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RIS with Nanomaterials for FutureG Applications

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Abstract— **Reconfigurable Intelligent Surfaces (RIS) also known as Intelligent Reflecting Surfaces (IRS) often depend upon metasurfaces. These typically comprise of a large array of passive elements that can be fabricated to modulate reflection amplitude or phase or both to create tunable functions that are independently controlled. Various RIS are developed to improve spectral efficiency through ultrawideband antennas, enhanced beamforming with higher gain and bandwidth, spatial reconfigurability, selective and adjustable isolation, and other desired features. Several approaches to tune the RIS performance are being explored. This paper reviews the primary approaches and the benefit of emerging tunable nanomaterials in achieving such RIS functions. Designs with 1-bit and 6-bit phase shifters are discussed in the first part. Various opportunities with nanomaterials and nanodevices to induce such phase shifts are discussed in the last part of the paper.**

I. Introduction

Future wireless communication systems will need ultra-wideband (UWB) wireless networks and associated radio designs to take advantage of the available spectrum and support significantly higher data speeds. High radiated power, a high signal-to-noise ratio, beamforming, and scanning in elevation and azimuth directions within a large range are needed to support these networks. Therefore, the 5G-and-beyond (FutureG) wireless communication system requires highly-integrated radio access solutions [1, 2]. The mmWave spectrum is currently being studied due to the rising demand for high-capacity communications. However, high gain-phased array antennas are necessary because of the large path and space loss at these frequencies. The significant path loss in mmWave communication is a disadvantage. Using extremely-directive high-gain antenna arrays with beamforming, the latter problem can be solved. However, blockage susceptibility, as seen in Fig. 1, is a significant issue that FutureG mmWave deployments must overcome. Wideband beamformers with compact form factors and low power have also been a major obstacle.

Although massive-MIMO devices can provide significant beamforming benefits, their energy efficiency declines as the number of antenna elements rises [3]. This is due to the fact that whereas data rates only increase logarithmically, the overall energy consumption grows linearly as the number of active components increases[4]. Implementing antenna intelligent surfaces, which are not only necessary to have high-gain capabilities but also adaptive beams to change non-line-of-sight (NLOS) between source and destination and manage interference sources, is one solution to address the aforementioned shortcoming. To create a smart wireless environment capable of high-data rate transmission and interference mitigation, current research includes the development of low-power RIS. These surfaces are capable of monitoring the wireless environment and adjusting to channel requirements even after being deployed, in addition to changing the surface qualities to control EM wave propagation.

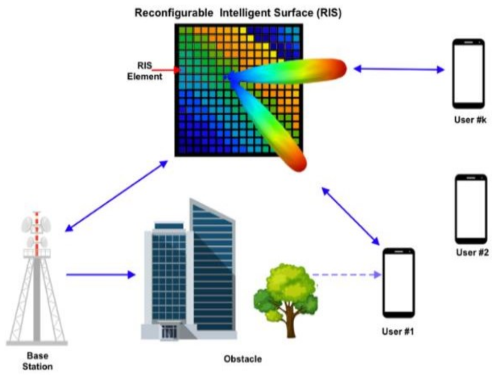

Fig. 1: Typical example of wireless link employing IRS to mitigate LOS obstructions.

In order to reflect the incident wireless signal passively, each of the numerous microscopic elements that make up the metasurface for RIS (also known as controlled reflecting elements) can change its phase shift. The reflected signals of various elements can be added to or counteracted in desired or unexpected directions by carefully choosing the phase shifts. The RIS-assisted massive-MIMO systems offer a programmable and customizable wireless environment in contrast to conventional MIMO systems, whose performance is based on their channels. This advantage allows for the joint optimization of the precoder/decoder (also known as a beamformer/combiner at the transmitter/receiver) and the phase shifts at the RIS, which can increase the possible data rates in RIS-assisted massive-MIMO systems. The multi-input single-output (MISO) RIS-assisted system was the focus of the initial studies on RIS-assisted joint beamforming. Transmit power reduction, weighted sum rate enhancement, energy efficiency enhancement, multicast rate enhancement, and latency reduction have all been researched with various optimization aims.

Tunable bandwidth reconfiguration with higher-order, multi-layer, and metal-based frequency Selective surfaces (FSS) embedded within the dielectric structure is

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becoming another key approach for all mmWave systems. In a typical FSS, two layers (a capacitive and an inductive layer) generate a response similar to a shunt L-C circuit. Approaches to tune FSS include sliding dielectrics [5] and conductors such as liquid metals [6]. For example, tunability arises when liquid metal is continuously transported over a capacitively coupled microstrip line feed network. This approach relies on creating mechanical systems such as a micropump unit. Liquid crystal substrates are emerging as a key candidate to tune substrate properties for reconfigurable beams [7]. In one such prominent example that utilizes GT7-29001 mixture from Merck KGaA, Darmstadt, Germany, the permittivity changes from 2.45 to 3.53 under electric fields as the crystal moves from antiparallel to twisted nematic mode and can be used to spatially or spectrally tune the beam.

The aforementioned bottleneck is solved by looking into ways to ensure accurate beam pointing and adaptive nulling with the simplest (in terms of SWAP-C or size, weight, and power - cost) beamforming circuitry. In this work, we will be presenting two major advancements in the a) implementation of the 1-bit phase only beam-former network for a 20x20 planar array, and b) achieving reconfigurability by benefiting from emerging materials.

II. 1-BIT AND 6-BIT PHASE SHIFTERS

When designing tunable FSS, PIN diodes and varactor diodes are frequently employed [8]. It is possible to tune across very wide bandwidths (>10:1). This method makes use of a DC power control circuit to provide the PIN diode with a differential voltage. One such method is the network used in this work, which uses 1-bit binary phase shifting. A single bit topology has a number of restrictions, such as quantization error, lack of amplitude control, and loss of directivity. Despite these difficulties, a 1-bit binary phase shifter approach has many benefits, including the ability to: a) significantly reduce the amount of hardware electronics needed, allowing for a more cost-effective approach with simpler beamforming circuitry and control; b) significantly reduce the amount of optimization complexity; and c) make the array with integrated beamforming circuitry simpler to package, deploy, and integrate.

In RIS, each element compensates for the spatial delay $k_0 * R_i$, where k_0 is the wavenumber and R_i is the distance between the source to that i^{th} element, just like in traditional reflect arrays. In order to perform beam steering, each element is given a phase shift so that total weights produce a collimated beam in the direction (θ_b, ϕ_b) where the desired azimuth and elevation directions that the beam can be steered to. The total phase shift required per element is given below:

$$\varphi_{RIS} = k_0(R_i - \sin\theta_b (x_i \cos\phi_b + y_i \sin\phi_b)) \qquad (1)$$

This adaptive beam and null steering rely primarily on phase state adjustment and assume that the array elements' amplitudes are distributed uniformly. The null should cause the desired pattern to change as little as possible during antenna synthesis. The goal pattern is obtained by subtracting a weighted cancellation pattern w* $AF(\theta_n)$ from the original pattern $AF(\theta_b)$ as shown by (2) (where Θ_n indicates the location of the null)

$$AF = AF(\theta_b) - w * AF(\theta_n) \qquad \textbf{(2)}$$

where w is given by

$$\frac{(AF(\theta_n))^H * AF(\theta_b)}{(AF(\theta_n))^H * AF(\theta_n)} \qquad (3)$$

The weights are calculated and obtained using a genetic algorithm (GA) for this multi-objective job. The GA algorithm's stochastic nature and broad search space guarantee that a global optimal is found while protecting against local minima.

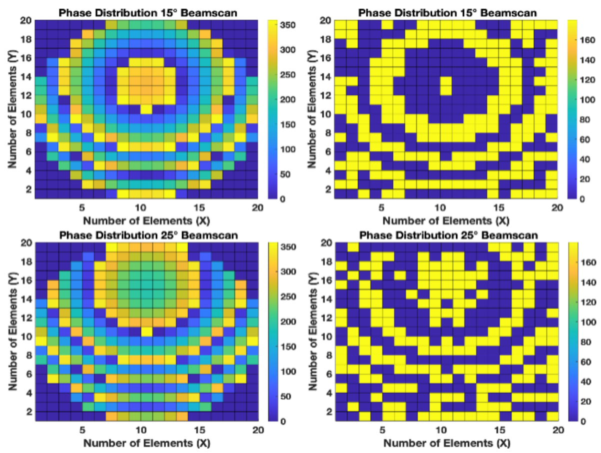


Fig. 2: Comparison of a 1-bit phase shifter beamformer (right) with a 6-bit beamformer's (left) phase distribution of a 20 × 20 array.

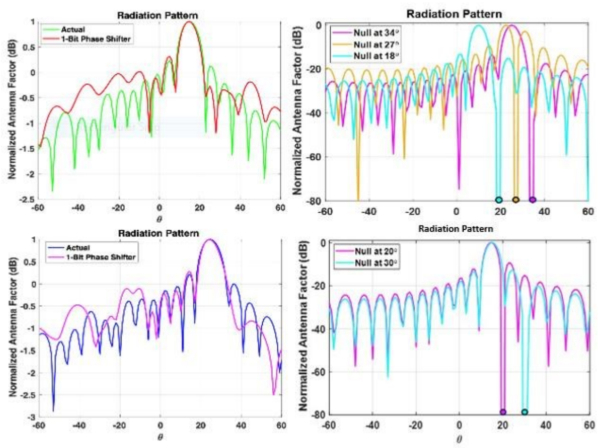


Fig. 3: Comparison of a 1-bit phase shifter beamformer with an actual 6-bit beamformer's beam steering and nulling performance of a 20 × 20 array.

The beam-former network uses a 1-bit binary phase shifting approach, as shown in Fig. 2, to guarantee precise beam pointing with adaptive nulling. As a result, there is a large decrease in the number of coefficients that need to be adjusted utilizing adaptive array processing methods in order to beam-steer, maximize null depth, and maintain trimodal functioning. The null and adaptive beam steer functions reduce interference and can be applied as an electronic deterrent. Notably, the binary phase shifters that make up the phase-only beamforming circuitry only use simple switchable open ($\Gamma = 1$ and phase $= 0^\circ$) and short ($\Gamma = 1$ and phase $= \pm 180^\circ$) stubs. Fig. 2 also displays preliminary findings comparing phase states and patterns for a 20x20 array using a 6-bit phase shift and a 1-bit topology. According to these findings, a 6-bit beamforming network requires a total of 2400 digital control lines, whereas a single bit configuration only needs 400 digital control lines. This results in a decrease in DC power and digital control requirements of at least 6 times. The beam steering and nulling performance for 1-bit and 6-bit phase shifters are shown in Fig. 3.

Emerging fan-out packaging technologies in panel substrates provide a unique manufacturing path for realizing RIS. The PIN diode chiplet can be embedded in the substrate cores with fan-out connections, which suppresses their insertion losses. Such embedded bridge connections are now becoming a mainstream packaging technology both for high- [9] and low-density interconnects [10]. A schematic cross-section of such systems is shown in Fig. 4.

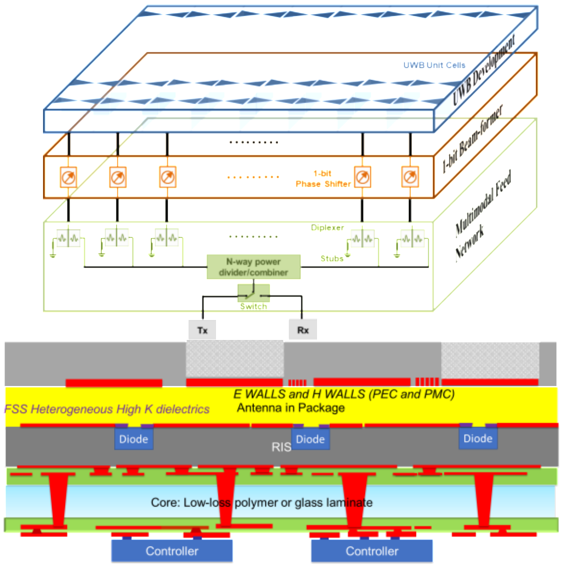


Fig. 4: Top level depiction of proposed RIS aperture and its package implementation.

III. EMERGING PCM AND MIT NANOMATERIALS

While PIN diodes are mature and allow easy implementation, they require assembly and associated system volume, packaging interconnect parasitic, and other associated design and routing challenges. Emerging nanomaterials that are directly grown on inorganic interposers or package substrates can allow easier heterogeneous integration. Emerging PCM (phase change materials) and MIT (metal insulator transition) materials are ideal candidates for tunable switches at a lower voltage. These include chalcogenides, transition metal oxides (VO_2), rare-earth nickelates, and others. They show unique properties such as Insulator-Metal Transitions (IMT) at low voltage or thermal actuation pulses. A comprehensive review [11] of this topic covers various device embodiments of switches and phase shifters derived out of this. These were also extended to reconfigurable reflectarrays and transmit arrays. In one such demonstration, reconfigurable reflectarrays were demonstrated by using copper patches that are split with VO_2 [12]. In this study, the conductivity is assumed to vary from 10^3 S/m by more than two orders of magnitude when heated, in order to achieve the 180° change in phase. Thermal actuation pulses are achieved with microheaters. Resistance varies over 5 orders of magnitudes with GeTe materials making it suitable for RF switching applications as a trade-off between MEMS and varactor PIN diode options [13]. The transition temperatures for certain materials such as TiO_2, Ti_3O_5, and Sb_3S_2 lie between 448-537 K, which makes them practically viable. An extensive review of such materials was provided in [13]. PCM switches have a lower actuation time compared to >10 µs of MEMS switches. These are also superior to liquid crystals that switch at millisecond intervals. Silicon-based PIN switches switch at nanosecond intervals, making them faster than these options.

With the advent of 2D materials on advanced wide bandgap substrates, multiple opportunities are shown to create RIS by tuning the carrier transportation with small electric or thermal stimulus. One such system is through ferroelectric polarization to tune carrier doping in GaN. High carrier density is shown with ferroelectric films on GaN [14]. By growing such films on AiP package substrates, RIS with ideal system performance can be achieved with complete heterogeneous system integration.

IV. CAPACITIVE PHASE SHIFTERS

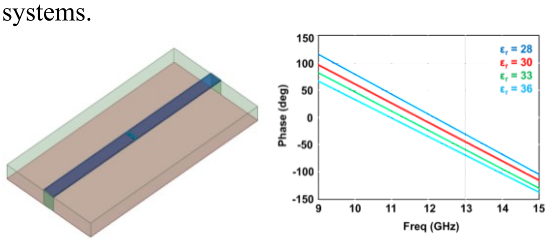
Electronic tunability of bulk substrate properties has been a long-standing challenge but is of its importance in RF electronics. Ferroelectrics and multiferroic materials are often explored to reconfigure FSS. In ferroelectrics, substrate permittivity tuning is directly achieved with electric fields whereas the same is achieved with strain-coupling between a magnetostrictive and ferroelectric layer in the case of multiferroics. Voltage tuning of BST requires strong electric fields of 100-200 kV/cm for achieving 20-40% tuning and 200-400 kV/cm for 50-70% tuning. For a 0.5 mm substrate, this would imply kilovolts. With such tuning, lens configurations are created recently by utilizing radio-transparent discretized electrode patches [15]. The electrical length in this case is tuned by applying voltages. The permittivity of BST can also be tuned with thermal gradients. Thermal tuning is related to the Curie temperature (T_c) of the BST, which varies with composition. Composites with high Sr content are incipient ferroelectrics (with T_c < room temperature) whose permittivity decreases with temperature. With higher Ba content, the T_c shifts to above room temperature. The easier ferroelectric orientation makes the permittivity increase with temperature till the T_c is reached. Such opportunities have been investigated to tune the frequencies of the passband in THz FSS both as thin-films [16] and also as thick substrates.

The permittivity of BST is anticipated as ~200 even in mmWave and sub-THz range. Although the dipole orientation polarization that happens at a larger scale relaxes in the GHz range, the ionic polarization is still retained significantly. Therefore, BST at the nanoscale is expected to have a loss tangent of ~0.1 and stable properties till high frequencies while also having tunable performance with thermal or strain stimulus. The strain states in ferroelectrics are dependent on the substrate lattice mismatch, CTE (coefficient of thermal expansion) mismatch, and crystallization conditions [17, 18]. By inducing strain through magnetostrictive coupling, the properties can be tuned.

For evaluating phase shifters, the most commonly used performance parameter is its figure-of-merit (FoM) which is defined as the total phase shift $\Delta_{\varphi max}$ divided by the maximum insertion loss (IL) IL_{max} as:

$$FOM(deg/dB) = \frac{\Delta\varphi_{max}}{IL_{max}} \quad (4)$$

Using a bias network to apply a voltage across the ferroelectric tunes its permittivity. As an illustrative case, in Fig. 5, we present a simple microstrip based phase shifter. This phase shifter comprises of a dielectric substrate with a permittivity of 2.2, and copper as the signal trace. The signal trace has a meandered line comprising BST. The material's dielectric constant, ε_r, is swept to replicate the dielectric tunability behavior, with a maximum tunability of ~22%. The capacitance values will change as a result of adjusting the permittivity of BST/polymer material, which also adjusts the phase of the transmitted RF signal [19]. Such phase shifters can be designed with various architectures for different applications including RIS. Even with a moderate change in permittivity, phase-shift can be achieved over a wide frequency range as shown in Fig. 5. By varying the permittivity from 28 to 36, a phase variation of 60^0 was achieved. Such designs can achieve 1-state phase shifters using BSTs that can be eventually integrated into RIS systems.



(a) (b)

Fig. 5: BST - based microstrip phase shifter: (a) schematic of the design, (b) simulated phase shifts in degrees for different values of dielectric constant.

V. Conclusions

Reconfigurable Intelligent Surfaces (RIS) are emerging as an alternative to MIMO systems. They have the potential to significantly improve spectral efficiency with much lower energy consumption. The main enabler for this is the ability to induce phase shifts to create selective steering and nulling. This paper examined RIS through 1-bit and 6-bit phase shifters. Various approaches to realize phase-shifters with emerging nanomaterials are also reviewed in the paper.

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