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Research Article

Design of a PIN Diode-Based Reconfigurable Metasurface Antenna for Beam Switching Applications

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In this paper, we propose a reconfigurable metasurface antenna for beam switching applications. The reconfigurable metasurface is formed by uniformly distributed double-split square rings loaded with positive-intrinsic-negative (PIN) diodes for dual operations of a wave reflector and a wave director. Specifically, when the PIN diodes are forward biased, an epsilon-negative (ENG) metasurface is realized which reflects all incident waves with appropriate polarization; when the diodes are reverse biased, at the same operating frequency, a mu-near-zero (MNZ) metasurface is acquired which directs wave propagation. For excitation, a dipole radiator loaded with the same type of PIN diode is designed. Simulation and measurement results show good agreement and verify the beam switching functionality of the proposed metasurface antenna.

1. Introduction

Recent advances in metamaterial and metasurface technologies have brought unprecedented opportunities in the realization of novel and practical electromagnetic structures and devices. By definition, metamaterials are artificial periodic structures with unusual electromagnetic properties such as negative permittivity and permeability that have not been found in naturally occurring materials [1], and metasurfaces are referred to as metamaterials with reduced dimensions [2, 3]. In addition to having low profile, metasurfaces offer even more functionality and flexibility in the design of electromagnetic structures and provide a higher degree of control over wave propagations. Typical applications of metasurfaces include wavefront control (according to the generalized Snell's law [4]) using planar lenses, vortex generator, and axicon [5, 6]; super-resolution imaging and lithography by utilizing evanescent waves [7]; radar cross-section (RCS) reduction [8]; and realization of electromagnetic absorbers and polarization converters.

Reconfigurable metasurfaces, recently attracting a considerable amount of interest, have the advantage of providing multifunctional control of electromagnetic waves with electrical tuning mechanisms such as changing the applied bias voltage. Typical active elements used in reconfigurable metasurfaces include positive-intrinsic-negative (PIN) diodes, varactors, or transistors, which have been utilized to achieve beam steering [9–15], polarization conversion and control [16–20], realization of compact absorbers [21, 22], and recently, proposed coding or programmable metasurfaces [23–28].

In this work, we propose a PIN diode-based reconfigurable metasurface for realization of dual operations when the diode is in different bias states. Specifically, when the PIN diode is forward biased, at the frequency of interest, the metasurface acquires the properties of epsilon-negative (ENG) materials which forbid wave propagation and reflect all incident waves with appropriate polarization; when the diode is in its reverse-biased state, the metasurface obtains properties of mu-near-zero (MNZ) materials which direct wave propagation [29–32]. Based on these two controllable

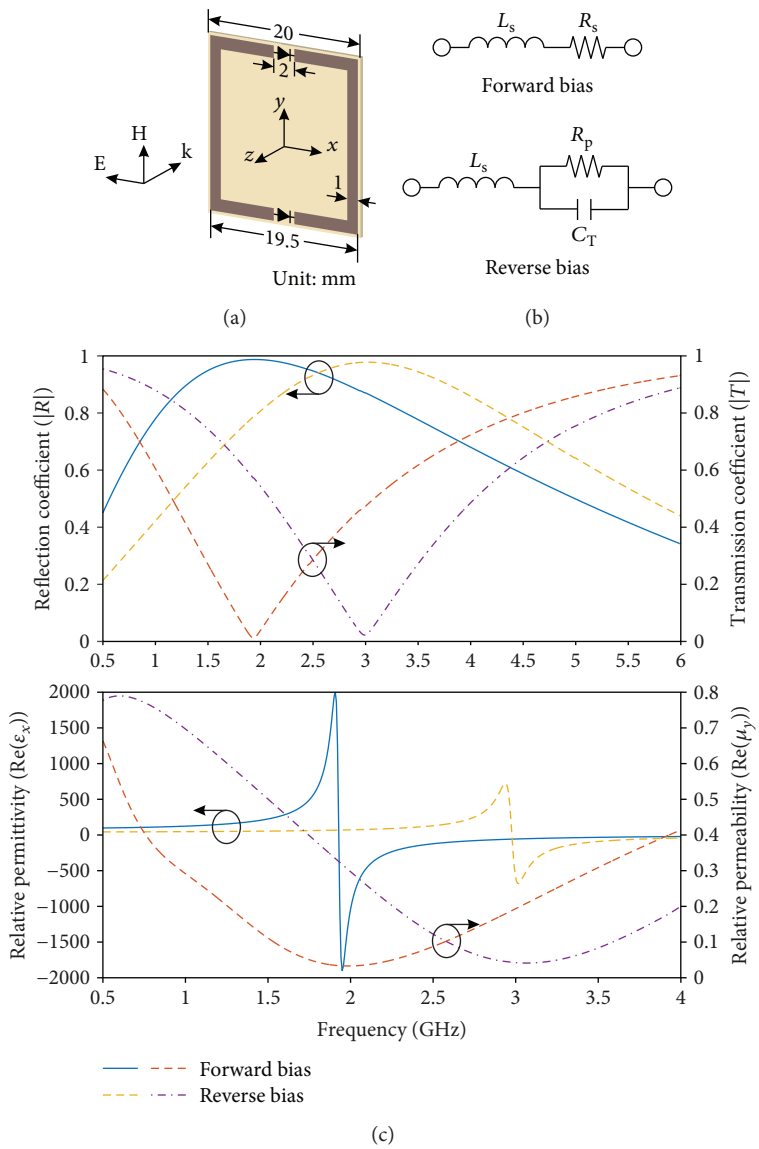

Figure 1: (a) Unit cell of the metasurface formed by square split rings loaded with two PIN diodes. (b) Equivalent circuits of the PIN diode in the forward and reverse bias states ($L_s = 1.8$ nH, $R_s = 1\ \Omega$, $R_p = 5$ kΩ, and $C_T = 0.3$ pF). (c) Calculated transmission and reflection coefficients and retrieved relative permittivity and permeability of the metasurface formed by double-split square rings loaded with PIN diodes in forward and reverse bias states.

functions of the proposed metasurface, we then further design a feeding dipole radiator to realize a compact beam switching antenna, and its radiation patterns can be electrically controlled by the applied bias voltage across the PIN diode. In contrast to our previous work on the realization of contrary beams at different frequencies [33], the PIN diode-based metasurface proposed in this paper allows to generate antenna beams in opposite directions at the same operating frequency.

2. Reconfigurable Metasurface Antenna Design

It is well known that most metasurfaces are formed by resonant structures such as split-ring resonators (SRRs). Thus, below the resonant frequency, the metasurface has positive material properties, while the permittivity or permeability of the metasurface becomes negative at frequencies above the resonance. Naturally, different wave behaviors through the same metasurface can be acquired depending on the operating frequency range. However, for most practical applications such as wireless communications, the operating frequencies must be fixed, and therefore, to achieve multifunctional operations, the metasurface needs to be tunable or reconfigurable. With the use of PIN diode in the metasurface design, the resonant frequency can be controlled by the applied bias voltage, and different properties of the metasurface can be obtained at the same operating frequency.

Here, we consider a metasurface formed by periodically arranged double-split square rings whose fundamental resonant frequency can be conveniently controlled by the

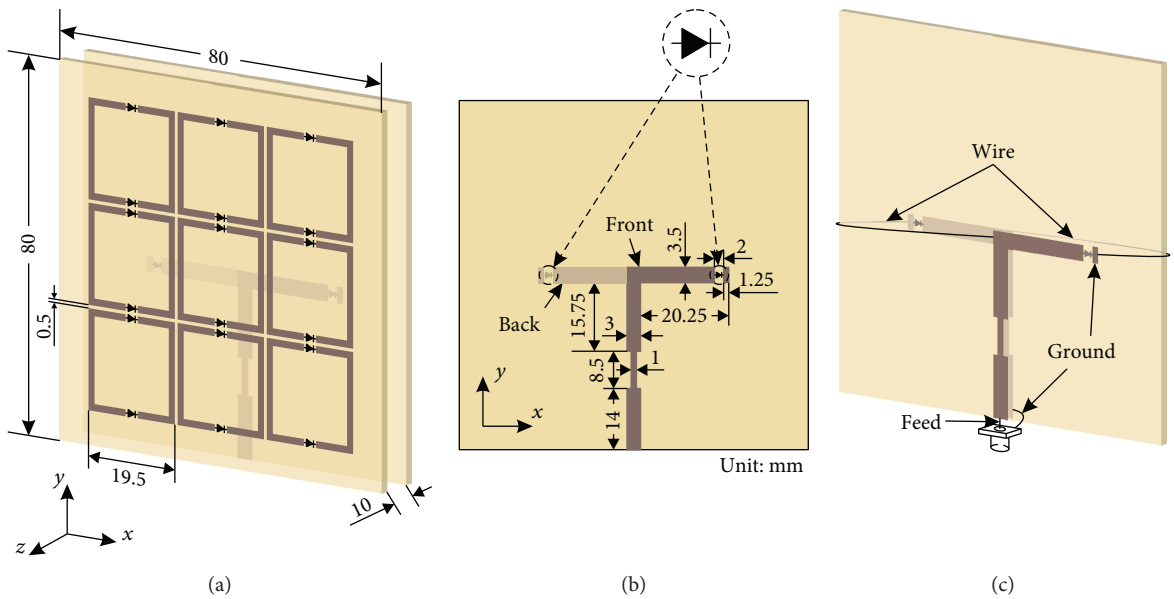

Figure 2: Structure of the proposed PIN diode-based reconfigurable metasurface antenna for beam switching applications: (a) perspective view and (b) the dipole excitation source. (c) Diagram showing how PIN diodes are connected to two radiating arms of the dipole.

dimensions of each ring. In addition, to realize a reconfigurable metasurface, two PIN diodes (Infineon BAR63-03W) are inserted into the gaps of each square ring, as shown in Figure 1(a).

The equivalent circuits of the PIN diode in its forward and reverse bias states are shown in Figure 1(b). A plane-wave analysis is then performed to calculate the transmission and reflection coefficients of the metasurface and a material parameter retrieval method is applied to extract effective permittivity and permeability of the metasurface, as shown in Figure 1(c). It is found that when the PIN diodes are in different bias states, there exist two resonant frequencies of the metasurface, which can be explained as follows. When the diode is forward biased, each square ring of the metasurface becomes a closed loop due to the small resistance, R_s, leading to a lower resonant frequency of the metasurface. When the diode is reverse biased, as shown in Figure 1(b), the small capacitance, C_T lowers the total capacitance of each square ring and causes the resonant frequency of the metasurface to shift higher. An alternation explanation of the operating mechanism is that the ring inclusions act as simple loaded electrically small dipoles (the vertical metallic segments along the y direction), and the capacitive loads applied to the end of small dipoles contribute to reduce their dimensions, then the inductor L_s in the gap introduced by the PIN diode further contributes to reduce the resonant frequency. When the PIN diodes are reverse biased, the capacitance C_T reduces the impact of L_s in the equivalent circuit model and the resonant frequency blueshifts.

At the frequency of interest at around 2.45 GHz, for the forward bias case, the effective permittivity, ε_x, is negative, while the effective permeability, μ_y, is near zero but positive. Thus, an ENG metasurface is realized which forbids wave propagation and reflects all incident waves with x polarization. When the diodes are reverse biased, the upshift of the resonant frequency results in a positive ε_x while μ_y still remains near zero, creating a MNZ metasurface at the same frequencies around 2.45 GHz. Although observed from the transmission and reflection coefficients that the metasurface is still highly reflective for plane waves, the MNZ metasurface is capable of altering wave vectors of near fields and acting as a wave director, according to our previous analysis [29–32]. Thus, a reconfigurable PIN diode-based metasurface is realized to achieve dual functionality of a wave reflector and a wave director depending on the applied bias voltage. Based on these two functions, in the following, we further design a reconfigurable beam switching antenna.

In the metasurface antenna design, the number of elements in the metasurface is 3×3 in order to maintain the overall small dimensions of the antenna, as shown in Figure 2(a).

For excitation, a dipole radiator is designed which contains two identical radiating arms with one arm on each side of a substrate. Both radiating arms are aligned along x direction to excite the correct polarization. A PIN diode (the same model as above) is also used in each radiating arm of the dipole radiator for tuning its resonant frequency, as the metasurface introduces different mutual coupling effects to the dipole when the PIN diodes on the metasurface are in different bias states. As illustrated in Figure 2(b), the PIN diode separates each radiating arm into a long section and a short section. For biasing both diodes at the same time, the long section on one side is connected by a thin wire to the short section on the other side, as depicted in Figure 2(c). The antenna is simulated using CST Microwave Studio™, and all parameters shown in Figure 2 are optimized ones, including the distance between the two substrates. The distance is chosen such that the antenna has high directivity when the diodes are in both bias states.

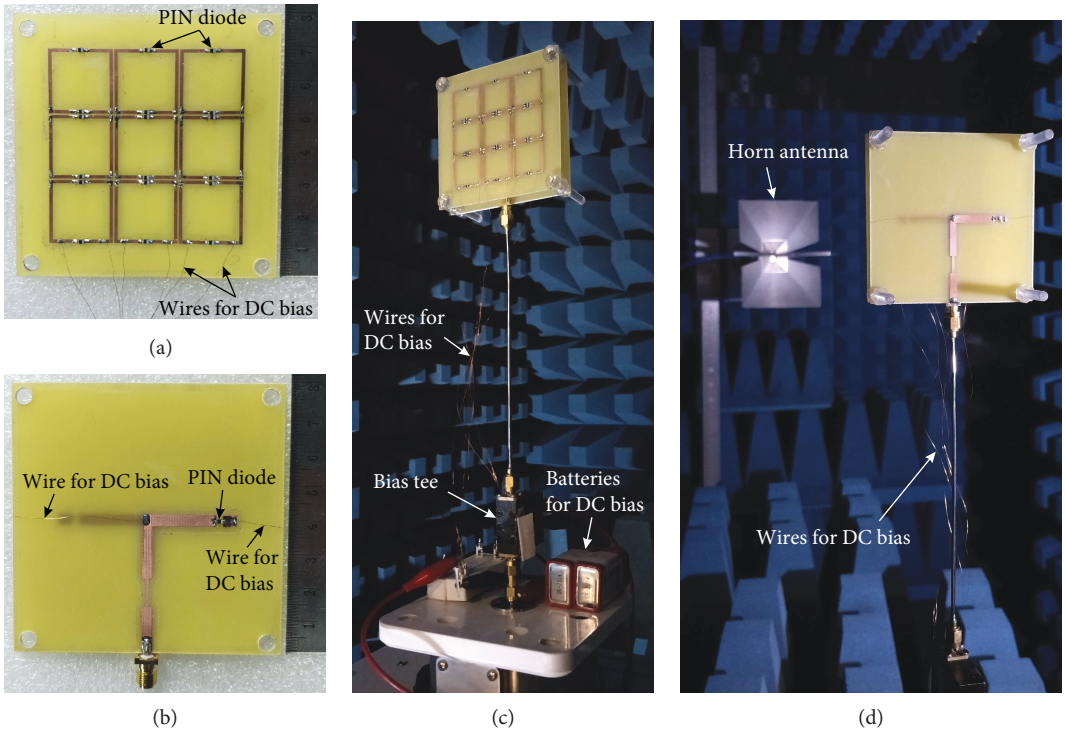

Figure 3: Prototype of the fabricated PIN diode-based reconfigurable metasurface antenna: (a) top view of the reconfigurable metasurface and (b) bottom view of the dipole excitation source. (c, d) Experimental setup during the measurement of the radiation patterns (gain) of the proposed reconfigurable metasurface antenna.

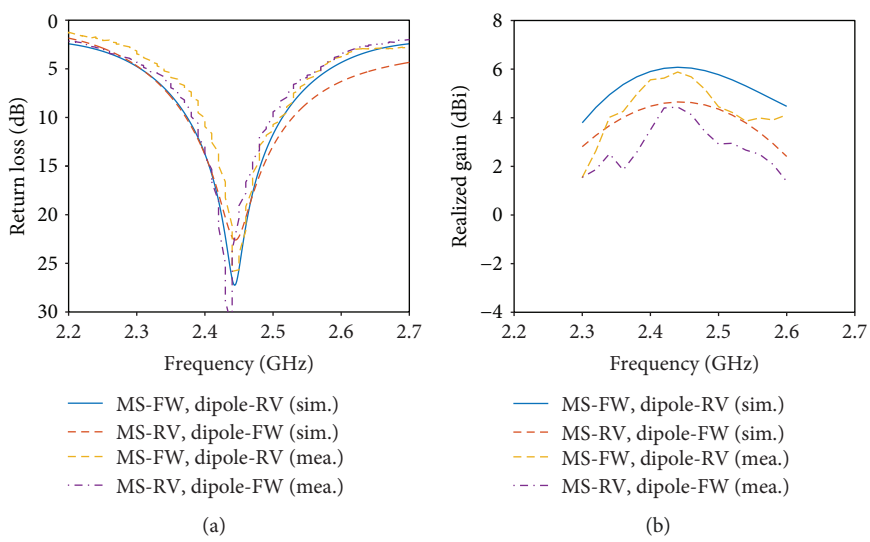

Figure 4: Comparison of simulated and measured (a) return loss and (b) gain of the proposed PIN diode-based reconfigurable metasurface antenna operating in forward and reverse bias states of PIN diodes. (Notations: MS: metasurface; FW: forward bias; RV: reverse bias.)

3. Results and Discussions

The proposed metasurface antenna is fabricated on FR-4 substrates with thickness of 1.6 mm and dielectric constant of 4.3. The prototype of the antenna and the measurement setup are shown in Figure 3.

Two 9-volt parallel-connected batteries are used to bias the PIN diodes on the metasurface, and a bias tee is used to combine the radio frequency (RF) signal and direct current (DC) bias voltage for feeding the dipole radiator.

Figure 4 shows the comparison of simulated and measured return loss and antenna gains in the forward ($+z$)

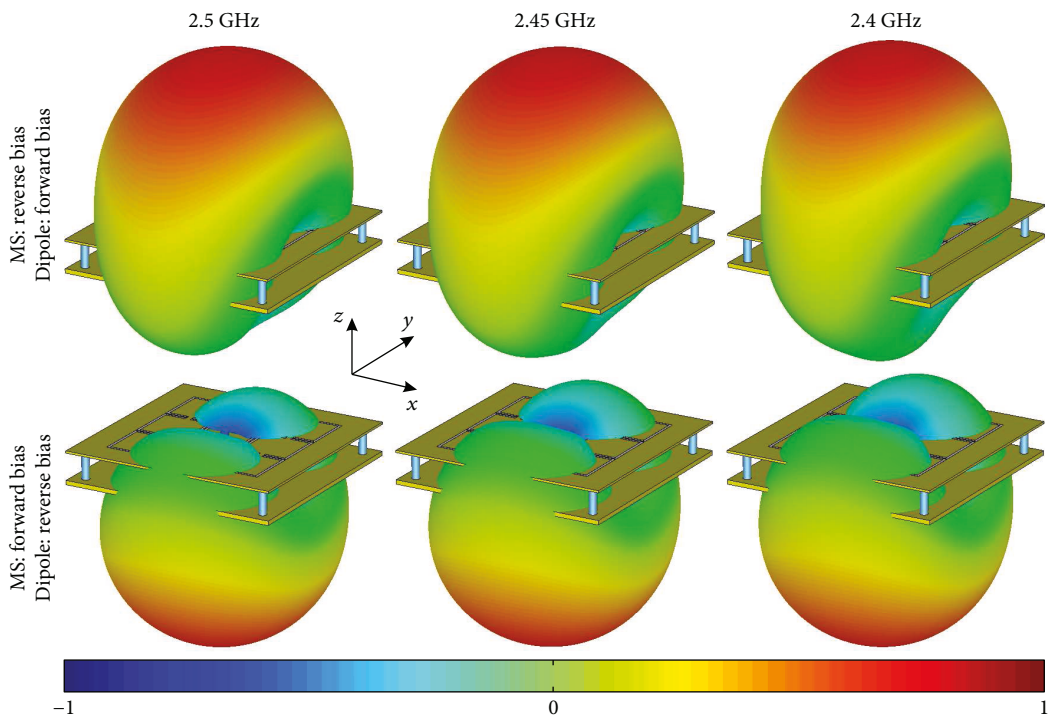

Figure 5: Simulated 3-D radiation patterns (normalized gain) of the proposed PIN diode-based reconfigurable metasurface antenna operating in forward and reverse bias states of PIN diodes at frequencies of 2.4, 2.45, and 2.5 GHz.

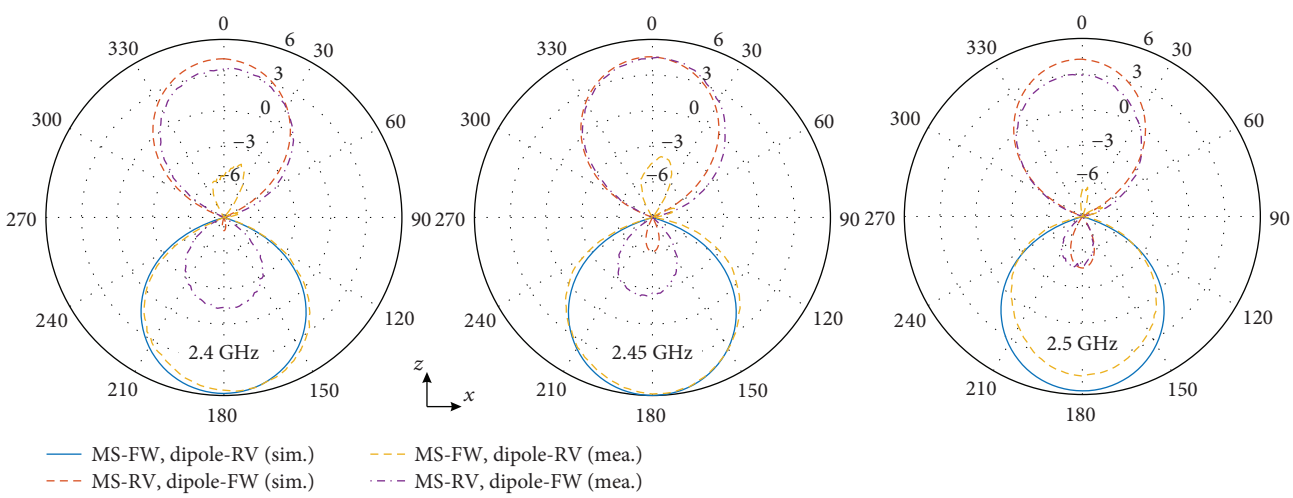

Figure 6: Comparison of radiation patterns (gain) in the x-z planes from simulations and measurement at the frequencies of 2.4, 2.45, and 2.5 GHz.

and backward ($-z$) directions when the PIN diodes are in different bias states. When the PIN diodes on the metasurface are forward biased, the mutual coupling between the metasurface and dipole radiator lowers the dipole's resonant frequency; thus, a reverse bias voltage is applied to the PIN diodes on the dipole to shorten the electrical length of its radiating arms.

On the other hand, when the PIN diodes on the metasurface are reverse biased, the resonant frequency of the dipole radiator shifts higher and a forward bias voltage is applied to the PIN diodes on the dipole to shift the resonance back to 2.45 GHz. Therefore, to conclude, when the metasurface is working as a wave reflector, the PIN diodes on the metasurface and dipole are forward and reverse biased, respectively; when the metasurface is acting as a wave director, the PIN diodes on the metasurface and dipole are reverse and forward biased, respectively. In addition, it can be observed that the metasurface antenna has good impedance matching for both diode states. The difference in antenna gains in Figure 4(b) is due to the fact that the efficiency of

the metasurface behaving as a wave reflector is higher than that as a wave director [29–32].

The calculated three-dimensional (3-D) radiation patterns (gain) from CST simulations and the comparison between simulated and measured radiation patterns are shown in Figures 5 and 6, respectively.

It can be clearly observed that when the PIN diodes on the metasurface are forward biased, the main antenna beam points toward the $-z$ direction, and when the diodes on the metasurface are reverse biased, the main antenna beam is directed to the $+z$ direction. Thus, the antenna beam can be switched conveniently according to the applied bias voltage. Moreover, the comparison between simulation and measurement results also shows good agreement which validates our proposed design.

4. Conclusion

In conclusion, we have proposed a PIN diode-based reconfigurable metasurface antenna for beam switching applications. The metasurface is designed for dual operations of a wave reflector and a wave director, by realizing an ENG metasurface and a MNZ metasurface at the same operating frequency when the diodes are in forward and reverse bias states, respectively. Simulation and experimental results show that the proposed antenna has good impedance matching with moderate gain performance across the frequency band of interest. In addition, the main radiation beam of the metasurface antenna can be readily controlled by applying appropriate bias voltages on the PIN diodes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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