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Reconfigurable Metamaterial Structure at Millimeter Wave Frequency Range

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ABSTRACT

In this paper, reconfigurable metamaterial structure at millimeter wave frequency range was designed and simulated for a future fifth generation (5G) mobile-phone beam switching applications. The new proposed structure was composed of a bridge-shaped resonator (BSR) in the front face and strip line at the back face of the unit cell which operates at 28GHz. First, non-reconfigurable low loss BSR unit cell was designed and subsequently, the reconfigurability was achieved using four switches formed in the gaps of the structure. The proposed structure achieves the lowest loss and almost full transmission among its counterparts by -0.06dB (0.99 in linear scale). To demonstrate the reconfigurability of the metamaterial, the reflection and transmission coefficients and real parts of the effective refractive index at each reconfigured frequency were studied and investigated. Simulation results showed that a high transmission and reflection peaks occur at each resonance frequency according to change the state of the switches.

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1. INTRODUCTION

Metamaterials (MTM) are artificial materials that exhibit unique responses to electromagnetic wave (EM) properties such as negative refractive index, inverse Doppler shift, and reversal of Cherenkov radiation [1]. The simultaneously negative permittivity and permeability properties were proved theoretically by Victor Veselago in 1967 and verified experimentally after 29 years by Pendry in 1996 [2], [3]. Because of these unusual electromagnetic properties, metamaterials can be utilized as a part of numerous important applications such as super-lenses [4], cloaking technology [5], design and enhance the antenna performance [6]. The study of the negative index metamaterials has been enhanced through various strategies and processes. However, few issues have been encountered such as the narrow bandwidths and losses that limit the spectrum and the range of their applications. Metamaterials suffer from high losses when the frequency is pushed to the higher range such as millimeter wave (MMW) bands [7]. However, the losses are very low and the unusual electromagnetic properties of the metamaterials can still be achieved within the microwave frequency region. The losses can give negative influences and adverse effects toward the realizations of the unique electromagnetic properties of the metamaterials. Throughout the years, the researchers had been proposed various technique to reduce such losses.

A number of diverse techniques are extensively reported in the literature to compensate the metamaterials losses at microwave and terahertz such as tailoring geometry of metamaterial unit cell [8], using the electromagnetically induced transparency (EIT) at low frequency range [9], integrate an active material [10]. Hence, new metamaterials structures with relatively low loss are desirable. The introduction of a new structure of metamaterial with proper arrangements, can overcome the losses and improve the performance of the devices at high frequency range.

Reconfigurable Metamaterials attract more attention in recent years since they show a variable response to an incident EM wave. The EM behavior of metamaterial unit cell is modified intentionally using different reconfigurable methods such as mechanical, thermal and electrical. The metamaterial can be reconfigured mechanically by changing the distance between the metamaterial elements, or the distance between the metamaterial and the substrate, thus modifying the local dielectric environment and hence the resonance response but with increasing the complexity of the design and cost of fabrication [11]. On the other hand, many materials undergo a change of their EM properties as a function of temperature such as refractive index. Therefore, the metamaterials can be reconfigured thermally by changing the response to external temperature [12]. However, a cold medium is a required for any device, thus this approach is not practical for real applications.

Over the past several years, electrically reconfigurable metamaterials have drawn significant interest due to their ability to modify the EM properties of metamaterials. In this method, active devices such as varactor diodes, PIN diodes and micro-electro-mechanical systems (MEMS) have been used to achieve reconfigurability. A varactor diode is extensively studied in the literature [13-15]. It is modeled as a variable capacitance and this property brings various advantages such as simple integration and bias distribution due to using only one diode to achieve the tuning. However, low sensitivity to capacitance variation especially at high frequencies is the main drawback of this method besides the lack of suitable varactor diodes in terms of operating frequency and physical size [16]. The best switch in terms of high efficiency, low insertion loss and high isolation is MEMS, but this method has its own drawbacks such as high operation voltages (70–150V), complex fabrication requirements, expensive, and slow switching speed [16], [17]. On the other hand, the PIN diode is modeled as a variable resistance to represent the impedance of diode for varying bias voltage. The use of PIN diodes [18-20] in a metamaterials shares similarities with the use of varactors in terms of their applications, ease of integration, simple control, and fast switching. Moreover, the PIN diode is available for high frequency applications.

In this paper, we proposed and simulated a new metamaterial structure with low loss operates at 28GHz, subsequently, the new structure is reconfigured using the copper strip as PIN diode formed in the gaps of the structure. Six frequencies, F1 to F6 are created with different negative refractive index values according to change the states of the switches for antenna beam steering in 5G mobile network applications.

2. DESIGN AND NUMERICAL RESULTS OF THE PROPOSED METAMATERIAL UNIT CELL

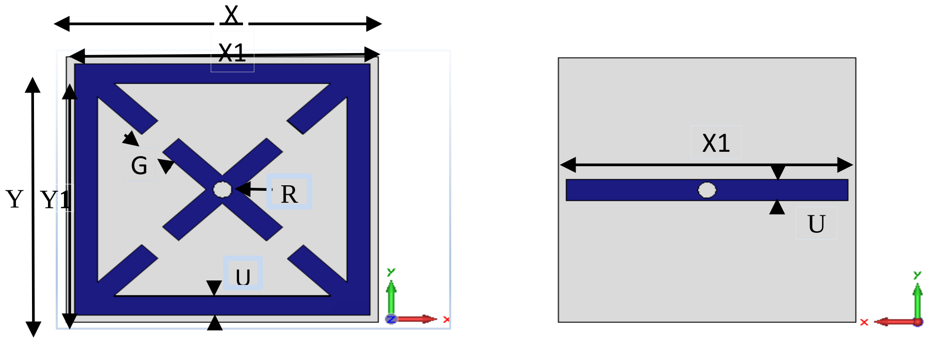
2.1. Metamaterial Unit Cell Structure

Bridge-shaped resonator (BSR) structure in the form of unit cell is depicted in the Figure 1. It consists of bridge shaped in the front face [see Figure 1(a)] and wire strip in the back face [see Figure 1(b)] and the both faces are connected through via in the center of the shape. The loop of square edge of the unit cell introduces inductance and gaps introduce capacitance thereby allows for the control of the resonant characteristic of the structure. BSR unit cell is printed on the 0.254mm Rogers RT5880 thickness with relative permittivity 2.2 and tangent-loss of 0.0009. The specifications of the design are tabulated in Table 1. The material of the metallic BSR is lossy metal copper with an electric conductivity of 5.8 × 10^7 S/m and the thickness of 0.035mm.

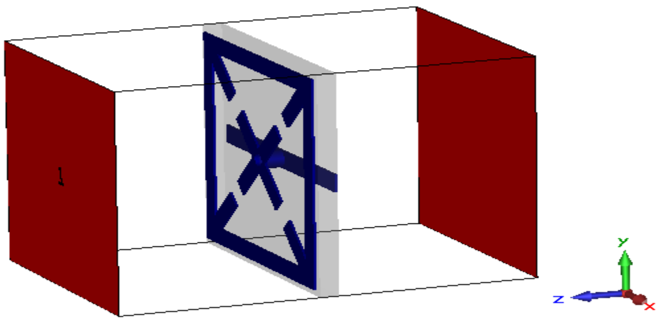
The ports and boundary conditions are assigned to excite the electromagnetics (EM) wave and extract effective constitutive parameters of the proposed unit-cell i.e. the refractive index. The x- and y-axes are allocated with perfect magnetic conducting (PMC) and perfect electric conducting (PEC) boundary conditions, respectively. The two waveguide ports are assigned with open (add space) in the z direction as shown in Figure 1(c). The unit cell is simulated in the time domain using CST Microwave Studio, which is based on the finite integration technique.

Table 1. The BSR dimensions at 28GHz

Parameter	Value (mm)	Parameter	Value (mm)
X	3.7	U	0.27
Y	3.7	R	0.15
X1	3.5	G	0.35
Y1	3.5	H	0.254



(a) (b)



(c)

Figure 1. The BSR unit cell, (a) front face, (b) back face, and (c) the simulation geometry

2.2. Low Loss Metamaterial

In this section, the performance of the new metamaterial structure operates at MMW frequency range is presented. BSR unit cell is proposed to operate at 28GHz band which is the candidate band for 5G mobile network applications. Figure 2 reveals the reflection coefficient, S_{11}, of the proposed unit cell. It can be observed that the unit cell achieves a bandwidth of 1.53GHz at -10dB. Noted, the main drawbacks inherent in the metamaterials are the narrow bandwidth and losses that limit their applications and late enable metamaterials based devices. In this work, the bandwidth of 1.53GHz is considered a good achievement despite the drawback of the metamaterial that presents a narrow bandwidth in nature. On the other hand, the losses in metamaterials at MMW frequency range are still a big issue and the quest for a low-loss structure at this range is highly demanded.

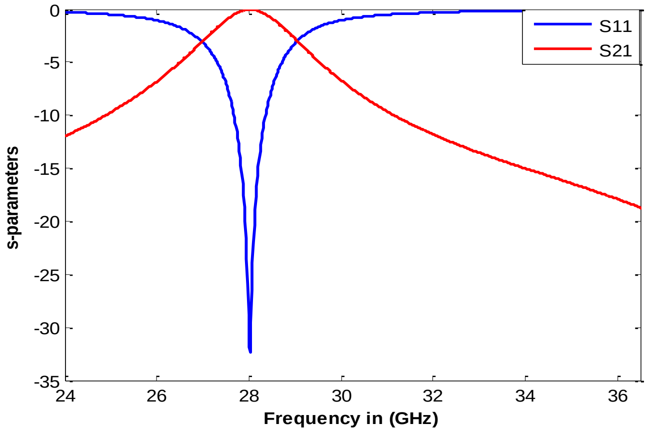


Figure 2. S-parameters of the proposed BSR structure

In this work, the transmission coefficient is used to measure the loss of the metamaterial structure. For low loss, the peak of the transmission coefficient should be near zero dB in (dB scale) or close to one in (linear scale) at desired frequency. The transmission band of the proposed BSR unit cell structure at 28GHz is shown in Figure 2. BSR shows the lowest loss by about -0.06dB (0.99 in linear scale) at 28GHz in compression with recent literature [21]. In other words, BSR unit cell achieves near zero loss which almost achieves the full transmission at 28GHz MMW frequency.

The losses can give negative influences and adverse effects toward the realizations of the unique electromagnetic properties of the metamaterials. In other words, the double negative nature of the metamaterial should be investigated to prove the principle of the metamaterials and the influence of the losses. The Nicolson Ross Weir (NRW) approach based complex reflection and transmission is used to reconstruct the constitutive parameters [22]. In this method, the both effective permittivity and permeability are directly calculated from complex reflection and transmission coefficients then the refractive index can be calculated as follows:

$$n = \sqrt{\varepsilon_r \mu_r} \quad (1)$$

Figure 3 shows the real parts of the refractive index. The double negative nature of the BSR unit cell is verified here by the negative reflective index n.

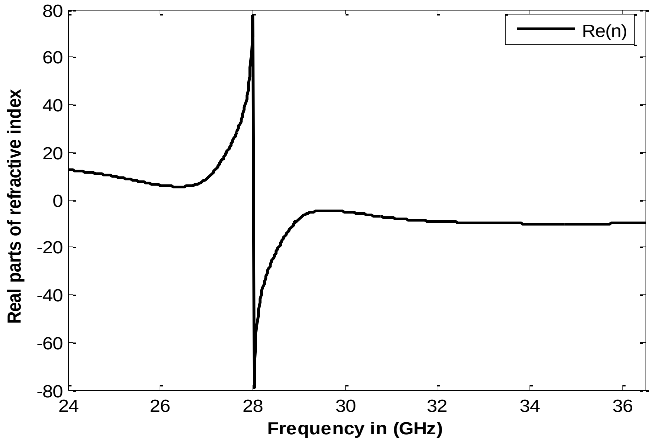


Figure 3. The real part of the effective refractive index

3. DESIGN AND NUMERICAL RESULTS OF THE PROPOSED RECONFIGURABLE METAMATERIAL

Based on the BSR structure in section 2, the reconfigurability property is added to the proposed metamaterial structure using copper strips act as PIN diodes as revealed in Figure 4. Four switches (D1, D2, D3, and D4) are inserted in the gaps of the two cross columns of the structure. In the simulation, we use a strip of copper to mimic the dimension of the PIN diode.

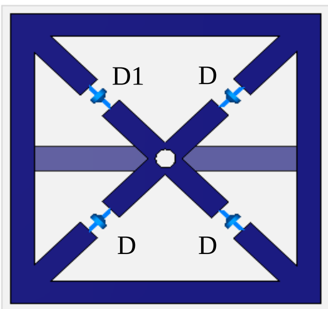


Figure 4. Reconfigurable metamaterial structure using PIN diodes

The CST software is used to simulate the BSR with an active device, PIN diode, by representing the PIN diode as a copper strip. The electric, magnetic, and feeding open boundary conditions are assigned as in section 2.1. In the simulation, copper strip represents switch is ON while vacuum represents OFF state of the switch. The presence of the switches in the gaps of the proposed unit cell gives different values for resonant frequencies from F2 to F6 and also different values of the negative refractive index. The simulated reflection coefficient of the BSR unit cell with different states of the switches is depicted in Figure 5. It is noticeable that the resonance frequency is increased by inserting more switches in the gaps. In other words, the resonance frequency is increased when the values of capacitances (gaps) are decreased. The switches arrangement, resonant frequency and refractive index values of the proposed unit cell are tabulated in Table 2.

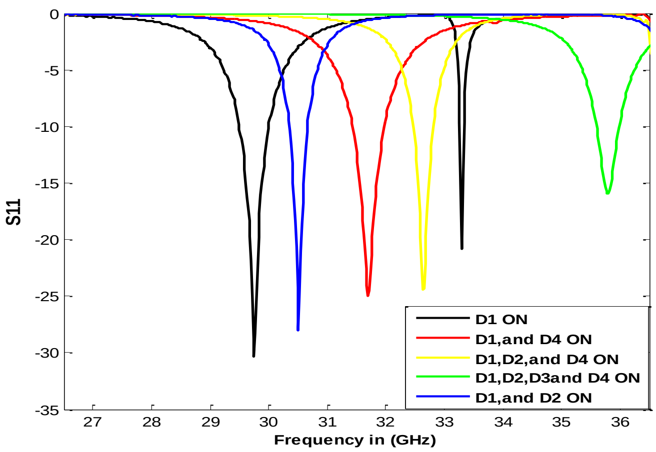


Figure 5. The reflection coefficients of the reconfigurable metamaterial structure

Table 2. Switch arrangement, resonant frequency and refractive index values of the proposed unit cell

Figure No.	Frequency	D1	D2	D3	D4	S11 of the BSR unit cell (GHz)	Refractive index (n)
Figures 2 and 3	F1	OFF	OFF	OFF	OFF	28	-80
Figures 5 and 7	F2	ON	OFF	OFF	OFF	29.7	-73
	F3	ON	ON	OFF	OFF	30.5	-72
	F4	ON	OFF	OFF	ON	31.8	-60
	F5	ON	ON	OFF	ON	32.7	-55
	F6	ON	ON	ON	ON	36	-45

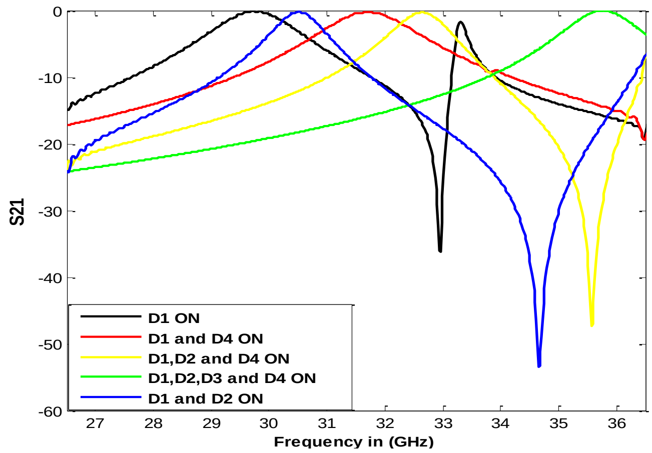


Figure 6. The transmission coefficients of the tunable metamaterial structure

The transmission coefficients of the reconfigurable metamaterial structure are shown in Figure 6. The BSR unit cell achieves a low loss at all simulated states, thereby the unique EM properties of the metamaterial unit cell can be achieved. As mention in section 2, the NRW algorithm is used to retrieve the constitutive parameters of the BSR structure. Figure 7 presents real parts of the negative refractive index at each reconfigured frequency. It can be seen that the values of n are altered according to the states of the switches. The lowest refractive index is n= -80 at F1 arrangement while n goes to the highest n = -45 at F6 arrangement. These different values of n can be exploited to steer the main beam of the 5G antenna with benefits over the conventional methods such as low profile structure, ease of integration on same antenna substrate, and the gain is enhanced through the switching process.

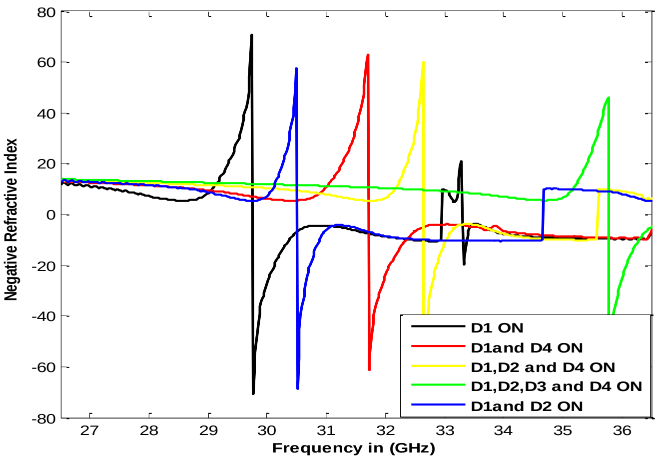


Figure 7. The real part of the negative refractive index of the tunable metamaterial structure

4. CONCLUSION

This paper presents a new BSR metamaterial unit cell operates at 28GHz for beam switching applications in 5G technology. The BSR introduces the lowest loss (-0.06dB (0.99 in linear scale)) reported in the literature so far. Then the reconfigurable BSR unit cell is achieved using four switches positioned in the gaps of the structure. By controlling the ON and OFF states of the four switches, six different frequencies and refractive index values are created. The reflection and transmission coefficients and real parts of the effective refractive index at each reconfigured frequency are studied and investigated. Simulation results show that a high transmission and reflection peak occurs at each reconfigurable frequency.

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