# Modulated Corner Reflector Using Frequency Selective Surfaces for FMCW Radar Applications

A.Lazaro, J.Lorenzo, R.Villarino, D.Girbau
Department of Electronic, Electric and Automatic Control Engineering (DEEEA),
Universitat Rovira i Virgili (URV)
43007 Tarragona, Spain
Tel. 34+977558668, antonioramon.lazaro@urv.cat

*Abstract*— **This work describes a modulated transponder based on a corner reflector where at least one of the metallic surfaces is replaced by an actively-controlled frequency selective surface (FSS) loaded with switching PIN diodes. The reflectivity of the faces loaded with the FSS changes with the bias of the diodes modulating the radar cross-section of the corner. The transponder therefore answers the reader, modulating the backscattered field. In addition, the retrodirectivity property of corner reflectors enables the response to be distinguished from the interference of non-modulated clutter reducing multipath effects. This approach allows high values of backscattered fields to be obtained over large angle beam widths and frequency bandwidths. An experimental setup based on a commercial X-band FMCW radar is used to measure the transponders. Experimental results obtained for a dihedral corner reflector and a cross reflector transponder at several distances are provided. In the first case, a sectorial angular coverage is obtained, whereas in the second case a quasi-onmidirectional performance is obtained.**

***Keywords— Frequency selective surface (FSS), high radar cross-section (RCS), Corner reflector, FMCW radar, transponder, RFID***

## I. INTRODUCTION

Dihedral and trihedral corner reflectors are of great interest because of their high Radar Cross-section (RCS) level [1]. Radar corner reflectors are designed to reflect the microwave radio waves emitted by radar sent back toward the radar antenna. The large echo of the corner reflector is due to the mutual perpendicularity of the two or three flat faces. Several papers dealing with the back-scattering from perfectly conducting dihedral corners have been published [l-3]. These reflectors have been used in maritime navigation for years to increase the RCS of ships, buoys and lifeboats, radar measurements and as calibration targets in SAR applications [1]. Corner reflectors, such as Van Atta arrays and Luneberg lens share the retrodirective property. This property is interesting in some applications due to the reduction of clutter interference as a result of multipath reflections.

The idea of radio-frequency identification (RFID) of objects was first introduced by H. Stockman [4]. The modulation of the backscattered RCS allows information to be sent back such as identification code or sensor data in wireless sensor networks. Modulated corner reflectors were proposed in the pioneering work by Stockman. The modulation was achieved by a motor-driven device or by moving the sides [1]. Other electronic methods for modulating corner reflectors are proposed in the literature [5]. Backscattering communications using modulated corner reflectors have some advantages compared with other approaches. Corner reflectors are easier to design and construct than Van Atta arrays or lenses. In addition, the size of corner reflectors decreases with the frequency, achieving large RCS at microwave and millimeter frequencies [1]. The frequency bandwidth is higher than in Van Atta arrays. The modulation of corner reflectors has been of interest for free space optical communications [6]. In this case, microelectromechanical (MEMS) mirrors on one side of the reflector are used to modulate the electromagnetic fields. However, the transmission rate is limited by the mechanical response of the MEMS. Frequency Selective Surfaces (FSS) have been used in radar applications and antennas for years [7]. In this work, a tunable FSS is used to change the reflectivity of one side of the reflector resulting in the electronic modulation of the RCS. Compared with previous works, the use of the FSS increases the differential RCS, enabling the tag or transponder to be detected. However, increasing the number of FSS elements also increases the directivity. The tag or transponder should thus be aligned with the reader. Using the modulated corner reflector proposed, this problem is mitigated thanks to the retrodirectivity property.

A prototype of the dihedral corner reflector at the X band is presented here. A simple FSS composed of dipoles loaded with PIN diodes is used [8]. When the diodes are conducting (ON state), the FSS is designed to resonate at the central frequency. The FSS thus acts as a reflecting surface and the reflector works as a common metallic reflector. However, when the diodes are OFF, the pass band frequency of the FSS increases [8], and the FSS is thus almost transparent to the incoming waves and the retrodirective property is lost. This solution allows the design of a large bandwidth modulated reflector suitable for radar and identification applications and in particular, for FMCW radars where the range resolution increases with the swept bandwidth. Due to their ability to determine range, FMCW-based systems are commonly used for measuring distances in applications such as tank level

This work was supported by the Spanish Government Project TEC2011-28357-C02-01 and BES-2012-053980,and H2020-MSCA-RISE- Grant Agreement 645771–EMERGENT.

gauging, automotive collision avoidance radars, altimetry, and marine radars. In recent years, FMCW radar has been proposed in the literature for wireless local positioning systems [9] and sensing [10]. The major challenges for wireless local positioning systems are disturbances caused by the multipath reflections [9]. Parasitic reflections are often several orders of magnitude greater than the target. Clutter contamination is therefore a significant problem in several applications. Furthermore, FMCW radars have a minimum measurement distance limited by the antenna coupling and a phase noise power interference [1]. In order to mitigate these common problems, a modulated backscatter transponder has been proposed in [11]. In this case, the spectrum at the output of the mixer is shifted by the modulated frequency of the transponder, $f_m$ [11]. The range measurement is performed by analyzing the spectrum of the beat signal around $f_m$ and by verifying the presence of a couple of peaks. The frequency difference between the peaks is proportional to the distance between the radar and the tag. Several approaches have been employed to implement the backscatter transponder. The simplest is to match/mismatch the output of the antenna's transceiver, achieving a modulation of the backscattered field [11]. However, the way to increase the detectability is increasing the differential RCS. This increase can be achieved using directive antennas, but the use of high directivity antennas is a problem in some applications (such as localization) in which the transponder's position is unknown. The results show that the high half-power beam width of the modulated corner reflector can be useful in mitigating these problems.

The paper is organized as follows. The operation principle is described in section II. A comprehensive model based on physical optics is given in this section. This model is useful for understanding the working principle and carrying out an approximate design. The proposed concept is experimentally validated in Section III. Other potential applications of the proposed technique are discussed and conclusions drawn in Section IV.

## II. Operation Principle

The aim of this section is to present a comprehensible model to understand the backscattered field by a corner loaded with FSS. The simplest corner reflector consists of a dihedral corner reflector where one metallic face is replaced by a tunable FSS as shown in Fig. 1. The angle between the two faces is $\alpha$ and the angle of arrival of the incident plane wave is $\phi$, measured from the plane-bisecting angle. For conventional corner reflectors, the angle $\alpha = \pi/2$. A simplified model based on physical optics (PO) is considered [2][3], neglecting the diffractions from the edges. The model takes into account the backscattering from the two faces and the double-bounce reflection between the two faces. The scattered field, from physical optics theory, can be four distinct main contributions [2]: two are the direct return from each face A and B, and the two double-bounce contributions of face A to B and back again, and from B to A and then to the radar:

$$\overline{E}_S \approx \overline{E}_{S,A} + \overline{E}_{S,B} + \overline{E}_{S,AB} + \overline{E}_{S,BA} \qquad (1)$$

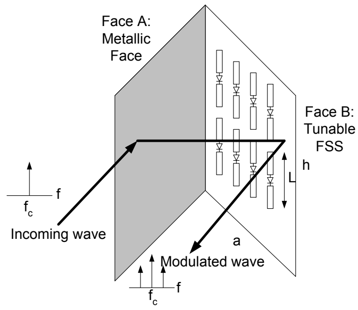


Fig. 1. RCS modulation principle.

In order to modulate the corner, one (or two) faces are loaded with a tunable FSS. The FSS unit cell is formed by dipoles loaded with PIN diodes. The corner modulates the incident field by switching the PIN diodes that load the FSS. FSS is known [7] to present a high reflectivity when the frequency of the incident wave is close to the dipoles' resonant frequency (when the dipoles become approximately half a wavelength). The band pass behavior of the FSS can therefore be modeled with an LC series equivalent circuit with a resonant frequency depending on the diode state. When the diodes are in the ON state, their impedance is low and there theoretically should be a short circuit for an ideal diode; hence the FSS has a high reflectivity and RCS around the resonant frequency of the dipoles. The corner loaded with an FSS with diodes ON then works as a conventional corner reflector. When the diodes are in the OFF state, the diodes ideally present high impedance (theoretically an open circuit). When the diodes of the FSS are OFF, the waves reflected in the metallic face are transmitted through the FSS that is transparent to the incident wave. Consequently, when the diodes are OFF, the retrodirective property of the corner reflector is lost, creating a decrease in the RCS in forward direction. The result is a modulation of the RCS at the switching rate of the diodes. In practice, the diode parasitics have an important effect in the frequency response of the FSS [8]. The effect of the FSS on each face can be modeled as a surface impedance following the method proposed in [3]. The reflection coefficient of face B is polarization-dependent and is given by [3]:

$$\Gamma_B = \begin{cases} -\dfrac{Z - \eta_0 \cos(\phi)}{Z + \eta_0 \cos(\phi)} & ,E\ pol \\ \dfrac{Z\cos(\phi) - \eta_0}{Z\cos(\phi) + \eta_0} & ,H\ pol \end{cases} \qquad (2)$$

where $\eta_0$ is the vacuum wave impedance and $Z$ is the surface impedance of face B. The reflection coefficient in face A, $\Gamma_A$, is given by (2) but replacing the angle $\phi$ by $\alpha$-$\phi$. In the case of a perfectly conducting face, $Z$=0. In the case of a face composed by an FSS, $Z$ can be estimated from the equivalent circuit. In practice, $Z$ can be found from numerical simulations. Taking into account that the backscattered field is proportional to the reflection coefficient of each face, (1) can be expressed as:

$$\overline{E}_S \approx (h/\lambda)\cdot(\overline{E}_{A0}\Gamma_A + \overline{E}_{B0}\Gamma_B + \overline{E}_{AB0}\Gamma_A\Gamma_B + \overline{E}_{BA0}\Gamma_A\Gamma_B) \quad (3)$$

where $h$ is the height of the corner, and $\lambda$ is the wavelength. The expressions of the terms $E_{A0}$, $E_{B0}$, $E_{AB0}$, and $E_{B0}$ can be derived from analytical models reported in the literature [2][3]. Assuming that, for instance, face B is loaded with the FSS, (1) can be split as a sum of two terms: a structural mode and an antenna mode, or a load-independent term and a load-dependent term, respectively [8]:

$$\overline{E}_S = \overline{E}_{est} + \overline{E}_m\Gamma_B \quad (4)$$

The reflection coefficient is modulated by switching the PIN diodes that load the dipoles of the FSS. The differential RCS [8] is the RCS due to the antenna mode, which depends on the load reflection coefficient difference ΔΓ between the two modulated states (diodes ON and OFF).

## III. Results

Two corner reflectors have been designed in order to verify the operation theory presented in the previous section. The first is a dihedral corner reflector where one metallic face has been replaced by an FSS. The second reflector is a cross reflector transponder, composed by two identical reflectors to the previous case. However, the concept can be extended to other corner configurations. The height $h$ of the reflectors is 57 mm, and the width and thickness of the faces are 69 mm and 0.83 mm respectively. The FSS is designed to cover the frequency band between 9.25 GHz and 10.75 GHz, which is the frequency band of the radar used in the experimental results (Siversima model RS3400X). Low-cost NXP BAP51-03 PIN diodes are selected to reconfigure the response of the FSS. The FSS is the same as the one presented in a previous work [8] and is composed of 10 loaded dipoles. The length of the arm of the dipoles is 6.25 mm, the width of the dipoles is 2 mm, and the horizontal and vertical spacing are 7.5 mm and 9.25 mm, respectively. 10 kΩ 0603 SMD resistors are connected at the end of the dipoles to bias the diodes, presenting high impedance, therefore works as RF blocks. The DC current when the FSS are biased ON at 3 V is 2 mA.

The experimental setup described in [8] has been used in order to characterize the frequency and angular behavior of the modulated backscattered field. Fig. 2 shows an example of the spectrum measured by the spectrum analyzer when the two transponders based on corner reflectors are illuminated at 10 GHz. A strong peak at the transmitted frequency due to the coupling between transmitter and receiver antenna can be observed. The sideband peaks are caused by the modulation of the transponder, and the frequency space between them is the modulation frequency (7 kHz). Due to the clipping effect of the diodes, the spectrum is very similar to that of a square signal (*sinc* function). The amplitude of the sideband is therefore proportional to the differential RCS. The level of the received power depends on the area of the faces of the corner reflectors, and the bandwidth is limited by the FSS. As shown in [8], the diode parasitics limit the reflectivity change of the face loaded with the FSS between the state ON and OFF. However, the bandwidth required for the radar (1.5 GHz) can be achieved using low-cost PIN diodes. A typical flatness of 4 dB is observed between 9 and 12 GHz.

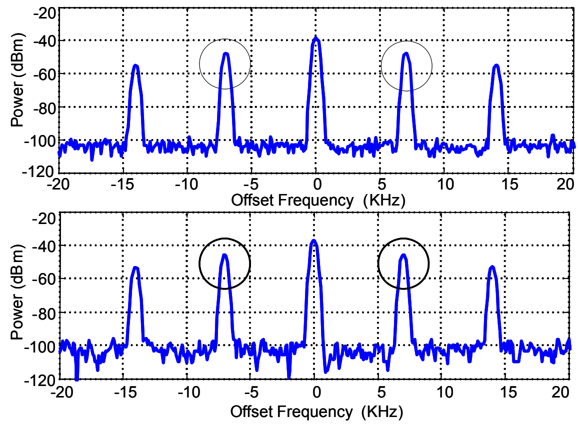


Fig. 2. Measurement of the spectrum at 10 GHz with a modulation frequency of 7 kHz at 90º of orientation. Transponder based on a dihedral corner reflector (top) and a cross reflector (bottom).

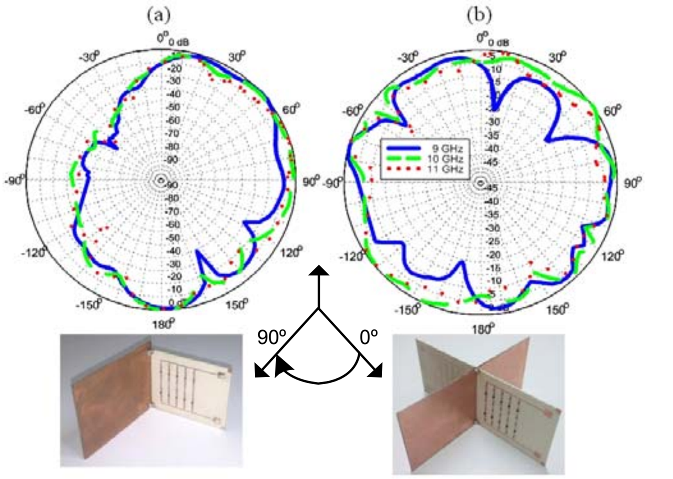


Fig. 3. Photograph and normalized measured power as a function of angle at 9, 10 and 11 GHz of (a) a dihedral corner reflector transponder and (b) the cross reflector transponder.

Fig. 3 shows the measurements of the received power at the sideband as a function of the orientation of the incoming wave. The orientation at 0 degrees occurs when the transmitter is perpendicular to the metallic face. For the case of Fig.3a a beamwidth larger than 90º is obtained. A nearly onmidirectional behavior is achieved in the case of Fig.3b. It is important to note that the differential RCS can be increased increasing the height of the faces, $h$. According to models [2][3], the backscattering of the faces is proportional to the *sinc*($ka$) and *sinc*($kb$) functions (where $k$ is the wavenumber). The beamwidth is therefore a function of the length $a$ and $b$ of the faces. Compared with the standard symmetrical dihedral corner reflector, the maximum backscattered field is shifted due the different reflectivities of the metallic and FSS loaded faces. Finally, some experimental results are obtained using a commercial radar system, in order to demonstrate the feasibility of the system. The radar is a synthesized, X-band, FMCW radar front end. The nominal transmitted power of the radar module is 0dBm±5dB. The radar sweeps the 9.25-10.75 GHz frequency band with a sweep time of $T$=75 ms and it is connected to a 20 dB standard pyramidal horn. The IF signal is sampled at $f_s$=20 kHz. Fig. 4 shows the IF spectrum at a distance of 3.2m for the two reflectors using a $f_m$=5 kHz. A peak at around 1 kHz due to the non-modulated (structural) mode of the transponder can be detected in Fig. 4. In Fig. 5, the transponder is located at a distance of 10 m and it is modulated at $f_m$=7 kHz. In this case, two peaks appear at the spectrum of the IF signal around the frequency modulation. Furthermore, some clutter removal can be achieved if the non-modulated signal is subtracted. When the distance increases; the separation of the frequency sidebands increases according to the theory presented. Fig. 6 shows the estimated distance obtained from the measurement of the two transponders derived from the spacing between the sideband peaks. The standard deviation of measurement error in the distance is 2.73 cm and 3.48 cm for the dihedral corner transponder and the cross reflector transponder respectively. The errors fall within the radar resolution $c/2B$ (10 cm in this case).

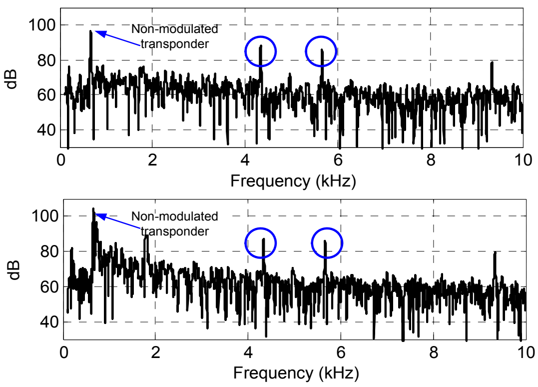


Fig. 4. Measurement of the dihedral corner reflector transponder (top) and a cross reflector transponder (bottom) at 3.2 m with $f_m$=5 kHz modulation.

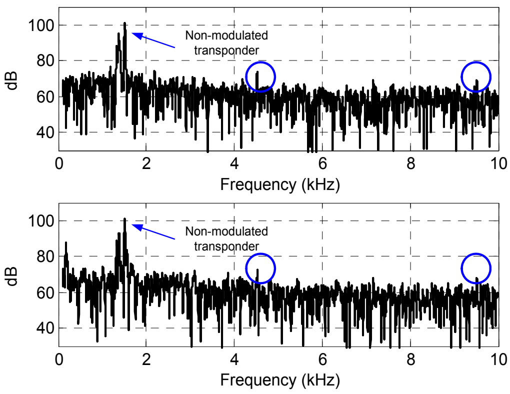


Fig. 5. Measurement of the dihedral corner reflector transponder (top) and a cross reflector transponder (bottom) at 10 m with $f_m$=7 kHz modulation.

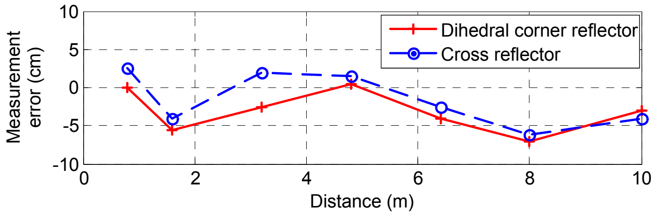


Fig. 6. Measured distance obtained from the dihedral corner reflector transponder (solid line) and the cross reflector transponder (dashed line).

## IV. Conclusions

This work has studied the feasibility of designing a backscattering transponder based on modulated corner reflectors using actively controlled frequency selective surfaces (FSS) to change the reflectivity of at least one of faces of the reflector. The communication between the tag and the reader is produced using the backscattering technique. The modulation of the RCS and the retrodirectivity property of the corner reflectors enable the effect of clutter to be reduced due to multipath reflections. Measurements with a dihedral corner reflector and a cross reflector have been presented as a proof of the concept. However, the concept can be extended to other corner configurations. The frequency bandwidth is limited by the FSS bandwidth, but using low-cost PIN devices as switching elements it is enough to archive the bandwidth required in common X-band FMCW radar applications.

## References


[1] M.I. Skolnik, "Introduction to Radar Systems," in *McGraw-Hill,* 2nd ed. Singapure, 1981.

[2] E.Knott, "RCS reduction of dihedral corners," *IEEE Transactions on Antennas and Propagation*, Vol.25, No.3, pp.406-409, 1977.

[3] P.Corona, G.Ferrara, and C.Gennarelli, "Backscattering by loaded and unloaded dihedral corners," *IEEE Transactions on Antennas and Propagation*, Vol.35, No.10, pp.1148-1153, 1987.

[4] H.Stockman, "Communication by means of reflected power," *Proceedings of the IRE*, Vol.36, No.10, pp.1196-1204, 1948.

[5] X.G.Sun and R.W.Babbitt, "Modulated retroreflection system for secure communication and identification," U.S. Patent 5 819 164, Oct.6, 1998.

[6] L.Zhou, J.M. Kahn, and K.S.J.Pister, "Corner-cube retroreflectors based on structure-assisted assembly for free-space optical communication," *Journal of Microelectromechanical Systems*, Vol.12, No.3, pp. 233-242, 2003.

[7] B.A.Munk, "Frequency selective surfaces," New York: Wiley, 2000.

[8] A.Lazaro, J.Lorenzo, R.Villarino, and D.Girbau, "Backscatter Transponder based on Frequency Selective Surface for FMCW Radar Applications," *Radioengineering*, Vol. 23, No. 2,pp.632-640, 2014.

[9] M.Brugger, et al., "The FMCW technology-based indoor localization system," *In Ubiquitous Positioning Indoor Navigation and Location Based Service (UPINLBS), Kirkkonummi (Findland)* ,pp. 1–6, 2010.

[10] H.Aubert, et al., "Wireless sensing and identification of passive electromagnetic sensors based on millimetre-wave FMCW RADAR", *In IEEE International Conference on RFID-Technologies and Applications (RFID-TA), Nice (France),* pp.398–403, 2012.

[11] J.Thornton, and D.J.Edwards, "Range measurement using modulated retro-reflectors in FM radar system," *IEEE Microwave Guided Wave Lett.*, vol. 10, p. 380–382, 2000.