International Journal of Microwave and Wireless Technologies, 2012, 4(1), 37–43. © Cambridge University Press and the European Microwave Association, 2012
doi:10.1017/S175907871100105X

RESEARCH PAPER

77 GHz offset reflectarray for FOD detection on airport runways

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In designing a Foreign Object Debris (FOD) detection system on airport runways, this paper deals with the performance of a 77 GHz reflectarray antenna (RA). Debris may be very small and have low radar cross section (RCS), leading to design a high gain primary-fed offset RA. To minimize the aperture blockage, the main radiation lobe is in the specular direction. The antenna has a maximum gain of 40 dBi and aperture efficiency of 50% over the frequency band 76–77 GHz. First measurements using a 77 GHz radar module were carried out on pavement.

Keywords: Antenna Design, Modelling and Measurements, Radar and Homeland Security

Received 8 June 2011; Revised 1 October 2011

I. INTRODUCTION

The purpose of this joint French–Japanese work is to design a detection system for debris or Foreign Object Debris (FOD) on airport runways [1–5].

The fold topic became of interest with the Concorde accident in 2000. Companies started to develop systems that are actually on international airports like Vancouver and Heathrow [1], Singapore [2], and Boston [3]. Except for [2], the companies have chosen to include a millimeter wave radar in this set-up. The Tarsier developed by QinetiQ operates with a 94 GHz radar, whereas FODetect (Xsight and Thales) operates with a 77 GHz radar.

The project includes as well the design and fabrication of a high gain antenna (LEAT, France) as the development of a millimeter-wave front-end (ENRI, Japan). Measurements campaigns are carried out jointly. The complete system is composed of the high-gain antenna and a radar module, working in W-band between 76 and 77 GHz. The antenna is a printed reflectarray antenna (RA), generally used for millimeter wave radar applications because of its excellent trade-off between high directivity and low loss, low profile, and low cost. Nevertheless, a primary source from center generates a masking effect called "aperture blockage", which decreases the antenna efficiency. To avoid this effect, the reflectarray is designed with an offset feed with a main radiation beam of the RA in the specular direction, for specular radiation minimization purpose. The side lobe level is a pertinent parameter for this system as debris can be close to each other with a high radar cross section (RCS) dynamic range. Therefore, a low RCS FOD detected in the main beam could be hidden by a higher RCS FOD detected in a side lobe. A primary feed with a prolate radiation pattern modifies the signal in such a way that 99% of the power is within the main lobe. As a consequence, the secondary lobes are greatly reduced and the overall noise level accordingly. Section II describes the antenna design and Section III deals with the antenna measurements, while Section IV presents the results from our measurement campaign.

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II. ANTENNA SPECIFICATIONS AND MODELIZATION

In 2009, from a preliminary study, a 35 dBi gain circularly polarized reflectarray has been developed [5]. Elementary cells were designed to achieve linear to circular polarization conversion. This configuration has the main advantage to simplify considerably the antenna implementation. Although radar tests were conclusive for small distances [5], the gain of the antenna was not sufficient to detect −20 dBsm target at 46 m as recommended by the FAA advisory circular for this application [6]. Furthermore, the use of a circular polarization did not show any greater interest compared to linear polarization for this application. For that reason, a second antenna with 40 dBi gain and linear polarization was designed. Moreover, in the perspective of the future 76–81 GHz radar module developed by the ENRI the antenna is designed for this band. In consequence, the design frequency of the antenna is 78.5 GHz. Nevertheless, only 76–77 GHz results are presented here (for concision purpose) because the whole radar system used for measurement presented in this paper is operating in this band.

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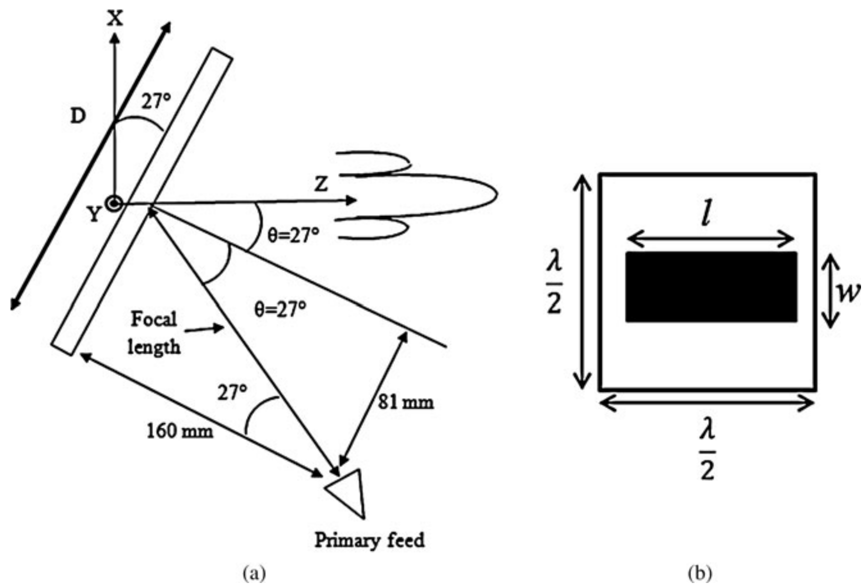

Fig. 1. (a) Scheme of the offset reflectarray. (b) Scheme of an elementary cell.

A) 27° offset reflectarray

As for every quasi-optical antenna, RA has to compensate for the phase delay of the spherical incident wave coming from the primary feed. In RAs, the phase compensation is obtained by adjusting patch dimensions. Patches are placed on the flat surface of a back-metallized substrate (Fig. 1) [7].

$$k_0(R_{ij} - \bar{r}_{ij}\,\bar{r}_0) - \psi_{ij} = 2\pi N \tag{1}$$

where Rij is the distance between the feed and the patch (i, j), rij is the distance between the patch (i, j) and the RA center, r_0 is the direction of the main beam, k_0 is the wave number, and ψij is the phase that has to be reflected by the patch (i, j) for delay compensation.

Equation (1) describes the phase compensation for a focused beam. It is possible to adjust main antenna parameters such as directivity, radiation pattern shape or number of beams with proper optimization. Moreover, RAs with feed from center have a high aperture blockage that decreases the overall aperture efficiency. Therefore, an offset primary feed at 27° has been chosen. Previous studies have shown that elementary cells radiate also in the specular direction [8]. In our case, a high lobe should appear at $\theta = -27°$. To solve this problem, the radiation direction of the focused beam is chosen in the specular direction, i.e. $\theta = -27°$. Figure 1 shows the antenna geometry.

Moreover, a primary source with a prolate radiation pattern is used to increase the total aperture efficiency [9, 10].

B) Prolate horn

The field radiated by a reflectarray is proportional to the Fourier transform of the tangential electrical field in the aperture, i.e. the Fourier transform of the radiation pattern of the primary feed. The influence of the latter on the RA radiated far field can be compared to the effect of a window in signal processing. Therefore, a prolate function is chosen for the radiation pattern of the primary feed. The prolate window modifies the signal in such a way that the main lobe contains 99% of the power. As a consequence, the secondary lobes are greatly reduced such as the overall noise level. The aperture efficiency is improved. The template of the prolate window can be approached with enough accuracy by a Kaiser window. The coefficient β enables to adjust the level of the primary feed radiation pattern at the offset angle of 27°. We have chosen to design the horn for having −20 dB at 27°, which corresponds to $\beta = 5$. Simulations were conducted using SRSRD software, developed by France Telecom Orange Labs dedicated to axisymmetric antennas [11].

Numerical results in the E, H, and 45°-planes are shown in Fig. 2. The results obtained agree well with theory over ±27° in the E, H, and 45°-plane.

III. MEASUREMENTS

The reflectarray is composed of elementary cells with rectangular patches etched on a 254 μm Duroïd substrate ($\varepsilon_r = 2.2$). The cell lattice is $\lambda/2$. Diameter and focal length to diameter ratio (f/D) are of 160 mm and 1.125, respectively. Elementary cells are simulated using Ansoft HFSS with the Floquet port method, which allows the simulation of a single cell within an infinite array. Reflection phase is obtained

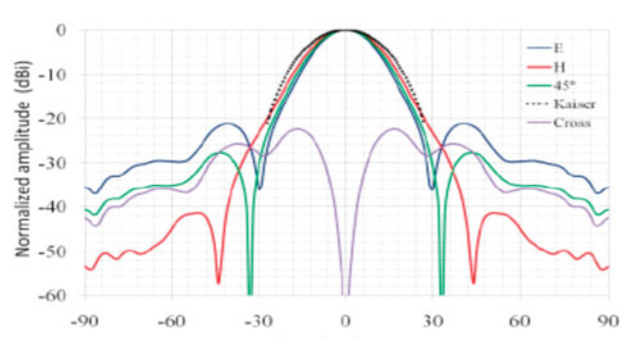

Fig. 2. Simulated radiation pattern and template of the Prolate primary feed at 77 GHz.

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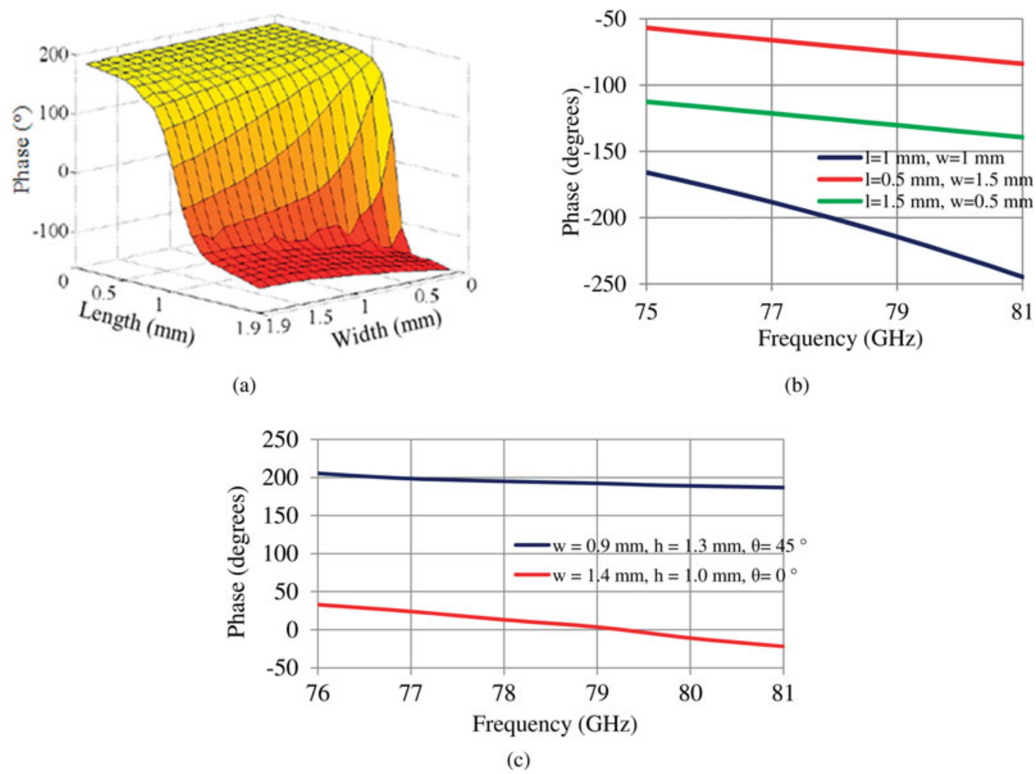

Fig. 3. (a) Phase versus width and length. (b) Phase versus frequency. (c) Phase versus frequency and incidence.

by variation of the width and the length of the rectangular patch. Then 340° phase excursion is achieved at 77 GHz as described in Fig. 3(a). As it is not possible to simulate large R.A. (here we have 40λ) with HFSS and home-made program based on an equivalent aperture method is developed at the LEAT for radiation pattern calculation purposes. Due to the approximations that have to be done results are expecting to be accurate within the main lobe only.

Several studies are conducted on the reflectarray cells. First the phase behavior versus patch dimension is determined (Fig. 3(a)). From these results it is possible to simulate the gain loss due to the fabrication errors ($\pm 50\ \mu$m) with our program. They have been estimated to be 0.7 dB at 77 GHz. Moreover, the reflected phase variation of the cell over frequency has been simulated. In a first step under normal incident for several patches dimensions (Fig. 3(b)), then for different incidences (Fig. 3(c)). One observes a linear variation.

The reflectarray has been fabricated and measured at LEAT. It is aligned by stand tilted at 27° in elevation to measure the main lobe in the $\theta = 0°$ direction. Measurements are shown in Fig. 4 over the bandwidth of interest.

The 3 dB aperture is 1.7° and secondary lobes remain inferior to 20 dB. The relatively high radiation level between −60° and −15° is due to the fixture that masks the

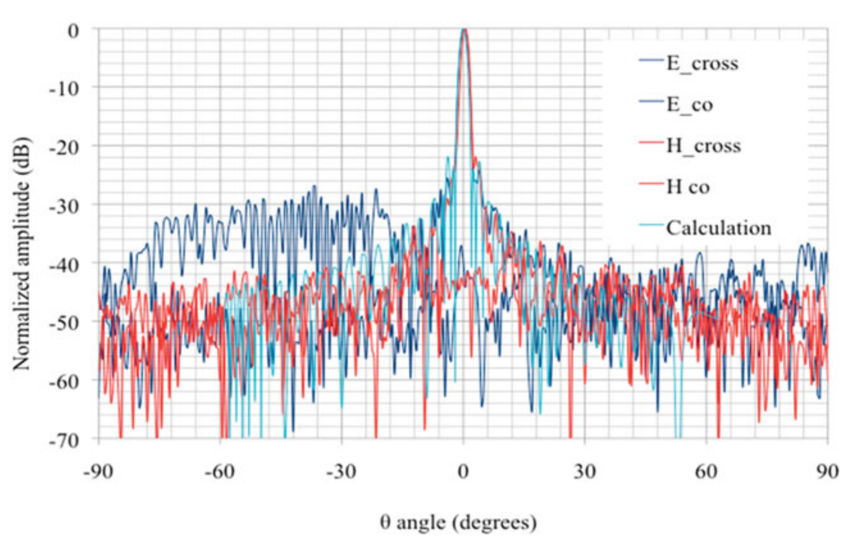

Fig. 4. Measured radiation patterns at 77 GHz.

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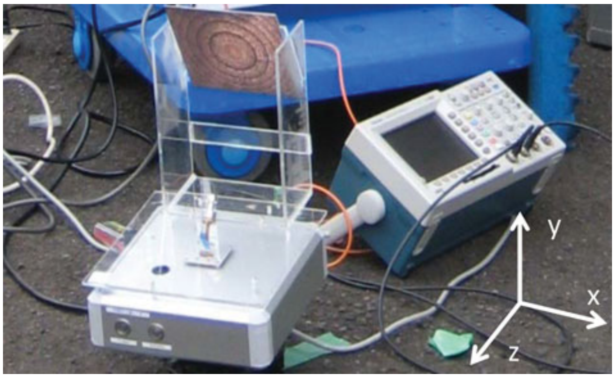

Fig. 5. View of the full system.

transmitting antenna during E-plane measurement. The antenna gain value is ranging between 38 dBi at 76 GHZ and is above 40 dBi after 76.5 GHz. It corresponds to an aperture efficiency varying between 30 and 50% that are state-of-the-art values in the W-band [12, 13]. As expected it rises near the central frequency and goes up to 70% at 78 GHz, which is to our best knowledge one of the highest value for the RA. Figure 5 shows the detection system, used during the measurement campaign in Japan. It is composed of the offset reflectarray, the frequency modulated continuous wave (FM-CW) radar module and another stand made at ENRI was used instead of the one used in the anechoic chamber.

The antenna gain has been measured again with this stand and its value was ranging between 36 and 36.5 dBi between 76.25 and 76.75 GHz. This 2.5 dB discrepancy is due to a misalignment between the primary source phase center and the reflectarray surface. A new stand has been fabricated and preliminary results have shown that the 40 dBi gain value has been again obtained. It should be sufficient for detecting −20 dBsm objects, but the extended bandwidth of the system up to 80 GHz will also improve the detection since the antenna gain is ranging between 40 and 42 dBi in the upper frequency band.

IV. RADAR MEASUREMENT

The monostatic FM-CW radar has been developed at the ENRI. It is composed of a Ku band driver circuit (12.3–13.3 GHz) and a radar module. The module is compact ($33 \times 35 \times 20$ mm^3), without connections and waveguides, and lightweight (180 g) without antenna.

Tests are conducted between 76 and 77 GHz, over a 500 MHz bandwidth. To avoid parasitic detections caused by near objects taken from the side lobes, we have seen that particular attention has been paid to the side lobes levels of the antenna (<20 dB SLL). The emitting power is less than 10 dBm according to the specifications for external measurement requested by the Japanese Administration. Measurements were conducted on pavement at ENRI site in November and December 2010, respectively. Although, several FOD systems already exist, there is no detailed evaluation of expected performances, except for the FAA circular of 2009 [6]. It describes relevant test object for FOD application. A target of −20 dBsm has to be detected up to 46 m for a system made with distributed radar modules on the runway. To evaluate the sensitivity and the detection capability of the radar, four standard targets were chosen:

- Three metallic cylinders' monostatic RCS have been calculated analytically [14] from 0, −10 to −20 dBsm.
- A corner reflector (28 dBsm) was employed.

Each cylinder has the same dimensions in diameter and height: cylinder C1 with 134.5 mm, C2 with 62.4 mm, and C3 with 29.0 mm. RCS values corresponding to an incidence at 0° and receivers placed 360° around the targets were simulated using Finite Element Boundary Integral (FE-BI) new module of HFSS [15]. Simulations have been carried out between 76 and 81 GHz in the perspective of the future large bandwidth front-end that is under development at the ENRI. Since there is no significant variation over the bandwidth of interest, Fig. 6 shows the simulation results at 78.5 GHz, which corresponds to the center of the frequency band. One observes that the maximum RCS value for each cylinder is not in the monostatic configuration ($\theta = 0°$). Therefore, it would be interesting to investigate using multistatic radar in the future for detection improvement.

Figure 7 shows a view of the four targets placed on pavement at ENRI and Fig. 8 represents a 60° scanning radar image obtained with a 0.12° angular step. The rotation of the whole radar (Front-end + antenna) is carried out in the xOz-plane with a motor placed under the antenna. The height of the whole system is 30 cm.

The four targets are detected at 10 m together with several elements of the environment. Indeed, metallic fences, long the pavement ENRI, are detected along tens of meters. We note the high reflection of the corner reflector on the right side, which masks the closest objects due to the longitudinal

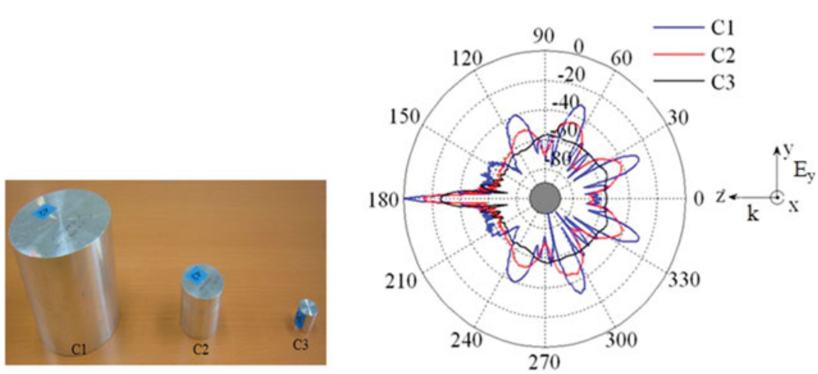

Fig. 6. Targets and the RCS numerical simulations.

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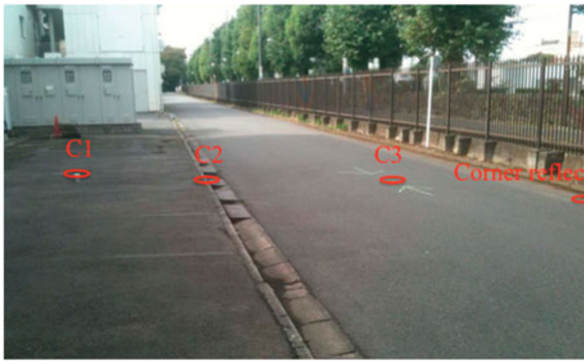

Fig. 7. Scene scanned by the radar.

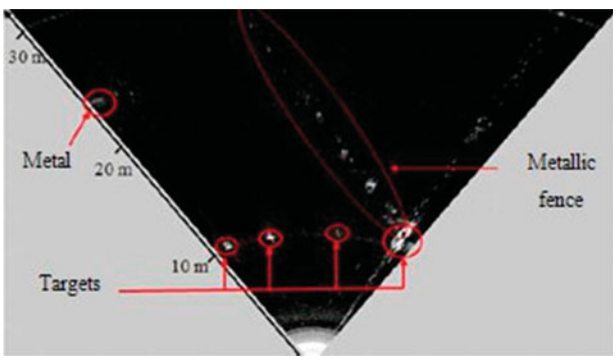

Fig. 8. Radar image with objects placed at 10 m from the radar.

resolution limitation (30 cm). Moreover, the −20 dBsm cylinder is detected up to 40 m.

V. CONCLUSION

An offset RA with 40 dBi gain at 77 GHz has been designed, fabricated and measured at LEAT anechoic chamber. Unfortunately, due to the distance separating LEAT and ENRI, the foreseen stand made at ENRI for assembling the FM-CW radar module and the RA was not enough accurate and lead to a 2.5 dB discrepancy in the antenna gain. A measurement campaign was carried out jointly in December 2010 with this configuration. Although, first results are conclusive for the radar detection capabilities, the level is not sufficient for detecting a −20 dBsm cylinder at 46 m. Fortunately, with a new stand, the 40 dBi antenna gain value has been obtained. Moreover, a new FM-CW module is under construction with an operating frequency bandwidth ranging between 76 and 81 GHz. With this configuration, we can take advantage of the best antenna gain value around 78 GHz. Finally, RCS simulation results have shown that multistatic measurements should improve the detection, but this set-up faces some important difficulties due to synchronization between the different receivers in the W-band.

ACKNOWLEDGEMENT

This work was supported by the JSPS and the French Ministry of Foreign Affairs under Sakura project number 21153ZF.

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https://doi.org/10.1017/S175907871100105X Published online by Cambridge University Press

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