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Limiting Frequency Selective Surfaces

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Abstract— **In this paper the concept of limiting Frequency Selective Surface (FSS) is presented. The design of a reconfigurable FSS equipped with PIN diodes, aimed at the protection of a radar receiver from high power impinging electromagnetic waves is outlined and verified against the measurement results of a hardware demonstrator.**

I. INTRODUCTION

Microwave receivers are very sensitive devices as they usually are designed to detect signals barely above the thermal noise level. However in present environments many systems crowd the frequency bands and reception of unwanted signals is common. Unwanted signals can be classified as nuisance, i.e., they hinder proper reception, or destructive, i.e., the front-end electronics are damaged. In military systems receiver protection is very common as these systems are usually collocated with high power transmitters belonging to their own system (radar) or systems in frequency bands that are very close to their own frequency (naval vessels with several radar and communication suites). More importantly in security and defence related systems the scenario of deliberate illumination of ones receiver with high power signals should always be taken into account. Systems like the C2000 communication network for the civilian security forces will benefit from protection of the receivers as they are a vital infrastructure.

Currently protection is implemented at front-end level between the antenna connector and the first sensitive device, the low noise amplifier [1], [2]. Such devices are mostly realized with diodes. Alternatively, damage of front-end modules can be prevented by rendering the antenna reflective for high power levels. For this purpose, the antenna could be covered with a reconfigurable Frequency Selective Surface (FSS). Since the FSS should be transparent in the operating frequency band of the antenna, an aperture FSS is the logical choice. An FSS contains resonant structures to obtain low-loss transmission at the operating frequency band and good rejection outside this band. By changing the length of the FSS element, the resonance can be shifted outside the antenna operating band to turn the FSS into a reflecting plate. The length changes are accomplished by active or passive tuneable electronics. Examples of actively tuneable solutions are externally biased diodes or RF MEMS switches. For both solution types the activation of the tuning elements is obtained through bias lines and requires first the detection of a high power level, therewith introducing a delay in the protection mechanism, e.g. [3]. A more effective protection can be obtained by tuning elements that are directly triggered by the impinging electromagnetic signal. Examples of such elements are PIN diodes. The self-actuation makes the delay between first reception of the high power signal and sufficient attenuation of the FSS smaller than what can be achieved with detection of the signal and subsequent activation of the external bias.

In this contribution, an aperture-based FSS equipped with PIN diodes is presented for the protection of a phased array antenna operating in S-band. A European patent application has been filed on this concept [4]. The main difference with existing solutions is the fact that no external control is needed and that protection is obtained outside the front-end module. The FSS based design complements rejection of out-of-band signals with rejection of in-band signals of destructively high power levels.

In Sec. II the FSS design is described. On the basis of the design, a hardware demonstrator has been manufactured and measured. In Sec. III the measurement setup is outlined and the achieved performance is evaluated against the system requirements. Conclusions are drawn in Sec. IV.

II. FSS DESIGN

In order to validate the concept of limiting FSS, a realistic design case has been defined consisting in the protection of a radar that operates in the S-band for elevation angles up to 45° and both linear polarisations, in receive-only configuration. An FSS aimed at the protection of the radar antenna from a high power microwave source should be transparent in the antenna operating frequency and angle range. In view of this, a suitable choice is a slot-based FSS consisting of four-legged loop elements [5]. This type of element can be tightly packed because of the relatively small element length at resonance ($\lambda/4$), therefore ensuring independence from the angle of incidence. Moreover, to obtain a sharp roll-off, the elements were capacitively loaded as outlined in [6].

First, a single-layer FSS was designed and manufactured as a proof-of-concept. The single-layer configuration still allows verifying the concept of limiting FSS and can be considered as first step toward a complete functional demonstrator covering the whole operating frequency band of the antenna.

The position of the diodes across the slot FSS element was determined on the basis of the minimum input compression level of the LNA (-20 dBm) and of the maximum power level that can be withstood by the LNA in the receiver chain (20 dBm). From the analysis of the electric field distribution on the element for plane wave incidence, it was decided to place four diodes at the internal corners of the FSS element, which were bended to facilitate their connection, as suggested in [7]. The location of the diodes is not at the voltage difference maximum as the FSS would then limit for too low incident power and hinder proper operation of the radar system. This configuration is particularly convenient because it controls both polarisations. Figure 1 shows the final geometry.

BAP55LX Silicon PIN diodes of NXP Semiconductors were chosen. The diodes have a nominal capacitance of *0.18 pF* for small-signal and *0.28 pF* for large-signal incidence and a series inductance of *0.4 nH*. The capacitance value added to the FSS capacitance leads to a shift of the resonance frequency of 25%. To compensate for this, the FSS geometrical parameters had to be retuned: $l = 16.95$ mm, $b = 1.67$ mm, $l2 = 3.34$ mm, $b2 = 3.06$ mm, $w = 0.65$ mm. The unit cell is square with $dx = 18.93$ mm. As support for the FSS, a dielectric substrate of RO4003 ($\varepsilon_r = 3.55$ and $\tan\delta = 0.0021$), $200\ \mu m$ thick was chosen.

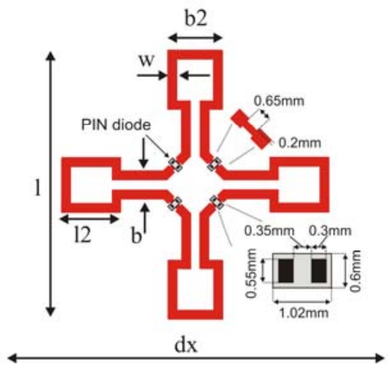

Figure 1 Final geometry of the FSS element with PIN diodes.

The effect of the diodes for low-power incident waves was evaluated by calculating the scattering matrix of the FSS unit cell with ports placed in correspondence of the diode connections, by means of CST Microwave Studio [8], and then using Agilent Advanced Design Systems (ADS) [9] to connect this matrix to the equivalent circuit of the diode. The corresponding FSS transmission coefficient is shown in Figure 2. The transmission coefficient of the single-layer FSS, calculated for a low power and high-power incident plane wave is plotted in the same figure. It can be observed that in the operating frequency band the transmission is always lower than -20 dB, while it shows a peak at about double of the fundamental resonance frequency. This is the first higher order mode resonance frequency and the conducting diodes act as short circuits. The limiting behaviour of the single-layer FSS can be recognised from Figure 3 where the output power is plotted as a function of the incident power (per unit cell) for different frequencies. At 2.8 GHz the FSS starts limiting for an incident power of -7 dBm (corresponding to the reduction of the transmission coefficient of -1 dB). The maximum output level that the LNA can withstand, 20 dBm, should not be reached before the maximum input power. At 6 GHz the limiting behaviour of the FSS is compromised because of the second resonance.

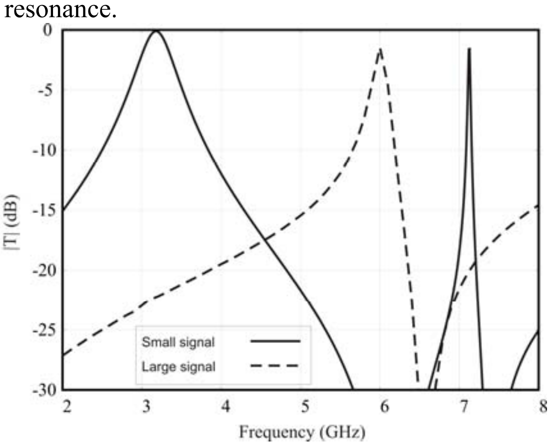

Figure 2 Simulated small and large signal (incident power is maximum input power/unit cell) transmission coefficient of the FSS with diodes.

III. Measurement of the Hardware Demonstrator

The size of the FSS panel that could be manufactured for experimental validation was limited by the soldering facilities available at the time of performing the tests. In view of this, it was decided to characterise the FSS in a waveguide simulator environment. For calibration purposes, the waveguide simulator was connected to the network analyser through two lengths of S-band standard waveguide [10]. Since for the present design the dimensions of the S-band waveguide cross-section are not integer multiple of the FSS periods, a transition from the standard S-band waveguide to the waveguide simulator had to be designed. The flared waveguide structure that was used for this purpose is shown in Figure 4. The horn with length *dpE* was designed to limit the phase difference in the wave front at the horn outlet, so that the phase front impinging on the FSS approximates that of a plane wave [11].

The FSS panel consisted of two unit cells along the *y*-direction, with $b1 = 3.79$ cm. With respect to the *x*-direction two layouts were considered, one for which the waveguide simulator allows measuring at almost broadside incidence and one in which the FSS panel width is close to that of an S-band waveguide and covers angles close to the maximum angle of incidence. In the first case, 12 unit cells were placed in the *x*-direction, with $a1 = 22.7$ cm. In the second case 4 unit cells were considered along the *x*-direction, with $a1 = 7.57$ cm.

To characterise the behaviour of the FSS as limiting structure, three types of measurements were performed:

1) small signal measurement of the FSS transmission and reflection coefficients without diodes;

2) small signal measurement of the FSS transmission and reflection coefficients with diodes;

3) large signal measurement of the FSS transmission coefficient with diodes.

The first two types of measurements were carried out with an incident power of 10 mW on the connector.

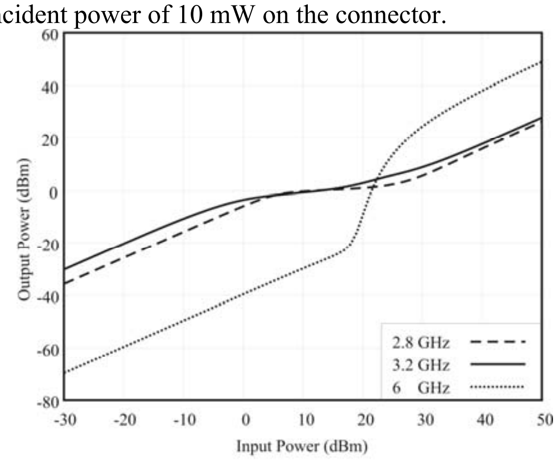

Figure 3 Simulated output power of the FSS with diodes.

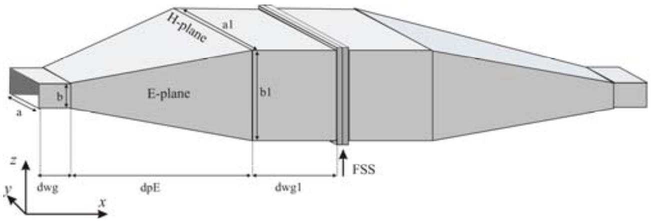

Figure 4 Schematic of the waveguide simulator used to characterise the FSS.

A. Small signal measurements without diodes

Figure 5 shows the comparison between calculated and measured reflection coefficients, for angles of incidence in the range 8.2°-13.6° corresponding to the frequency range 4.6-2.8 GHz. The connection of frequency and angles of incidence is due to the waveguide simulator [9]. In the figure ‘no cal’ refers to the case in which no full calibration was performed but only a short was used as reference for the reflection coefficient level. The peaks that appear in this case in the measurements at a distance of 200 MHz can be interpreted as due to a standing wave between the two waveguide ports. This spurious contribution was eliminated by applying a time gate of 1 *m*, which corresponds to the total length of the waveguide simulator leading to an excellent agreement between calculations and measurements. Analogous curves are plotted in Figure 6 for the smaller waveguide simulator, corresponding to the range of angles of incidence 26.7°-45°. Also in this case calculated and measured values overlap when full calibration and time gating are applied.

B. Small signal measurements with diodes

The PIN diodes were then soldered to the FSS elements, as depicted in Figure 7. The measured reflection and transmission coefficient showed a shift in frequency and a higher insertion loss with respect to the prediction of 0.1 dB. A characterisation of the diodes by means of a trough-reflect-line calibration confirmed the actual value of the diode capacitance to be 30% lower than the value indicated in the data sheet and the resistance significantly higher.

In Figure 8 the measured and the simulated transmission coefficient are compared for the first considered angle range, once in the diode model the parameter values indicated in the data sheet have been substituted with the measured values. The agreement is good apart for a small shift in the resonance frequency of about 1.5%.

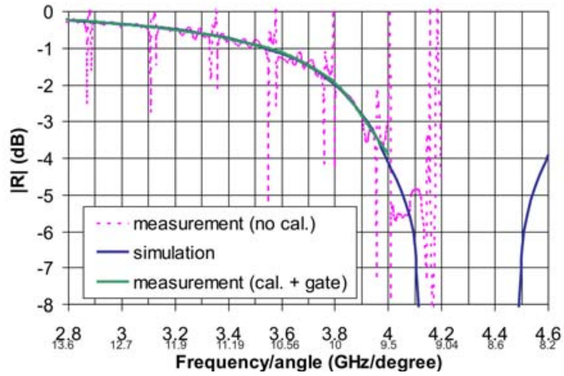

Figure 5 FSS reflection coefficient for angles of incidence in the range 8.2°-13.6°: comparison between measurement and simulation results.

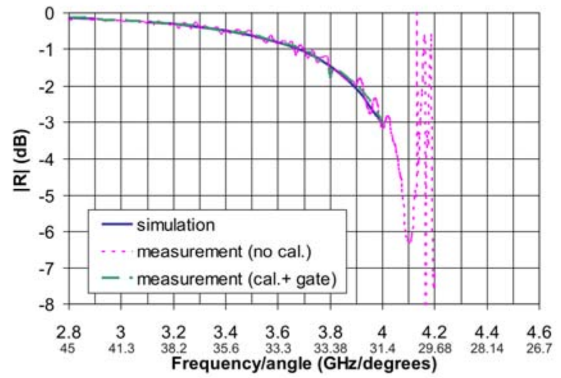

Figure 6 FSS reflection coefficient for angles of incidence in the range 26.7°-45°: comparison between measurement and simulation results.

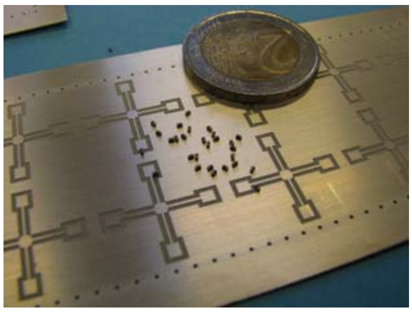

Figure 7 Detail of the larger FSS panel with PIN diodes.

C. Large signal measurements with diodes

A power sweep from 2.5 -37.5 dBm (limited by our measurement equipment) was applied to the two FSS panels in the waveguide simulator (24 unit cells and 8 unit cells respectively). Figure 9 shows the measured transmission coefficient for the two simulators as a function of the input power. It can be observed that the diodes yield a attenuation of the incoming signal of maximum 10 dB (for the larger incidence angles), in contrast with the 20 dB predicted for the nominal values of the diode parameters. Also the onset of limiting is at a much higher input power than simulated. This is in agreement with simulations with the adjusted diode model.

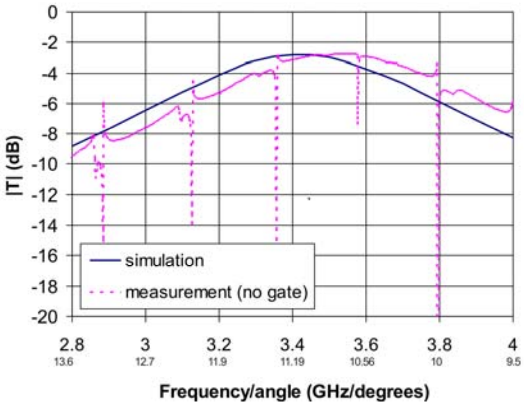

Figure 8 FSS transmission coefficient for angles of incidence in the range 8.2°-13.6° when the diodes are connected to the FSS.

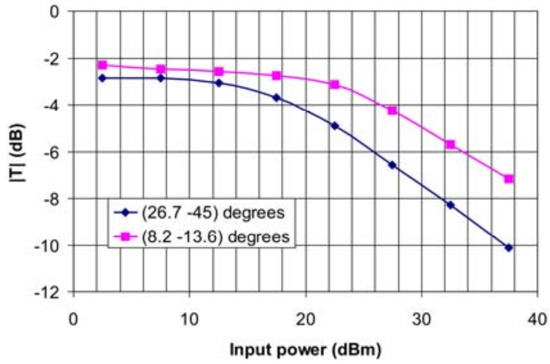

Figure 9 Measured transmission coefficient of the FSS with diodes as a function of the input power.

IV. Conclusions

In this contribution, the design of an FSS aimed at the protection of a radar antenna operating in receiving-only mode in the S-band is outlined. The FSS is equipped with four PIN-diodes diodes connected at the cross points of the elements to limit the transmitted power.

Because of manufacturing constraints, the experimental validation of the design is first performed with a single layer structure. Simulations based on a non-linear model of the diode show that a single-layer FSS delivers to the antenna element a maximum of 20 dBm. The FSS seems therefore suitable as first protection level of an integrated architecture concept .

Measurements of a hardware demonstrator have validated the concept. In particular, measurements of the FSS reflection and transmission coefficient without diodes have shown good agreement with the simulation results for nominal values of input power. The agreement is also good when the diodes are connected to the FSS, once the measured values of the diode parameters are included in the simulation. Finally, for high incident power level the FSS shows the expected limiting behaviour. However, because of the high losses of the chosen PIN diodes in the unbiased state, the transmission coefficient is worse in the low power state and the maximum power passed through the FSS to the antenna face is higher than predicted for the nominal values of the diode parameters and not sufficient to guarantee protection of the antenna front-end. Other PIN diodes are currently being investigated. As soon as a suitable type will be identified, new measurements will be carried out. The measurement results will eventually be included in the final version of this paper.

Acknowledgment

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