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Direct Antenna Modulator for m-QAM Applications

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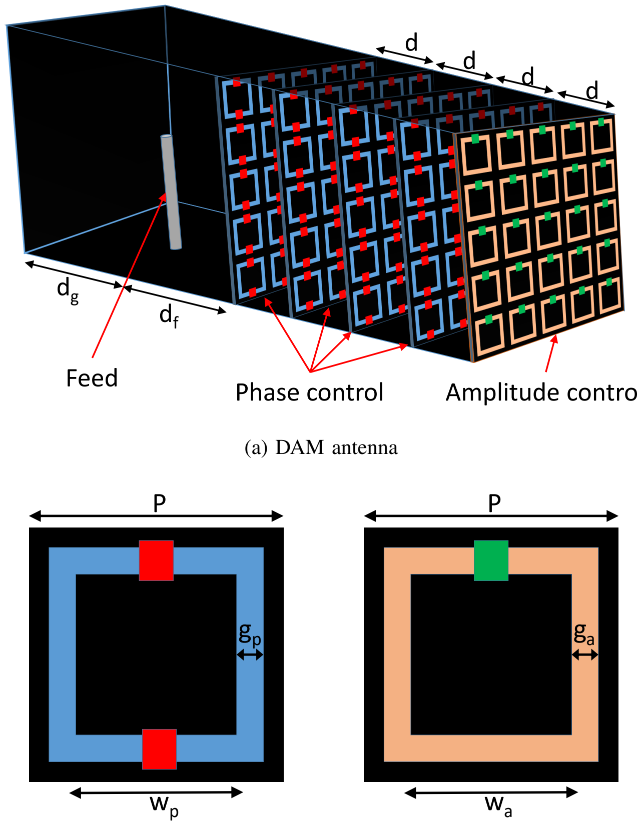
***Abstract*—This paper introduces a concept for direct antenna modulation using a metasurface based antenna. The antenna can be controlled with the use of an external bias to control both the amplitude and phase of the transmitted signal, in a continuous way, to provide m-QAM direct antenna modulation. The DAM comprises of five metasurfaces, four of which control the transmitted phase through the use of a varactor diode, and the fifth uses a PIN diode to control the transmitted phase. Numerical simulations are presented which show that the transmitted phase can be varied over a 360° range with a amplitude dynamic range of 25dB.**

***Index Terms*—Antennas, metamaterials, metasurfaces, direct antenna modulation.**

I. Introduction

Direct antenna modulation (DAM) is a technique where baseband data is used to control the radiation properties of an antenna to produce a modulated signal, and can remove the requirement for conventional modulation techniques. A specific advantage of DAM is that it eliminates problems associated with power amplifier (PA) non-linearity, which appear in classic m-QAM modulation techniques due to the baseband signals having a high peak-to-average-power ratio (PAPR). Low power, low complexity DAM solution may have application in the Internet of Things (IoT), where reducing power consumption and complexity is a key concern [1]. The basic concept of DAM is where a single frequency carrier is amplified, using a PA operating in its high efficiency non-linear region, and passed through an antenna where the phase and/or gain is controlled using an external signal source (voltage, current, light etc) which is derived from baseband data. A specific method for achieving DAM is through the use of reconfigurable metamaterials/metasurfaces, where a metamaterial is an engineered structure containing metallic and dielectric materials, often in a periodic arrangement, that has properties that can not be achieved through natural materials. Examples of such metamaterials are frequency selective surfaces (FSS), and high impedance surfaces (HIS).

Research in this area has focused on two methods, the first being where a signal is passed through a reconfigurable metamaterial, and the second where a reflective metamaterial is illuminated by an external source. The basic method for achieving DAM was set out using simulations of PIN diodes placed across aperture FSS elements, providing reconfigurability between bandpass and low pass frequency responses which are capable of achieving amplitude shift keying (ASK) [2]. FSS concepts were adopted for signal control in secure building applications which demonstrated the basic techniques [3], and led to the demonstration of a end-to-end QPSK communication system based on a multi layer FSS design, [4]. Further developments to this technique showed how a reflective reconfigurable intelligent surface, [5], could be employed to achieve 8-PSK modulation [6], and a FSS based system also demonstrated 8-PSK, [7].



(a) DAM antenna

(b) Unit cell for phase control

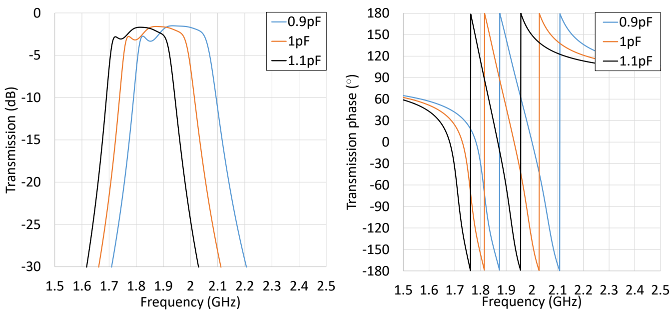
(c) Unit cell for amplitude control

Fig. 1. Illustration of DAM. Note: the red blocks are varactor diodes and the green blocks are PIN diodes and the black regions are metallic.

This paper develops techniques introduced in previous work to achieve a DAM which is capable of transmitting m-QAM data. Section II introduces the antenna concept and explains its basic operation. Section III reports numerical simulation of the DAM in the context of its antenna properties and modulation capabilities.

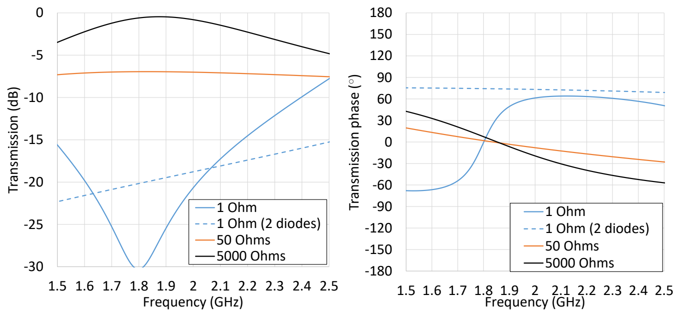
II. DAM Antenna Design

The proposed DAM is illustrated in Fig. 1a, which consists of a metallic enclosure of width W, height H, and depth L, for clarity one of the metallic walls is not included so that



(a) Amplitude (b) Phase

Fig. 2. Simulated transmission coefficient of four layer metasurface



(a) Amplitude (b) Phase

Fig. 3. Simulated transmission coefficient of amplitude controlling metasurface

the internal structure is visible. The DAM is fed by a short monopole of length L_m and is spaced a distance d_g away from the back wall of the enclosure. For this DAM design a combination of metasurfaces is used to carry out phase and amplitude control. To achieve phase control varactor diodes are placed between the metallic elements of a square loop aperture bandpass metasurface with period *P*, patch width w_p and gap width g_p, as illustrated in Fig. 1b. Changing the capacitance of the diode alters both the amplitude and phase of a transmitted signal at a specific carrier frequency. Using four layers of the same metasurface, each spaced distance d apart, provides a flat filter response over the capacitance tuning range such that these layers are intended to provide phase change only. This approach is detailed further in [7] and provides good phase control with a minimum of amplitude perturbation. The novel contribution in this work is to add a further metasurface which acts to control the amplitude of the transmitted signal and hence allows both phase and amplitude modulation. Control of the amplitude of the transmitted signal is achieved by placing a single PIN diode across the metallic elements of another square loop aperture metasurface with the same period *P* as the phase change design, but with different patch width w_a and gap width g_a, as illustrated in Fig. 1c, where by changing the bias voltage the PIN diode resistance can be varied.

III. Numerical Simulations

A. Metasurface Design

To illustrate the DAM performance it is first meaningful to demonstrate how the metasurfaces operate. Simulations were carried out on an infinite periodic array of unit cells, achieved by applying unit cell boundary conditions within CST microwave studio. For demonstration purposes the metasurfaces were designed to operate near 2GHz (*P*=22.5mm, w_p=15mm, g_p=1mm, and *d*=47mm), the metasurface substrate was FR4 (ϵ_r=4.3, $\tan(\delta)$=0.025, and of thickness 1.6mm). Fig. 2 shows the transmission coefficient, amplitude and phase, for varying varactor diode capacitance (the diode was modelled as a series RLC circuit, $R = 0.4\Omega$ and *L*=0.5nH). The results show how the phase changes almost linearly with frequency, over the frequency range of interest and within that range the amplitude changes by approximately 1dB.

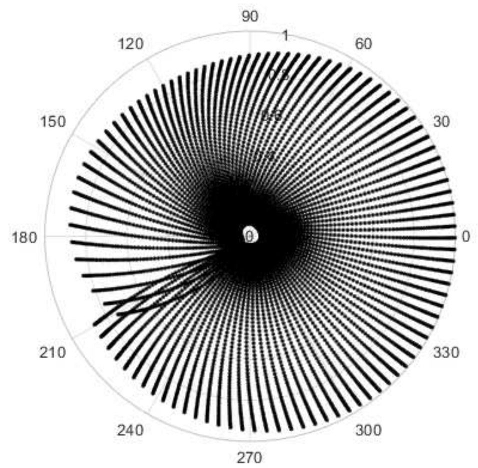
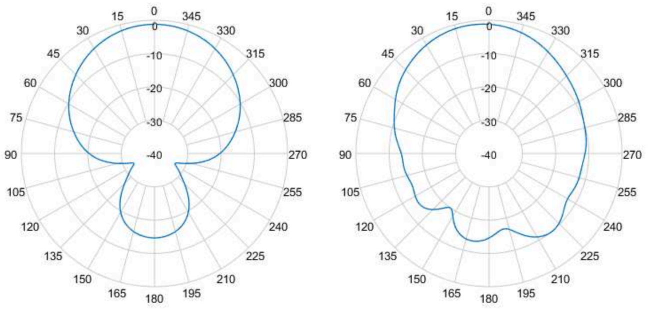


Fig. 4. Normalised complex E-field radiation from DAM at 1.8GHz for varying varactor and PIN parameters

The simulated results of the fifth metasurface, controlling the transmission amplitude is shown in Fig. 3 (*P*=22.5mm, w_a,=21mm, and g_a=0.25mm). In this case the PIN diode was modelled as a series RL combination ($R = 0.4\Omega$ and $L = 0.5nH$), in series with a parallel RC ($R = 1 - 5000\Omega, C = 0.2pF$). It can be seen that the transmission amplitude can be varied over a 30dB range, near 1.8GHz where the insertion phase at that frequency is close to 0°. The resonance observed in Fig. 3a is due to using one diode in the unit cell design, which produces a resonant loop in the metasurface. If two diodes where used, as in Fig. 1b the frequency response would be high pass, **as shown in Fig. 3. In order to maximize the amplitude dynamic range g_a should be small as this parameter controls the current path on the resonant loop.**

B. DAM Design

The DAM was designed using the metasurfaces from Section II, with some modifications to the spacing *d* to account for waveguide effects in the DAM enclosure. Following a heuristic design process simulations were carried out, monitoring the complex radiated far fields as a function of varactor capacitance and PIN resistance and are shown in Fig. 4 (*L*=342mm,



(a) H-Plane (b) E-Plane

Fig. 5. Simulated DAM realised gain pattern at 1.8GHz

W=112.5mm, d=57mm, $d_f = d_w$=57mm, and the length of the monopole was 35mm). The results show that as the varactor capacitance is varied the far-field phase can be controlled over a $360°$ range with a maximum amplitude reduction of approximately 2dB, for a fixed PIN resistance. As the PIN resistance is reduced the amplitude of the far field reduces as expected, with dynamic range of approximately 25dB, which compares reasonably with the periodic unit cell simulations. As the diode parameters can be varied in a continuous manner (analogue control) this means that any amplitude and phase that lie between within the E-field envelope ar possible and this makes this structure ideal for high order complex data modulation, such as m-QAM. **To implement the DAM in a wireless communications system would require a different architecture to the classic approach. A simple implementation would convert binary baseband data directly to control voltages (applied to the varactor and PIN diodes), via a look-up table or similar, which would provide the required amplitude and phase to represent the complex symbol to be transmitted.**

Fig. 5 shows the normalised E & H far-field radiation patterns for the DAM when the varactor capacitance is 1pF and PIN resistance is 5000Ω, where the maximum realised gain is -1dBi and the antenna reflection match is -10dB at 1.8GHz.

IV. Conclusion

A direct antenna modulator based on a reconfigurable metamaterial has been presented and analysed using numerical simulations. It has been shown that four, bandpass, metasurfaces that are controlled with a varactor diode can provide 360 ° of phase change for a capacitance variation between 0.9pF-1.1pF. Amplitude variation can be controlled using a fifth layer that is controlled with a PIN diode by varying the resistance. Simulations from both period boundary analysis and the full antenna design show good agreement and demonstrate capability as a modulator for m-QAM applications. Future work will focus on practical demonstration within an end-to-end communication system.

Acknowledgment

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