A NodeMCU-based programmable Reconfigurable Intelligent Surface for mm-Wave 5G Applications

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Abstract*— The reconfigurable intelligent surface (RIS) is a promising technology in metamaterial advancements for millimeter wave (mm-Wave) applications that could revolutionize future 6G wireless communications. RIS surfaces offers energy and spectrum efficiency by providing extended signal coverage and improved data rates. In this article, a compact RIS unit cell is realized, and its operation is demonstrated using simulation results. The footprint of the unit cell is 10x10x1.6mm^3. The unit cell is designed using an FR4 substrate with a G-shaped patch layer and full ground plane. The VO2 (Vanadium dioxide) is used as a reconfigurable element for getting beam-forming capability. The switching states give peak resonance at 24.3 GHz (OFF), 24.4 GHz, and 30.05 GHz (ON). The radiation efficiency at the operating frequencies is -13.75 dB, -7.63 dB, and -5.73 dB. The NodeMCU-based bias setup is demonstrated for getting the controllable states of VO2. Hence, the programmable feature along with the beam forming capability is realized to meet the emerging trends and demands in mm-Wave 5G communications.

Keywords*— *Programmable, Reconfigurable Intelligent Surface, Vanadium dioxide (VO2), NodeMCU, mmWave 5G communications

Introduction

Reconfigurable Intelligent Surface (RIS) has evolved as a trending word in recent years because of its spectral and energy efficiency that helps for futuristic mmWave communication applications. RIS is also helpful at MIMO (Multiple Input Multiple Output) systems. Because of its large signal coverage [1] it is mostly used in mmWave communication in 5G. RIS hardware is of low cost and low power consumption as its advantages. mmWave band gives a high bandwidth and high data rate which is essential for wireless communication [2]. Beamforming and beam steering polarization conversion are some of the key operations for using RIS to get control over incident EM waves.

RIS consists of reconfigurable elements that help in the study the intelligent characteristics of reflected waves. Most of the recent literature on RIS tends to use switches such as P-I-N (Positive Intrinsic Negative), Varactor, Vanadium dioxide (VO_2), and liquid crystals [3]. The studies related to RIS mainly deal with multifunctional, polarization, and incident angle-independent characteristics. RIS surface is a difficult task for present mmWave communications [4,5]. The present trend of RIS is not focused on angle insensitivity which is essential for mmWave wireless communications.

The literature tends toward programmable RIS surfaces to get real-time properties such as beam steering, beam forming, etc... Programmability can be applied to RIS surfaces by controlling the switch states of active elements [6,7]. We can say that the emerging scope in RIS design is by adding the Programmability for this RIS surface. The programmability can be realized using embedded boards such as Raspberry Pi, NodeMCU, Arduino, etc..[8]. The programmability for RIS using NodeMCU with its operation is given using Fig 1.

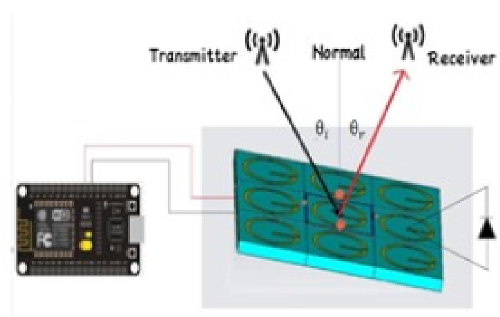


Fig 1. Development of NodeMCU-controlled RIS

In this work, an angle and polarization- insensitive RIS unit cell operating at mmWave is expressed using NodeMCU controlled for beamforming. The unit cell is designed on an FR-4 substrate with measurements of 10x10x1.6mm^3. The diode is taken for its performance at mmWave frequencies. The unit cell consists of patch with VO_2 inserted in the middle section is discussed in section 2. In section 3, the beamforming properties are explained using simulation results by giving the properties of VO_2. The biasing circuit is realized using a NodeMCU board, which helps in achieving programmability for RIS design.

1. UNIT CELL DESIGN

The RIS unit cell with its dimensions is mentioned in Fig2. The design contains a rectangular G-shaped patch having slots on top and bottom and a complete ground plate. FR-4 substrate (dielectric constant of 4.3 and loss tangent of 0.025) is designed with parametric values of 10x10x1.6mm^3 In the Top layer, a VO_2 diode is placed to achieve structure. The electric conductivity of VO_2 at the insulating phase is 200 s/m and at the conducting phase, it is defined as 10,000 s/m.

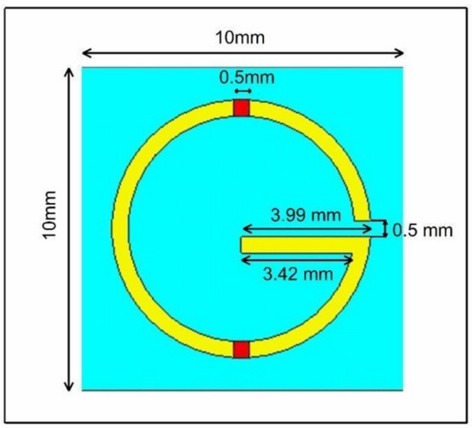


Fig 2. Proposed unit cell geometry.

The reflecting properties of the unit cell is explained using CST simulation results. In this, a linear polarized wave is incident on layer in a normal direction. Depending upon the operating state of VO_2 diode, the polarization angle changes when compared to the incident angle. The reflecting behaviors are represented in the upcoming section.

2. SIMULATION RESULTS AND REFLECTION CHARACTERISTICS

The reflection coefficient parameters of the unit cell are examined and analyzed using its simulation results for the biasing states. The structure gives its resonances at 24.364 GHz, 24.435 GHz and 30.057 GHz. The Fig 3 gives the reflection coefficient magnitude under the normal incident wave.

The reflection phase and magnitude parameters of unit cell in ON-state are given at Fig 4. It is observed that in ON-state, it gives dual resonance of 24.435 GHz, 30.057 GHz with the reflection phase of 38.912^0, and 86.406^0 respectively. For the OFF-state, the resonant frequency value is 24.364 GHz and its phase angle is -118.2^0. as shown in fig 5. It is observed that peak resonant frequency is constant in both operating states for which similar reflection properties with oblique incidence are obtained.

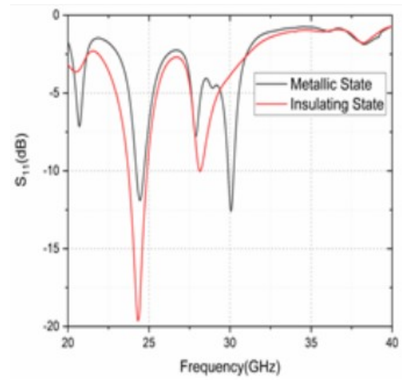


Fig 3. Simulated reflection magnitude property of the unit cell

The surface current density of the design at resonant frequencies are plotted in Fig 6. In ON-state, the maximum surface current density is concentrated across the VO_2 diode, whereas the low surface current is at OFF-state. The resonance character is also shown using surface current distribution.

The beamforming of the unit cell is exhibited using 3D simulation results that are shown in Fig 7. The peak gain of a unit cell is manipulated in both operating stages and is achieved by manipulating beam direction. At 24.364 GHz frequency, it provides a peak gain of 9.56 dB. Similarly, it gives peak gain values of 16.17 dB, 20.01 dB at 24.435 GHz and 30.057 GHz.

The angular stability of the unit cell of polarization is given in Fig 8. It gives the deflections of incidence and polarization angles. In reconfigurable states, the reflection magnitude is stable up to 90^0.

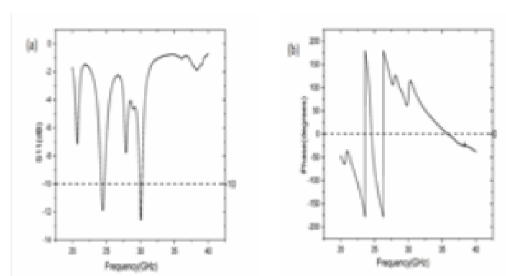


Fig 4. Reflection properties in ON-state.

(a)Magnitude. (b)Phase

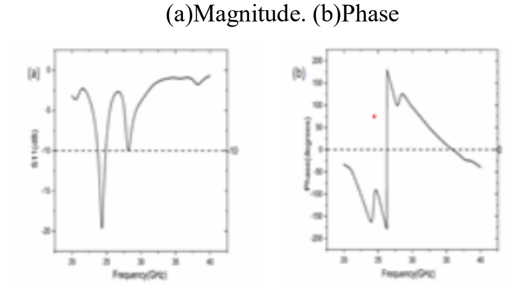
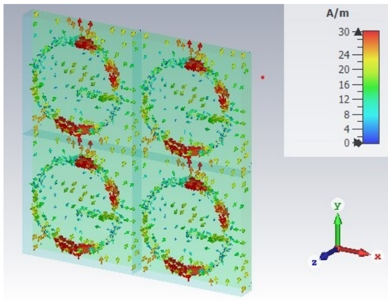
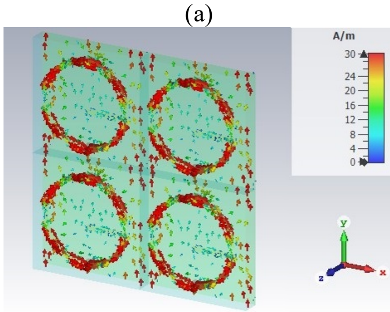


Fig 5. Reflection properties in OFF-state.

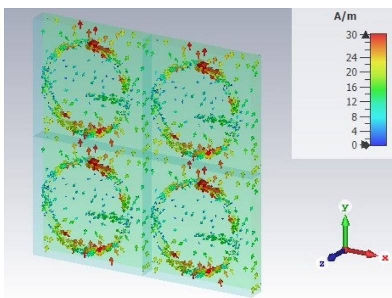
(a)Magnitude. (b)Phase



(a)



(b)



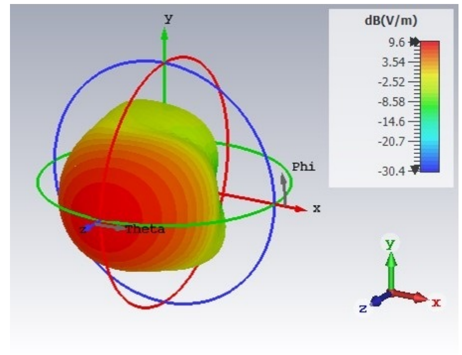
(c)

Fig 6. Surface current distribution in dual state operation at (a) F_r =24.435 GHz (b) F_r =30.057GHz (c) F_r =24.364GHz

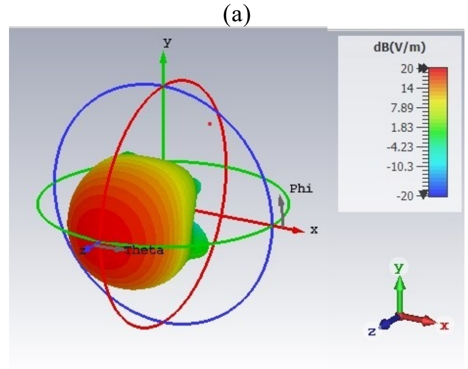
3. BIAS CIRCUIT AND DISCUSSION

The NodeMCU is involved to the circuit to achieve programmability for RIS surface that helps to control VO_2 diode as described in fig.8. The reconfigurable state is achieved by supplying 5V for ON-state and 0V for OFF-state. This is cost-effective and hence it is included to have programmability features for VO_2 controlled RIS surface.

The significance of this work is presented by comparing it with existing literature as shown in Table 1. Almost, the existing RIS designs are related to manual control that restricts the optimal performance at mmWave. The RIS performance is assessed using programmability, size, and application of reconfigurable elements. The optimum reflection and beamforming characteristics of the proposed design using programmable NodeMCU give a suitable option to satisfy the current demand for mmWave communications.



(a)



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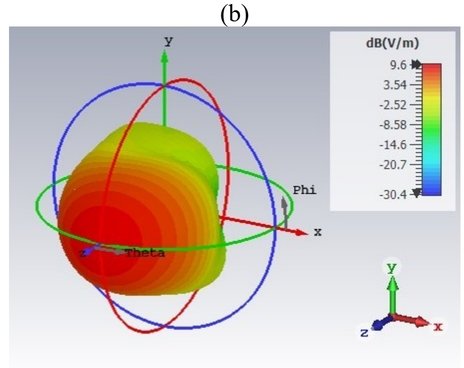

(c)

Fig 7. Simulated 3D pattern with beamforming at frequencies(a)F_r =24.435 GHz (b) F_r =30.057GHz (c) F_r =24.364GHz

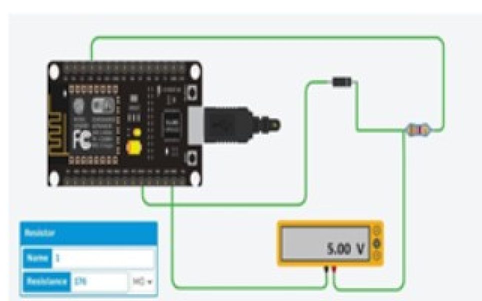

Fig 8. Diode model setup

Table 1. Comparison with existing mmWave RIS surfaces.

Ref.	Unicell size/substrate	Frequency (GHz)	Reconfigurable element	Application	Programmable device
[9]	3.3X3.3/ Silicon	27.5-31	VO_2	Transmission	Micro heaters
[10]	0.5X0.5/ sapphire	20	VO_2	Transmission	No programmable device
[11]	960X462/ Silicon	2 - 18	P-I-N	Beam Steering	Genetic Algorithm
[12]	3.85X3.85/ Silicon	27.5	P-I-N	Bandwidth	No programmable device
[13]	5.34X5.34/ RO4350B	30.6 - 31.7	Varactor diode	Beam steering	Bias Voltage
[14]	3X3/ RO3003	22.7 - 25.6	Varactor diode	Bandwidth	No programmable device
[15]	10X10/ FR-4	32.5 - 34	AlGaAs	Beamforming	Bias voltage/Arduino
Proposed	10 X 10/ FR-4	24 - 31	VO_2	Beamforming	Bias voltage/NodeMCU

4. CONCLUSION

In this design, a NodeMCU- Controlled mmWave RIS unit cell that has beamforming ability and angular stability for mm-wave communications is analyzed. The model is designed using a VO_2 diode that is perfect for mmWave frequencies and it resonates at 24.364 GHz,24.435 GHz and 30.057 GHz frequencies. The overall model is modified into a programmable RIS by giving NodeMCU control. The methodology and design characteristics were also studied. Hence, the design of NodeMCU-controlled RIS surface has the capacity to meet the needs of 5G mmWave applications.

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