Protection of RF electronics using tuneable 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

The need of protection architectures of sensitive RF electronics from high power signals is particularly sensed in military scenarios in which the use of electronic systems plays an important role in the acquisition of the ‘situation awareness’. Moreover, also civilian applications, such as the infrastructures for the C2000 communication network in the security sector and for mobile communications (e.g. base stations), require increasing levels of protection of the electronic equipment. More specifically, scenarios exist in which, although a radar is off, the front-end modules of its phased array antenna can be damaged by a close-by high-power source. As an example we mention the situation that a military ship with several radars is moored at a harbour and despite harbour regulations a radar of a neighbouring ship is transmitting.

The protection is typically implemented at front-end level. For example, in phased array antennas limiting devices are used to reduce the power input to the Low Noise Amplifier in the receiver chain [1], [2]. Such devices are realized with discrete components like diodes or are integrated in a MMIC circuit. Alternatively, damage of front-end modules can be prevented by rendering the antenna elements perfectly 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 receiving frequency band of the antenna, an aperture FSS is the logical choice. Typically, the element geometry is chosen such that the FSS resonates at about the centre frequency of this band with a maximum of the transmission coefficient. By changing the dielectric properties of the substrate or 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 property and length changes are accomplished by active or passive tuneable electronics. Examples of actively tuneable solutions are tuneable substrate materials such as liquid crystals 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. A more effective protection can be obtained by exploiting passive self-actuating tuneable technology. In this case, the tuning elements are directly triggered by the impinging electromagnetic signal. Examples of such elements are PIN diodes.

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 [3]. 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 performances are evaluated against the system requirements. Conclusions are drawn in Sec. IV.

II. FSS DESIGN

We consider the following realistic scenario: the protection of a S-band receive-only phased array from a high-power electromagnetic wave produced by a radar located in its proximity. For this scenario the limiting FSS should be transparent in the receiving frequency band of 3-3.3 GHz for elevation angles up to 45°, and opaque outside this band to limit the antenna RCS. A suitable choice for the FSS element is the four-legged loop element which can be tightly packed because of the relatively small element length (λ/4). To obtain a sharp roll-off and a limited angle dependence, the elements are capacitively loaded as in [4]. The resulting element geometry is depicted in Figure 1.
A single-layer FSS provides only one pole to the equivalent band-pass filter and is therefore not sufficient to cover the considered frequency band. For this purpose, three FSS layers should be cascaded. However, such structure turned out to be rather difficult to manufacture, as it consists of several dielectric layers, some of which should be glued together at relatively low temperatures. The stack can then not withstand the temperature needed for soldering the diodes to the FSS. To avoid this problem, 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 elements were designed to resonate at 3.2 GHz, with dimensions: $l = 27.4 \text{ mm}$, $b = 2.7 \text{ mm}$, $l_2 = 5.4 \text{ mm}$, $b_2 = 4.95 \text{ mm}$, $w = 0.95 \text{ mm}$, and were arranged in a square lattice with $dx = 30.6 \text{ mm}$.

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, a maximum of the field in correspondence of the capacitive loading was observed. However, placing the diodes at these points would result in an early activation of the devices, already in correspondence of -20 dBm per unit cell. For this reason, four diodes were eventually positioned at the internal corners of the FSS element, which were bended to facilitate the positioning of the diodes, as suggested in [5]. The configuration is particularly convenient because it controls both polarisations. Figure 2 shows the final geometry. BAP55LX Silicon PIN diodes of NXP Semiconductors were chosen, with pad width of 300 $\mu$m, length 550 $\mu$m and separation 330 $\mu$m. A tolerance of 50 $\mu$m was taken into account in dimensioning the slot width with respect to the pad size.

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. To compensate for this, the FSS geometrical parameters had to be retuned: $l = 16.95 \text{ mm}$, $b = 1.67 \text{ mm}$, $l_2 = 3.34 \text{ mm}$, $b_2 = 3.06 \text{ mm}$, $w = 0.65 \text{ mm}$. The unit cell is square with $dx = 18.93 \text{ mm}$. Figure 3 shows reflection and transmission coefficient of a single-layer FSS without diodes, after the tuning, printed on a dielectric substrate of RO4003 ($\varepsilon_r = 3.55$ and $\tan\delta = 0.0021$), 200 $\mu$m thick. The calculations refer to broadside TE plane wave incidence and were performed using CST Microwave Studio [6]. As expected, the first higher order mode is excited at a frequency double of the main resonance.

The effect of the diodes for low-power signals was evaluated by calculating the scattering matrix of the FSS unit cell with ports placed in correspondence of the diode connections and then using Agilent Advanced Design Systems (ADS) [7] to connect this matrix to the equivalent circuit of the diode. The single-layer FSS transmission coefficient for small signal is shown in Figure 4, where a shift of the resonance frequency of 25% (with respect to Figure 3) due to the diode capacitance can be observed. The transmission coefficient and the output power of the single-layer FSS, calculated for a high-power incident plane wave (44 dBm per unit cell) is plotted in Figure 5. It can be observed that in the operating frequency band the insertion loss is always lower than -20 dB, while it shows a peak at about double of the fundamental resonance frequency. At the first higher order mode resonance the conducting diodes act as short circuit cutting the FSS in two halves that resonate at this frequency, generating the transmission peak in Figure 5.
The limiting behaviour of the single-layer FSS can be recognised from Figure 6 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) and provides an output of 20 dBm for 44 dBm of incident power per unit cell. At higher frequencies, the output power increases (22.5 dBm at 3.4 GHz). At 6 GHz the limiting behaviour of the FSS is compromised because of the second resonance. The corresponding transmission coefficient as a function of the incident power is plotted in Figure 7 for the same frequencies: 2.8, 3.2 and 6 GHz.

III. MEASUREMENT OF THE HARDWARE DEMONSTRATOR

Manufacturing and measuring a large FSS panel (of the order of 5-6 $\lambda$) in a far-field setup appeared to be unfeasible for several reasons. Most importantly, the soldering facilities available at the time of performing the tests could process panels of maximum size of 30 cm. 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 [8]. 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 8. The horn with length $dpE$ was designed to limit the phase difference in the wave front at the outlet of the horn, so that the phase front approximates that of a plane wave [9]. Therewith, the minimum elevation angle that could be achieved in the simulator was limited by the maximum horn size that could be manufactured and handled in the measurements. In fact, the smaller is the elevation angle, the larger is the FSS panel and, hence, the longer is the horn needed to obtain a negligible phase difference.
Figure 8 Schematic of the waveguide simulator used to characterise the FSS.

For the problem discussed in this document, we chose an FSS layout with two unit cells along the $y$-direction, since for this number of cells the FSS panel height $b_1 = 3.79\ cm$ was close to the height $b = 3.40\ cm$ of the S-band standard waveguide and the required flaring was limited. With respect to the $x$-direction two layouts were considered, one for which the simulator is operated at almost broadside incidence without requiring a prohibitively large horn and one in which the FSS panel width is almost the same as that of an S-band waveguide. In the first case, 12 unit cells were placed in the $x$-direction, with $a_1 = 22.7\ cm$. The choice of $dp_E = 54.72\ cm$ resulted in a maximum phase error of 30.7°. In the second case 4 unit cells were considered along the $x$-direction, with $a_1 = 7.57\ cm$. The same choice for $dp_E$ yields a maximum phase error of 0.25°. Figure 9 shows a photo of the measurement setup.

To fully characterise the behaviour of the FSS as limiting structure, three types of measurements were identified:
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.

Calibration of the reflection measurements was carried out by considering as reference the reflection of a metallic panel of the same size as the FSS. Transmission measurements were calibrated against the transmission coefficient of the empty waveguide simulator.

The first two types of measurements were carried out with an incident power of 10 mW as standard provided by the network analyser.

In Figure 10 the calculated reflection coefficient of the FSS without diodes, in the angle range 8.2°-13.6° corresponding to the frequency range 4.6-2.8 GHz, is compared to the measured one with and without calibration and time gating. In the measured reflection coefficient, before calibration and time gating are applied, we can observe that peaks appear at a distance of 200 MHz. At the phase velocity of the fundamental mode, this corresponds to a distance of 1 m, which is about the total length of the waveguide simulator. Therefore, the peaks 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 over the signal. As it appears in Figure 10, the agreement between calculations and measurements is then excellent. Analogous curves are plotted in Figure 11 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 calibration and time gating are applied. In all the figures the frequency is indicated together with the corresponding angle of incidence measured with the waveguide simulator.
IV. CONCLUSIONS

Frequency Selective Surfaces equipped with reconfigurable technology can be designed to protect an antenna from high incident powers. 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 original design consists of a three-layer structure which, for nominal operating conditions, is transparent in the receiving band of the antenna and reduces the RCS in the defined rejection band for angles of incidence up to $\pm 45^\circ$ and for both linear polarisations. The FSS uses four 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 confined to 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 22.5 dBm for 44 dBm incident power per unit cell. The FSS seems therefore suitable as first protection level of an integrated architecture concept where also more conventional limiters are used.

Measurement of the reflection and transmission coefficient of a hardware demonstrator for small signals, when the diodes were not yet soldered to the printed board, have shown very good agreement with the simulation results. Measurement of these parameters with the PIN diodes, for small and large signal will be presented at the conference.

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