This is a repository copy of *Frequency Selective Surface Loaded Antenna for Direct Antenna Modulation*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/121845/

Version: Accepted Version

Frequency Selective Surface Loaded Antenna for Direct Antenna Modulation

Stephen Henthorn[1], Kenneth Lee Ford[1], Timothy O'Farrell[1],

[1]University of Sheffield, Department of Electrical and Electronic Engineering, Sheffield, UK, sdhenthorn1, l.ford@sheffield.ac.uk

Abstract—A reconfigurable antenna loaded with Frequency Selective Surfaces (FSS) to achieve direct antenna phase modulation is presented and simulated. Placing FSS with integrated varactor diodes into a monopole-fed cavity allows control of the transmitted phase of a carrier signal with a bias voltage. As such, Direct Antenna Modulation (DAM) can be achieved, producing a phase modulator that can be included in a low complexity transmitter. Simulation shows such an antenna can achieve QPSK modulation with between 3.5dB and 4.5dB magnitude variation between constellation points with acceptable phase stability with radiation angle in the antenna 3dB beamwidth.

Index Terms—reconfigurable antenna, frequency selective surfaces, phase shift keying.

I. INTRODUCTION

In conventional radio modulation, baseband data is mapped onto a radio frequency (RF) carrier wave at low power. This signal is then filtered and amplified to provide a waveform suitable for transmission over a wireless channel, and passed through a passive antenna. However, modulating the carrier at low powers requires the power amplifier (PA) to amplify a signal with a bandwidth associated with the symbol rate. As such, in order to avoid distortion due to non-linear effects, the PA must run with some back-off from its full efficiency [1].

Direct Antenna Modulation (DAM) has emerged as a potential solution to this problem, as it allows modulation of a continuous wave (CW) carrier at the antenna, so the PA can amplify the carrier signal in its non-linear region with no distortion. Various approaches to DAM have been examined, including using an array of switchable passive reflectors surrounding a driven element to produce direction dependant modulation [2]. Pulse-width modulation on the feed of a passive antenna to control the symbol amplitude, which allows complex symbols to be produced with two linearly polarised antennas arranged orthogonally has been demonstrated, [3]. Another method is to vary the antenna load to control the antenna currents and so the constellation produced in the farfield [4]. Research has shown how the use of integrated active components in high-Q patch antennas can be used to amplitude modulate emitted signals, with the aim of operating with symbol rates beyond their bandwidths [5].

In this paper, reconfigurable FSS are proposed as phase modulators for DAM. FSS have been previously proposed as amplitude modulators in [6]. Integrating varactor diodes within FSS allows their resonant frequencies to be altered by a bias
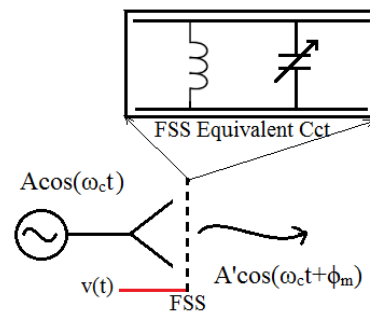

Fig. 1. Phase modulation with FSS

voltage [7]. This has been used previously to steer directional antenna beams [8] and to scramble GSM signals passing through a wall [9]. Using this technique, the transmitted phase of an antenna loaded with such FSS can produce a phase modulator suitable for use in Phase Shift Keying (PSK) communication systems. This concept will be analysed, and an FSS and antenna will be designed, simulated and characterised for QPSK modulation over a range of radiation angles.

II. DAM WITH FSS

Varying the bias voltage feeding an FSS allows the frequency response of the surface to be varied. As such, the transmitted phase of an incident continuous wave (CW) can be controlled giving the fundamentals of a phase modulator. This allows phase modulation to occur at high power directly in a transmitter, such as the one shown in Fig. 1, removing the need for power amplifiers (PAs) to back off from their most efficient region to account for broadband modulated signals and signals with high Peak to Average Power Ratios (PAPR). It also removes the need for large form factor, expensive and power inefficient electronics such as mixers and filters operating at RF. This complexity is replaced in the FSS transmitter with some mapping of digital data to a biasing signal $v(t)$, operating at the symbol rate, and the FSS itself. As such, FSS transmitters are a low complexity and increased efficiency replacement for conventional phase modulating transmitters.
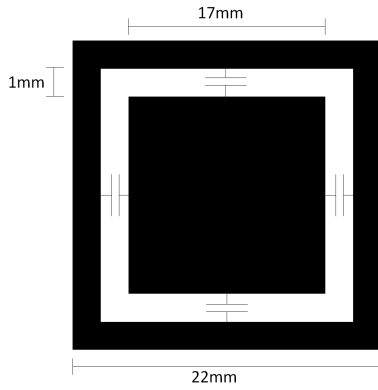
Fig. 2. FSS unit cell design

III. FSS DESIGN

In order to obtain phase change for modulation in the transmissive region of an FSS's frequency response, a bandpass unit cell design is required. For this reason, and for their stability with angle of incidence, a square-loop design was chosen (Fig. 2). The dimensions were chosen to give operation at 1.8GHz, a typical wireless communication frequency. In order to provide 360° possible phase change for as little magnitude variation as possible, three layers of the designed FSS were used, with each layer $\lambda/4$m from the next.

To assess its use as a phase modulator, the FSS design was simulated in CST Microwave Studio in free space, using Floquet boundaries to approximate an infinitely sized three-layer surface. PEC was used for the conducting surfaces on a 0.8mm FR4 substrate with a dielectric constant of $\epsilon = 4.3$. The varactor diodes were modelled as lumped elements with the properties of SMV147 diodes, chosen for their low capacitance and large tuning range, from 0.7pF to 7pF. They were simulated with a series resistance of 4.9Ω and a series inductance of 0.7nH. It is mostly the diode resistance, which is high for a variable capacitor, that accounts for the 5dB loss at maximum transmission shown in simulation (Fig. 3), and also increases the slope away of magnitude at the edges of the response. The design frequency of 1.8GHz is shown with a dotted line in both the magnitude and phase plots.

The simulation shows 360° of phase change is possible for 8dB difference between the least and most transmissive points with realistic components. This is large, but practical PSK transmitters do not need to achieve 360° of phase change-for example, QPSK requires only 270° phase change between its furthest constellation points, which is achievable for 3.5dB variation according to simulation. Both the overall loss and the magnitude difference of constellation points could be reduced by using lower resistance variable capacitors and low loss substrates.

IV. RECONFIGURABLE ANTENNA DESIGN

Previous simulations assumed each layer of FSS was an infinitely sized sheet of repeating unit cells in free space. In
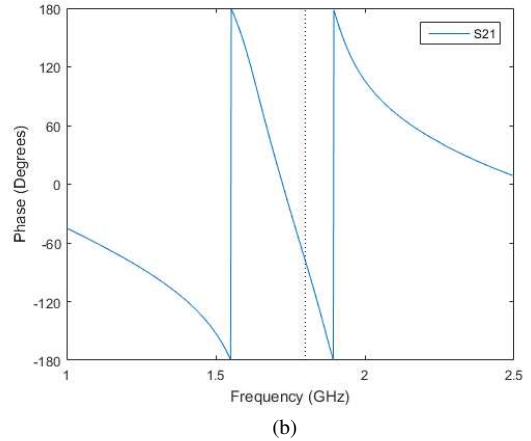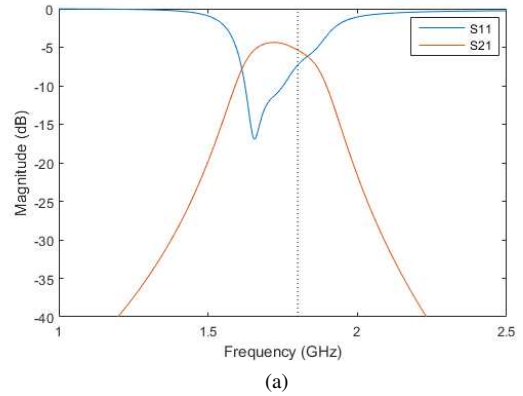

(a)

(b)

Fig. 3. Simulated s-parameters of infinite 3-layer FSS, (a) magnitude (b) phase

a practical free space system, a finite-sized FSS would suffer from edge effects, where signals diffract around each layer of the surface. To ensure that all the fields pass through a low form factor FSS, the FSS layers were placed in a conducting cavity. This also reduces the form factor of the system, as fewer unit cells of the FSS are required. It should be noted that putting the FSS in a cavity introduces a shift in resonant frequency of 350MHz compared with the free space case, which is accounted for by adjusting the diode capacitance. The use of a cavity lends itself to the idea of incorporating the FSS into a reconfigurable antenna.

To demonstrate the principle of a reconfigurable antenna for phase modulation, a linearly polarised antenna design was chosen for simulation, using a monopole feed into a cavity. QPSK was chosen as the modulation scheme for the antenna to achieve. The cavity was designed to allow the test frequency of 1.8GHz to propagate inside it while minimising form factor and, for ease of fabrication, to ensure that there are an integer number of FSS unit cells. The final design is shown in Fig. 4. Again the diodes were modelled as lumped elements with the characteristics of SMV147 varactor diodes, and the FSS layers were spaced 40mm apart. Each layer consisted of a 4x4 grid of unit cells with their edges in contact with the conducting
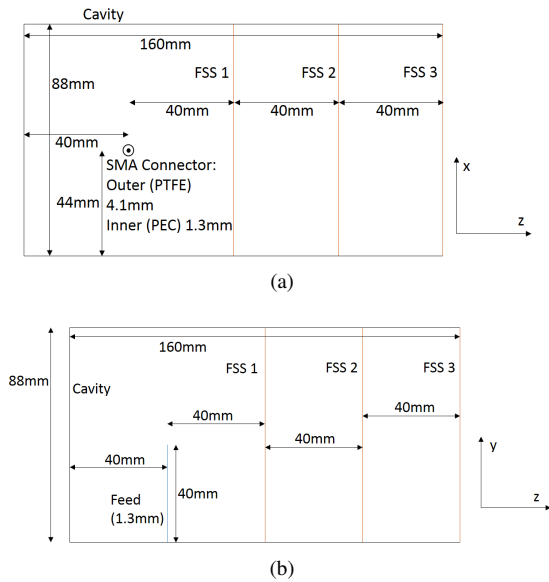
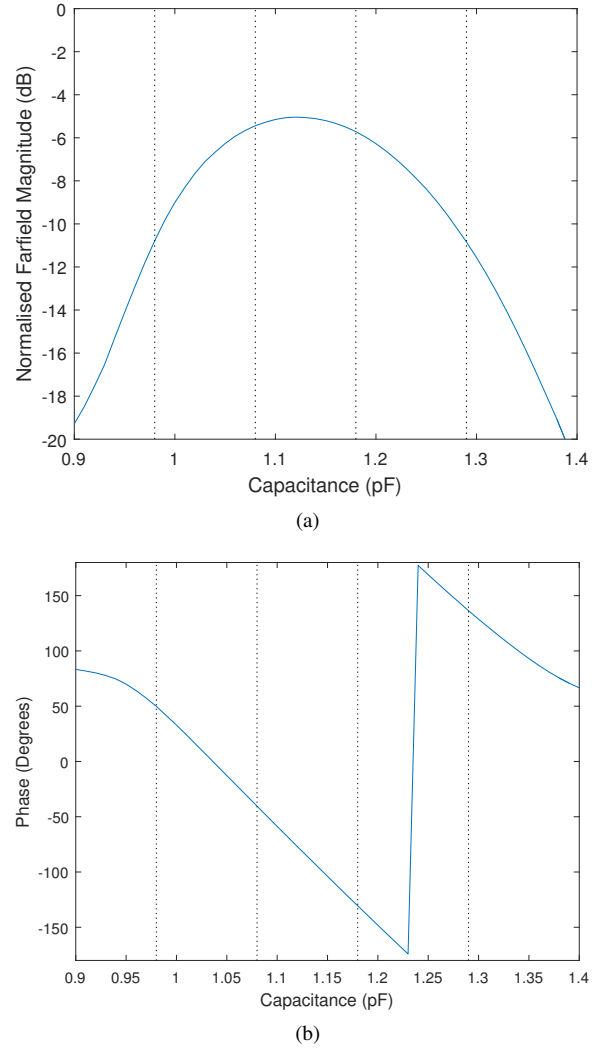Fig. 4. Reconfigurable antenna design, (a) bottom view, (b) side view

Fig. 5. Simulated (a) magnitude, (b) phase of reconfigurable antenna with changing capacitance at boresight in the farfield, normalised to empty cavity simulation

walls of the cavity.

The cavity itself was modelled as a set of zero thickness PEC plates in contact with the edges of the FSS, and the probe was a 40mm cylinder of 1.3mm thickness. It was surrounded at the base by a dielectric cylinder of 4.1mm thickness to recreate the geometry of an SMA input to the base of the probe. This probe was placed in the centre of the plate width, 40mm from the first FSS and 40mm from the back wall of the cavity. In order to connect the centre patches of the unit cells to a control signal, biasing lines are required on the FSS. To minimise their effect on the transmitted signal, they were designed and oriented such that the longest sections of track were orthogonal to the probe feeding the cavity. The lines were modelled as zero thickness PEC tracks with 1 mm width.

The farfield simulations of the reconfigurable antenna with incorporated FSS in Fig. 5 show the change of magnitude and phase with respect to capacitance normalised to the field simulated for the cavity with no FSS. This shows that the 270° of phase rotation required to produce a QPSK constellation can be achieved by this antenna design, where the chosen points are shown as dotted lines in Fig. 5. There is 5.3dB variation between the most transmissive and least transmissive points in this range. There is some loss in the centre of the pass region, and the minimum loss in the FSS is simulated at -5dB when the fully loaded reconfigurable antenna is compared with an empty cavity. This loss and the variation over the phase range can be reduced by using lower loss variable capacitors, as varactor diodes, and in particular SMV1247 diodes, have large series resistances, especially at high frequencies of operation.

In order to examine the stability of the constellation produced by the reconfigurable antenna modulator with angle to the antenna, the farfield phase and magnitude were simulated at various angles in azimuth and elevation an equivalent distance into the farfield. Fig. 6 shows the constellation points as described previously in Fig. 5, with capacitances at 0.98, 1.08, 1.18 and 1.29pF producing the different phases. Each set is normalised so the constellation point at 1.08pF has magnitude 1 and phase $\pi/4$. With azimuth (Fig. 6a), the constellation varies very little over a 120° beamwidth, with a maximum phase variation of 1.05° at the 1.29pF constellation point. The magnitude variation within each constellation varies between 5.40dB at boresight and 5.48dB at 60° azimuth. It should be noted that in the x-z plane, as defined by the coordinates in Fig. 5, the phase and magnitude variation is symmetrical around 0°. This is not true, however, for variation in elevation (y-z plane) (Fig. 6b), where slight differences between symmetrical angles occur. The phase variation is also more noticeable but still slight, with a maximum variation of 11.1°, which here occurs at the 0.98pF constellation point. The magnitude variation here is also larger, though still small, with the 1.18pF point varying between 0.226dB below the maximum transmission point at boresight and 0.368dB below
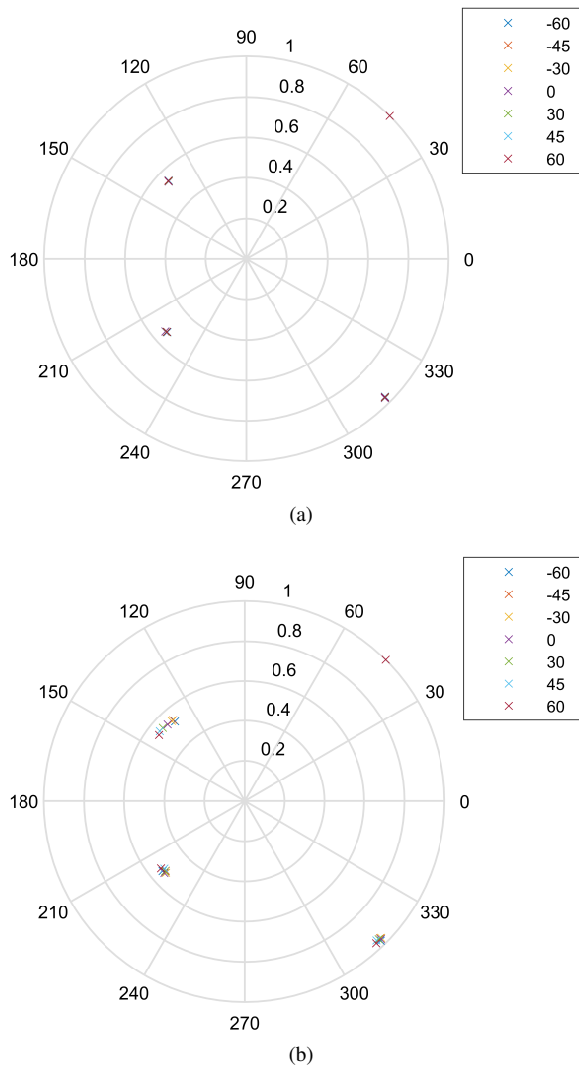
Fig. 6. Constellation variation with angle, with each constellation normalised to maximum point at pi/4, (a) x-z plane, (b) y-z plane

it at 60° elevation. As such, the FSS modulator is stable with angle within a 120° beamwidth, with maximum changes of 11.1° in phase and 0.15dB in magnitude of individual points between different viewing positions.

V. Conclusion

A reconfigurable antenna incorporating FSS for PSK DAM systems has been designed, simulated and characterised. It shows 270° of phase rotation for QPSK can be achieved with 3.5dB magnitude variation, with stability across a 90° beamwidth in both elevation and azimuth.

Acknowledgment

References

[1] A. Raghavan, N. Srirattana, and J. Laskar, *Efficiency Enhancement of RF Power Amplifiers*. Wiley-IEEE Press, 2008, pp. 173–198. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6130105

[2] A. Babakhani, D. B. Rutledge, and A. Hajimiri, "Transmitter architectures based on near-field direct antenna modulation," *Solid-State Circuits, IEEE Journal of*, vol. 43, no. 12, pp. 2674–2692, 2008.

[3] P. Daehee, K. Minhoe, and C. Dong-Ho, "Novel single-RF MIMO system based on repetitive pulse width modulation," *Communications Letters, IEEE*, vol. 20, no. 1, pp. 165–168, 2016.

[4] M. A. Sedaghat, V. I. Barousis, M. R. R, ller, and C. B. Papadias, "Load modulated arrays: a low-complexity antenna," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 46–52, 2016.

[5] M. Manteghi, "A wideband electrically small transient-state antenna," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 4, pp. 1201–1208, 2016.

[6] G. I. Kiani, T. S. Bird, and K. L. Ford, "60 GHz ASK modulator using switchable FSS," in *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*, Conference Proceedings, pp. 1–4.

[7] C. Mias, "Waveguide and free-space demonstration of tunable frequency selective surface," *Electronics Letters*, vol. 39, no. 11, pp. 850–852, 2003.

[8] M. Sazegar, Y. Zheng, C. Kohler, H. Maune, M. Nikfalazar, J. R. Binder, and R. Jakoby, "Beam steering transmitarray using tunable frequency selective surface with integrated ferroelectric varactors," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 12, pp. 5690–5699, 2012.

[9] J. Roberts, K. L. Ford, and J. M. Rigelsford, "Secure electromagnetic buildings using slow phase-switching frequency-selective surfaces," *Antennas and Propagation, IEEE Transactions on*, vol. 64, no. 1, pp. 251–261, 2016.