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Theoretical Investigation of the Passive Transmitter Based on Reconfigurable Metasurface

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Wireless communication has become a standard solution to satisfy the ever-increasing demands of information transfer in our daily life. Furthermore, reconfigurable metasurfaces comprised of multiple tunable unitcells have drawn significant attention due to their superior electromagnetic performance, while the desired electromagnetic response can be controlled by computer. We therefore present a prototype of a wireless communication system based reconfigurable metasurface that works in the microwave frequency range. A 2-D periodical array of a reconfigurable metasurface is loaded with a varactor diode to effectively adjust the in-band transmission and reflection coefficients that maintain different far-field electromagnetic characteristics. The reconfigurable metasurface does not radiate electromagnetic waves and only carries information by adjusting its reflection and transmission coefficients. With this reconfigurable metasurface, a passive communication method can be realized.

Keywords: reconfigurable metasurface, wireless communication, reconfigurable transmission surface, active frequency selective surface, software defined radio

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1 INTRODUCTION

It is foreseen that the commercial service of the fifth-generation (5G) of mobile communications will be launched on a worldwide scale starting in 2020. The application of the Internet of Things as an important part of the fifth-generation of mobile communication has a very broad development prospect [1]. At present, wireless sensors in IoT devices are facing two major problems: power consumption and transmission distance [2]. The server's increasing demands are driven by various intelligent devices, such as smart meters, telemedicine, virtual reality, and autonomous driving, all of which include a lot of wireless sensor devices. With the growth of these mobile Internet services, the requirements for sensor power consumption have become increasingly higher. Currently, short-range wireless communication methods mainly include near-field communication (NFC), Bluetooth, and Zigbee, and most of these methods mainly work with frequency types such as S-band. A metasurface, composed of sub-wave-length resonators in 2-D plane [3–6], can provide a new way to control electromagnetics (EM) in terms of propagation modes, polarization, and wave-fonts [7–12], and recently an active anisotropic metasurface whose reflection phases can be electrically and independently tuned for two orthogonal polarized waves was reported [13]. Due to their unique EM properties, we propose a passive transmitter, using a reconfigurable metasurface design work in 2.4 GHz, to reduce the transmitter's power consumption and to make the metasurface compatible with the standard IEEE 802.11ac. IEEE 802.11ac is a wireless networking standard in the 802.11 set of protocols (which is part of the Wi-Fi networking family), providing high-throughput wireless local area networks (WLAN) on the 2.4 GHz and 5 GHz band.

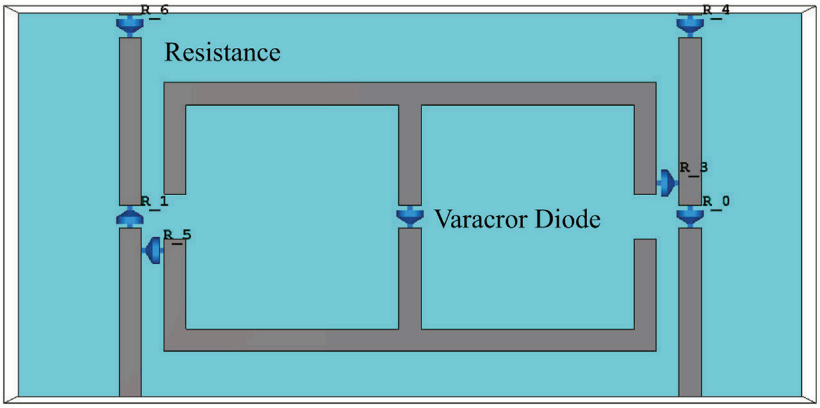

FIGURE 1 | The tunable unit of reconfigurable metasurface.

In this paper, a single layer reconfigurable metasurface has been presented with the aim of reducing power consumption. The proposed geometry consists of periodic metallic Patterns imprinted on the top of the dielectric substrate, where varactor diodes are mounted in the center of each unit cell. The reconfigurable metasurface has been constructed such that it can integrate two different characteristics (single band reflection and transmission) with independent control of the biasing states of the varactor diodes. In order to communicate with the passive transmitter a receiver has been designed with a software-defined radio (SDR) [14–18]. A software-defined radio is a radio communication system where components that have been traditionally implemented in hardware are instead implemented by means of software on a personal computer or an embedded system. While the concept of SDR is not new, the receiver in this paper only provided a method to verify this design. The varactors in the reconfigurable metasurface are controlled by the base band signal.

The remainder of this paper is organized as follows. **Section 2** presents the proposed design concept for a passive transmitter, then describes the system composition and characteristics of power consumption. **Section 3** discusses the theoretical investigation of this design and show the simulation results. Finally, concluding remarks and a comparison of the proposed passive transmitter to the traditional short-range wireless communication methods are presented in the last section.

2 RECONFIGURABLE METASURFACE PASSIVE TRANSMITTER

2.1 The Design of Unitcell

The reconfigurable metasurface is a lattice of 2-D subwave-length meta-atoms loaded with varactor diodes [14–23]. The Schematic view of the unitcell is illustrated in **Figure 1**. It includes one metallic layer that is placed on one substrate (F4B with a dielectric constant of 2.65 and loss tangent of 0.001). On the top layer is a "E" shape metallic strip combined by a varactor diode surrounded by metallic strips. The Structural parameters are chosen as follows: The width of the unitcell $W = 35mm$, the height of the unitcell $H = 17\,mm$, the strip width $l = 1\,mm$, the width of 'E' strip $X = 18\,mm$, the height of "E" shape strip $Y_1 = 5.5\,mm$, and the gap of the varactor diode $g = 1\,mm$, in other words, the total height of the central patch $Y_2 = 12\,mm$ and the thickness of the substrate $t = 0.8mm$. The varactor diode is placed across the gap on the top layer, and six resistors with a resistance of 10 K ohms are placed symmetrically, as shown in **Figure 1**, to limit the bias current and to isolate the surface current. By tuning the reverse DC bias voltage across the varactor V_b, the reflection coefficient of the reconfigurable metasurface is manipulated. In this work we select the varactor diode infineon BB857, whose services resistance $R_s = 1.5\,\Omega$, inductance $L_s = 0.7\,nH$, and capactitance C ranges from 0.54 to 6.6 pF when its reverse biasing voltage changes from 28 to 0 V. In this unitcell we know that the gap of the "E" shape strips the metallic wires on the top layer combined by a varactor, so that the varactor is a parallel connection. The transmitter properties of the unitcell is a function of the biasing voltage V_b. The resonance moves from low to high frequencies when V_b decreases from 28 to 0 V.

2.2 System Model

A Full structure sample containing 5×9 unitcells are placed on the EM absorbing material, as shown in **Figure 2**. Then we change the resonance frequencies, the metasurface can work as an absorber and reflector. The receiver in this system will continuously radiate horizontally polarized EM waves. In this paper, a software-defined radio is used to implement a continuous wave radar working at 2.4 GHz as a signal receiver, which is illustrated in **Figure 3**.

In this passive transmitter radio frequency (RF) source and amplifier is not employed, so the transmission coefficient is obtained as

$$\Gamma = S_{21} - S_{21air} \tag{1}$$

where S_{21} is the transmission coefficient through the reconfigurable metasurface and S_{21air} is the coefficient when the EM waves through the air.

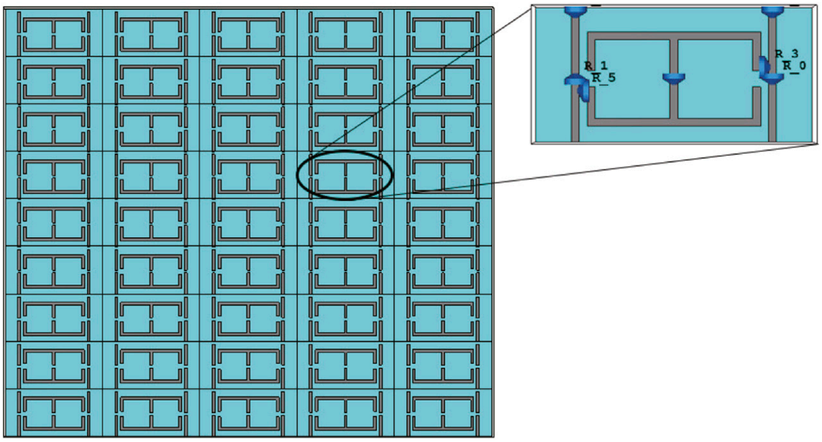

FIGURE 2 | Schematic of the reconfigurable metasurface with a periodic structure.

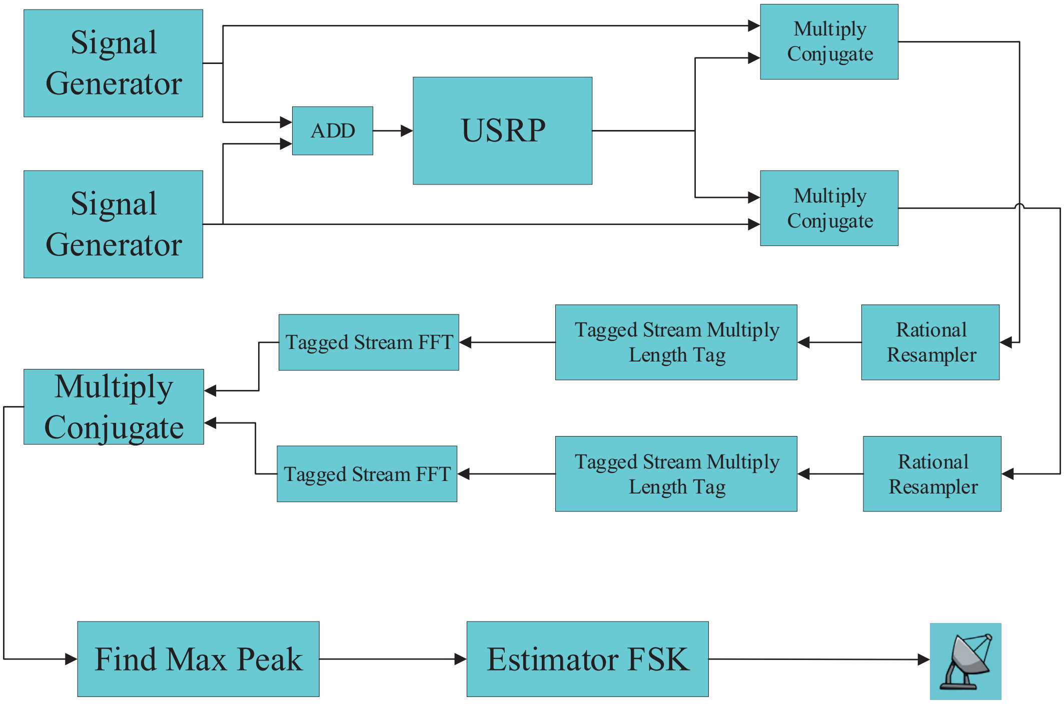

FIGURE 3 | The block diagram of the receiver based on the software defined radio.

For simplicity, let us assume that a wireless source emits a seemingly random signal $s(t)$, and the received sequence of binary digital information is $r(\tau)$, we refer to the time τ in $r(\tau)$. In an analogy with continuous-wave radar $s(t)$ and $g(\tau)$ can be correspondingly regarded as the launch wave and radar echo. We need to convert the $g(\tau)$ into that of the distinguishable carry wave control coding patterns of the reconfigurable metasurface $\Gamma(\tau)$. At any given time τ_0, if $\Gamma(\tau_0) = \Gamma_0$, the stray received sequence $g(\tau_0) = s(t) \times \Gamma_0$. So, the received sequence with the information modulated by coding patterns.

When the metasurface is driven by the EM wave E_i, normally incident from the top toward the metasurface at f_i, the response can be represented as

$$E_r = \Gamma \times E_i = \Gamma \times e^{j2\pi f_i t} \tag{2}$$

where E_r stands for the reflected wave. From the theory of Fourier transform, the frequency response can be expressed as

$$E_r(f) = \Gamma(f) * [\delta(f - f_i)] = \Gamma(f - f_i) \tag{3}$$

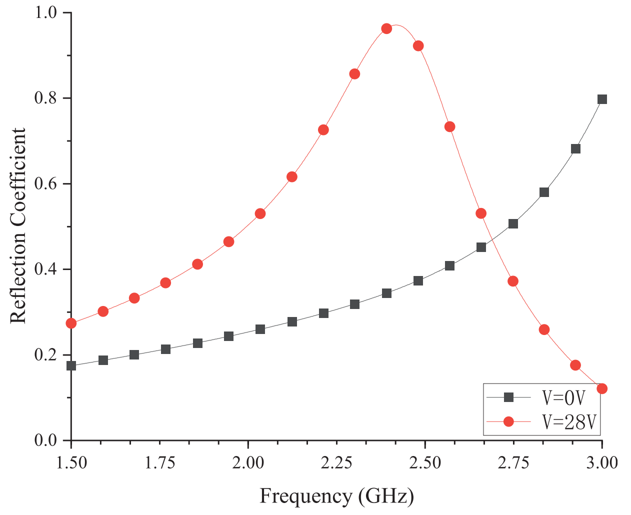

FIGURE 4 | The reflection coefficient of a reconfigurable metasurface at different voltages.

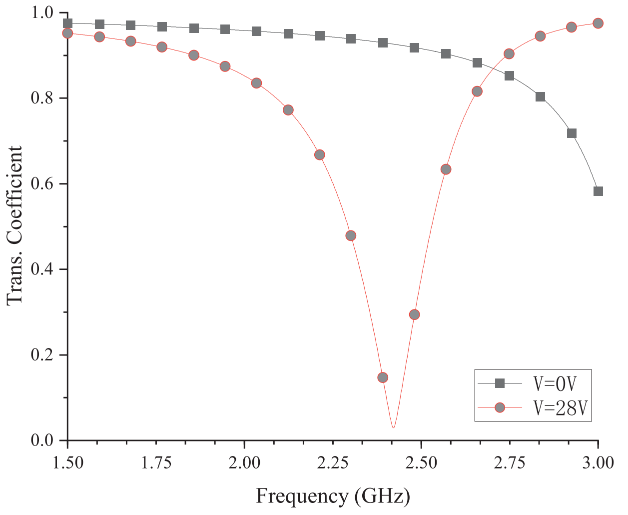

FIGURE 5 | The transmission coefficient of a reconfigurable metasurface at different voltages.

where $*$ stands for the convolution operation, and δ is the Dirac delta function, respectively. We know that the reflection responses are highly dependent on the transmission coefficient's frequency response from **Eq. 2**.

In this work, the varactor diodes are working at two states, one is without biasing voltage ($V = 0V, C = 6.6pF$) and the other is with biasing voltage ($V = 28V, C = 0.54pF$). In this case we can realize a 1-bit digital codes, the reflector state is defined as the code "1" and the transmission state is defined as the code "0". So, a Frequency-shift keying (FSK) transmitter can be realized based on this reconfigurable metasurface.

3 SIMULATIONS AND DISCUSSION

To verify the performance of the proposed metasurface, Frequency domain simulations are performed using the CST studio and GNUradio software. In our Simulations, the unitcells are driven by the horizontal polarized wave from 1.5 GHz to 3 GHz. The reflection and transmission coefficient are shown in **Figure 4** and **Figure 5**. As an illustrative example, we find that the reconfigurable metasurface worked at 2.4 GHz by adjusting the biasing voltage, and the EM resonance changes as expected.

Furthermore, we simulated the reconfigurable metasurface's farfield properties. From the farfield simulation results, it can be intuitively seen that the main lobe of the reconfigurable metasurface covers half of the space and the amplitude of the backward radiation is very low. In this case, its farfield reflection properties can be well modulated.

Particularly, the reflectivity and phase difference of the two elements under the illumination of forward x-polarized incidence are depicted in **Figure 6**, respectively. It is clearly shown that the complete reflection with direction difference approximately approaching 180°, is well kept in $2.4\,GHz$. The transmitter is composed of 9×5 unitcells. Since the varactor diodes works at 0v and 28 V reverses the bias state, its reverse current is about $10\,nA$, the power consumption of a single structural unit is about $300\,nW$, and its total power consumption is less than $1\,mW$. The power consumption comparison of communication is shown in **Table 1**.

Based on the design proposed above, we can combine it into a new communication system. The reconfigurable metasurface whose biasing voltage are controlled by the base band signal plays the role of transmitter. The continuous wave radar designed by GNUradio is used as a receiver. In this communication system the transmitter does not radiate any EM wave, which is of great significance for EM silence. In IoT applications, a large part of the sensor data transmission is unidirectional, and the power is limited. The passive trans proposed in this paper may solve these problems.

4 CONCLUSION

In summary, we provided a theoretical framework for modulation, and simulated a prototype system tailored to the use of ambient commodity $2.4\,GHz$ Wi-Fi signals. The proposed design is comprised of switchable active comments mounted across the metallic grids, and with base band control of the biasing conditions of the varactor diodes, the metasurface realized different modes of operation. For different biasing voltages the reconfigurable metasurface showed different electromagnetic characteristics, and then used these characteristics to achieve information transmission and reduced the power consumption of this kind of transmitter. At present, traditional short-range communication methods such as Bluetooth consume more

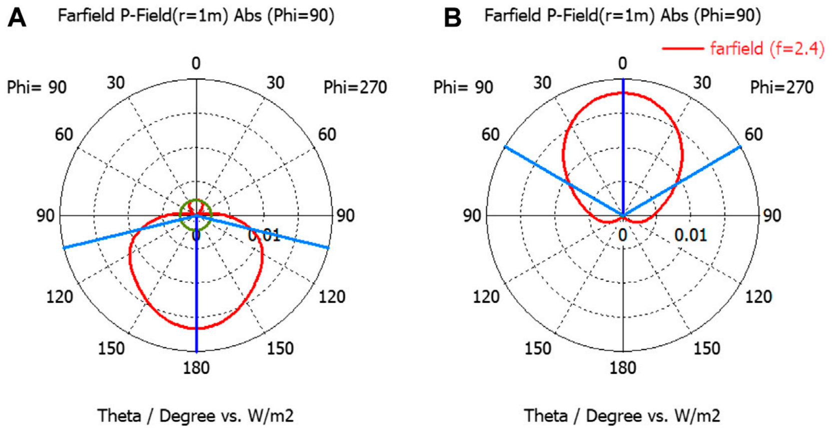

FIGURE 6 | Simulation results of the reconfigurable metasurface's far-field radiation properties. **(A)** V = 0 V the metasurface working as a reflector. **(B)** V = 28 V the metasurface working in the transmission state, which can be regarded as an absorber due to the combination with the absorber placed behind the metasurface.

TABLE 1 | Comparison of wireless technologies' power consumption.

Wireless technologies	Power consumption	Communication distance
ZigBee	100 *mW*	100 *m*
Wi-Fi	> 100 *mW*	1000 *m*
Bluetooth	10 *mW*	10 *m*
Passive transmitter	< 1 *mW*	Depends on the receiver's resolution

than 10 mW. The passive transmitter based on a reconfigurable metasurface proposed in this article works in the reverse bias state of the varactor. The power consumption is therefore less than 1 mW and the distance of communication depends on the receiver's resolution. It will also have applicational prospects in confidential communications. We believe that our passive transmitter, based on a reconfigurable metasurface, provides a fundamentally new view on wireless communication systems that can impact a wide range of future passive and IoT communication systems at radiofrequencies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SY designed and performed the design and simulation as well as wrote the paper. All authors participated in the data analysis and read the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.