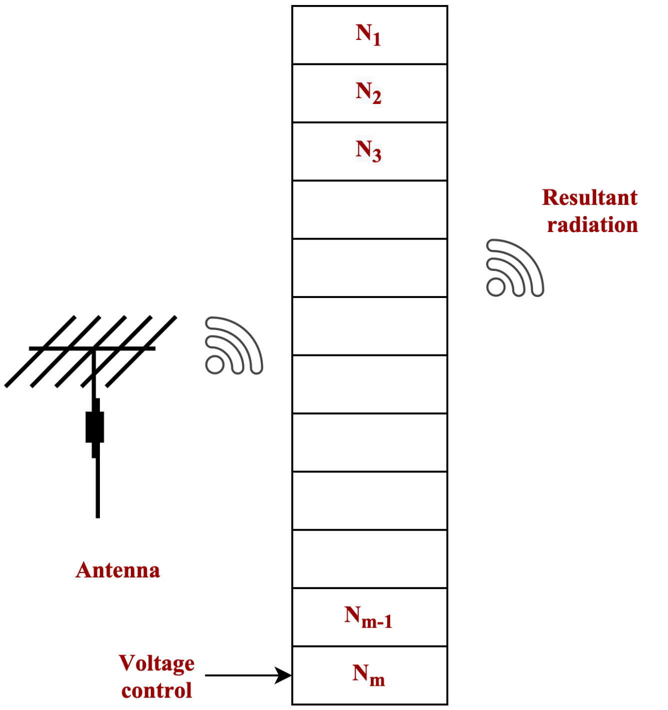

Fig. 1: MM-based materials

MM-based radios comprise periodic metallic UC fabricated on a substrate and positioned above the radiating surfaces. They function as Frequency-Selective Surfaces (FSS). UCs are linked to variations to provide BS. By adjusting the electric field of each UC, the permittivity and permeability can be altered, hence modifying the material's refractive index. In this arrangement, an FSS device is positioned before the horn antenna (Fig. 1). The FSS unit comprises a rectangular metal-based ring and an adhesive patch. These diodes are placed in alignment with the polarization orientation of the incident electrical field. By adjusting the variations, the propagation stage of the radiated wave can be modified to facilitate BS.

A lens based on MMs has been built for BS. In these antennas, MMs function as a lens. MM layers are positioned atop radiating components. A BS in combined lens antennas is accomplished through the displacement of the radiating array components situated at the back focal plane of the lens. The refractive indices of MM lenses can be altered by adjusting the functional device within the MM.[8]

MMs can enhance the beam scanner range and efficiency of traditional antennas. The incorporation of MMs in antenna construction results in a reduction in size and suppression of side lobes.[9] MM antennas can facilitate communication linkages, navigational devices, and surveillance devices. Antenna builders must contemplate some issues related to MMs. Due to their function as FSS, antenna performance varies with frequency, rendering MM antennae potentially unsuitable for narrowband purposes.

Design

The frontal, posterior, lateral, and three-dimensional internal views of two contiguous UCs, along with the analogous circuit design of the UCs. The UCs consist of two analogous dielectrical substrates, designed RT/Duroid 5880 with a dielectric constant of 2.1, and three copper sheets measuring 36 micrometers in thickness. The varactor arrangement features two horizontal strips on the upper level, each linked to a pad. One of the horizontal strips is equivalent to the dimensions of the UCs, denoted as W. The second strip, designated as S, is smaller, linked via the circular patches in the lowest copper level, and serves as the DC biasing level. The central copper sheet serves as a metal grounding and is isolated by an opening from the via that intersects it.

A minor breach of the & axis symmetry occurs within a singular UC due to using one via and the varying strip widths. The UCs on the & column are a replica of the left-hand UCs, resulting in a symmetric array (Fig. 2). The UCs are regulated by the interaction between the radiated electric field element and the edges of the UC sheets. is inversely related to the length D across the leading edges of the strip, as delineated in the formula.

$$C_{int} = \frac{\pi \varepsilon_o \ \varepsilon_r}{\log(4(S_l + L) / S_l} \qquad (1)$$

denotes the breadth of the strip. The width P of the UC exceeds the length L, enabling the strips to be arranged to , and result in minimal intrinsic capacitance. The computed capacitor contributions from the patch ends are 0.05 pF and 0.06 pF for = 0.9 mm and =0.5pF, = 0.7 mm, totaling = 0.08 pF. The capacitor and coupling factor among neighboring UCs diminish. This design facilitates function at Ka-bands frequency ranges, providing adequate surface space for varactor incorporation while minimizing absorption and diffusion. The decrease in Elevates UC losses, thereby imposing limitations. It disrupts the regularity of the electric field dispersion within the UC and reduces bandwidth.

The MS architecture and the straightforward Direct Current (DC) bias technique of this geometry diminish the level of difficulty and retention of the UC, with the red dashed boxes indicating the position of two neighboring UCs. The via and clearances introduce losses to the UC and impose limitations due to the necessity of supplying DC power to every varactors. The

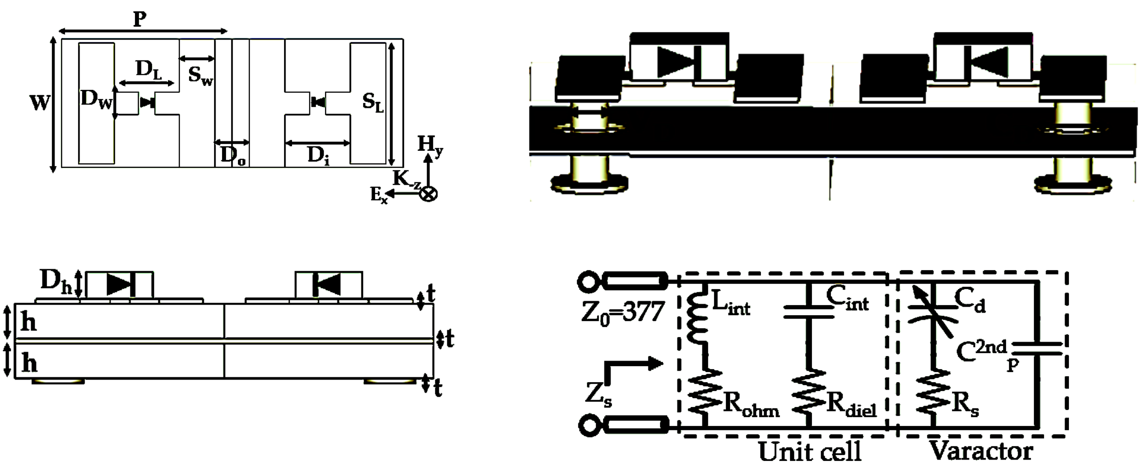

Fig. 2: UC design (a) Front, (b) Three dimension, (c) Profile (d) Equivalent circuit

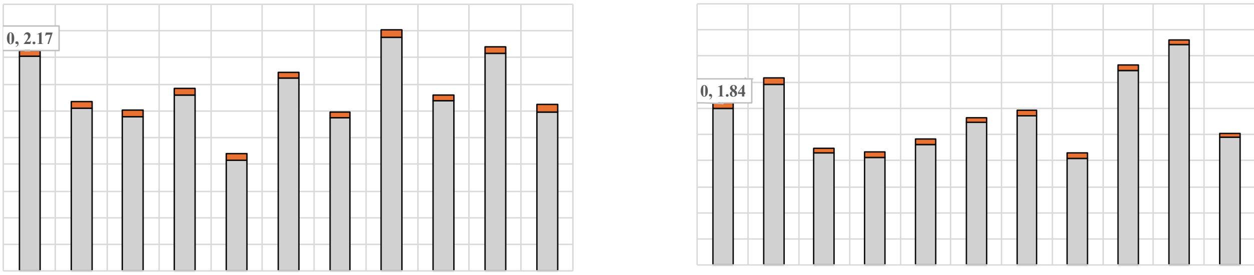

Fig. 3: BS angle analysis (a) Azimuthal (b) Elevation

elongated strip in every UC is linked to the elongated strips of adjacent UCs down the row. These sheets serve as a shared DC grounding for the variations in every row, eliminating the necessity for another via in every UC. The small strip obtains a distinct DC power supply from the rear of its exterior, which allows each MS UC to be individually adjustable. The phase reflections are autonomously controlled in two dimensions, with varactors positioned between neighboring UCs, and each UC is supplied alone with DC grounds or designated DC voltages. A limitation is established for the capacitance ratio between every UC and the four surrounding UCs. This constraint precludes an autonomous configuration of the reflection phase in two dimensions. This represents an enhancement of the prior experimental research, which exhibited beam coordination in one dimension at 20-24.5 GHz operational frequencies. This study presents concurrent and autonomous 2D beam directing at an operational frequency of 38 GHz for the incoming polarizations.

Results and Findings of Reconfigurable MS Reflective BS

The ultimate MS is a static 2D array dimension conceived and modeled according to the UC above, reflecting outcomes. The array dimensions are 74.3 mm x 189 mm, comprising twelve rows and eight columns of UCs, totaling 95 UCs, which can be activated with distinct DC supplies as required. Fig. 3 illustrates the MS reflectors with the axes BS specification and provides a sample of a 3-D far-field reflected output, devoid of phase manipulations.

Outcomes of BS angle calculations from 0 to 50° in azimuthal, and 0 to 50° in elevation, are presented in Fig. 3, compared to the reference results at 0°. The variation in frequency for 210 MHz to about 38 GHz for the identical incident wave at a BS direction of 20° in azimuth and 15° in elevation is illustrated. The findings indicate a convergence in frequency variations, resulting in a bandwidth of approximately 420 MHz.

To accommodate rotational spatial cones of 25° and 15°, BS capabilities of 15° in azimuthal and 5° in elevation are necessary, resulting in optimum values of Ax = 22.7° and Ay = 7°. The cumulative MS phase distribution is 204.7°, less than 305°, and satisfies the criteria. To accommodate a spatial size of 35° and 7°, BS capabilities of ≤ 10° in azimuthal and 5.8° in inclination are necessary, resulting in optimum values of Ax = 30.4° and Ay = 4.2°, respectively. The cumulative MS stage dispersion in use is 268.7°, which conforms to the criterion. It presents the outcomes of the static phase ranges for off-formal incidence irradiation derived from the edges of the aforementioned spatial cone instance, compared to the simulation outcomes for a standard incidence scenario. The MS reflector can sustain and encompass a viable geographical cone. It presents the 2D BS outcomes at 38 GHz for the specified rotational partial corners.

Applying the formula in scenarios with non-uniform levels, resulting from varying losses in MS reflection UCs, produces a minor discrepancy in the modeled BS viewpoints, denoted as 0, and the estimated BS angles. A minor adjustment in the variance of the phase variables, Ax and Ay, can rectify the discrepancy. Owing to the symmetry of the MS reflector, identical BS outcomes in 1D and 2D configurations can be achieved in the opposing path by inverting the capacitors and stage distribution gradients.

Conclusion

The theory and models of the reconfigurable MS reflectors for 5G mobile communications, utilizing a novel resonance UC, are given. This UC provides a stage range of movement over 307° and surpasses 310° in the Ka-bands across a bandwidth exceeding 4.3 GHz, exhibiting remarkably low losses. This enables 2D BS (azimuthal and elevations) with about 400 MHz capacity modeled at 38 GHz. The UC layout conforms to Printed Circuit Boards (PCB) technologies with commercially available components. Engineering constraints and characteristics resulting from stage sensitivities and high frequencies were examined, including resistance components due to errors and parasitics in manufacturing, as well as second-order parasitic capacitor effects from varactor construction. A trade-off exists between the inefficiencies and the stage variable range of the UC. Improvement was conducted on the UC characteristics to achieve losses below 6 dB and a stage variable range over 310° at 38 GHz, a frequency pertinent to upcoming 5G technology. A substantial dynamic phase range was attained while preserving minimal distortions, enhancing reflector effectiveness.

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