Monopulse RLSA Antenna at 24 GHz Based on a Gap-Waveguide Cavity Feed

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Abstract—The purpose of this work is to design a frequency-scaled monopulse Radial Line Slot Array (RLSA) antenna intended for a space debris detector radar. Firstly, the slots arrangement is designed and optimized by using a global optimization algorithm where the analysis is based on an in-house Method of Moment algorithm. A Δ pattern prototype is manufactured and tested. Secondly, a monopulse feed based on a multimode cavity is introduced for simultaneous Σ and Δ operation. The cavity is located below the ground plane of the RLSA and is coupled to the antenna by means of a circular slot and is implemented using gap-waveguide technology. Simulations show good impedance matching and isolation between channels and stable Σ and Δ patterns for the monopulse operation.

I. INTRODUCTION

This paper shows the design of a monopulse antenna for space debris detection. This topic is becoming an important challenge due to the high number of elements, coming from old satellites, in orbit around the earth. According to the European Space Agency [1], small objects (from 1 to 10 cm of diameter), are the most potentially harmful since they are too small to be detected individually. A consortium of research groups in Madrid (from Technical University of Madrid, Universidad Carlos III and Universidad Autonoma de Madrid) is currently working in a research project with the purpose of the study of a space debris radar. Different monopulse antenna designs are analyzed in the project. In [2] a predesign at 94 GHz is proposed. This paper focuses on the design of an innovative feed network based on Gap-Waveguide Cavity Feed at 24 GHz, and also includes the design aspects of a radial line slot array antenna for this application. Previous studies for monopulse antennas based on Radial Line Slot Antennas were presented in [3]. The paper shows the design method for the slot arrangement and the antenna design aspects. The results will be checked with a prototype for the Δ pattern at 24 GHz.

The paper is divided in the following sections. Section II shows the specifications of the monopulse antenna system. Section III shows the radiating array design and fabrication of the prototype. Section IV shows the feeding structure and Section V the conclusions.

II. MONOPULSE ANTENNA SPECIFICATIONS

The antenna is left hand circularly polarized. This first prototype of the antenna is limited to a diameter of 20 cm due to fabrication restrictions. For this application the specified frequency band is very narrow, and only the analysis of the central frequency is required. The antenna is printed on a PTFE substrate: dielectric constant of 2.17 and width of 3.175 mm.

The monopulse antenna has two patterns: sum (Σ) and difference (Δ) (Fig. 1). For the detection of the angle of arrival, it is necessary to use amplitude and phase radar [3]. Elevation θ is determined comparing the amplitude of both patterns (Fig. 1, above), while azimuth ϕ is determined through the comparison of the phase of both patterns (Fig. 1, below) since the phase for the sum pattern is uniform while the phase for the difference pattern depends linearly with the azimuth angular position. The antenna is designed to maximize the gain at the central frequency (24 GHz). Both patterns are obtained through different excitation modes in the radial line. If the slots are arranged in concentric rings, an azimuthally uniform phase generates the difference pattern. On the other hand, a rotating phase mode generates the sum pattern.

III. MONOPULSE ANTENNA DESIGN

The radiating part of the antenna consists of circularly arranged rings of slots. The optimization algorithm is based on two algorithms: first a global algorithm based on simulated annealing is used and second a local one based on a conjugate gradient is used [4]. In this way, the number of iterations of the first algorithm is reduced. The parameter to maximize is the difference between the directivity and the spillover power for the sum pattern (power after the last ring of slots), in order to consider a quality factor based on uniformity of the amplitude and phase and maximization of the radiated power. As it is shown in [5], if the losses are not very high, the assumption of no losses in the radial line gives similar results to the case of lossy substrate. The analysis is performed using a Method of Moment algorithm with only 1 base function per slot and analytic expressions for the self-impedance of slots and feed

Fig. 1. Sum and difference amplitude and phase patterns

Fig. 2. Manufactured Radial Line Slot Antenna for Δ pattern excitation

pins [6]. This makes possible to optimize large antennas in reasonable time. The result of the optimization is the length and radial position of the slots for each ring. In this case, a 12 rings antenna has been designed.

In order to validate the design, a first simple antenna is designed and fabricated. The antenna consists in a Radial Line Slot Antenna excited with a coaxial pin in its centre. This excitation generates, therefore, a difference pattern. Fig. 2 shows the fabricated antenna and Fig. 3 shows some of the measured radiation patterns. The plotted traces are for the different values of the ϕ angle.

The measured results show two effects: first the central frequency has been shifted to 23.5 GHz (2% of frequency shift). This is due to the fabrication process, since the slots are a bit larger than the designed ones (around 0.1mm larger). The second effect is the angular position of the null (2 degrees) and the difference between maxima in the difference pattern. Some simulations have been performed, and it has been detected that an error of 0.25mm in the position of the central pin is the origin of this effect. This first study gives us the fabrication limits for the final antenna.

Fig. 3. Difference pattern Radial Line Slot Antenna at 23.5 GHz for different values of the ϕ angle

IV. MONOPULSE FEED BASED ON A GAP-WAVEGUIDE CAVITY

As mentioned above, given that the slots are arranged concentrically, any cylindrical equiphase wave-front in the Parallel-Plate Waveguide (PPWG) that conforms the radial line will lead to a Δ pattern, whereas any wave-front with a 360° phase change along its contour will lead to a Σ pattern.

To generate the equiphase and rotating (360° change) field distributions (sym. and rot. fields onwards), beamforming networks based on Butler matrixes and four coaxial probes have been successfully used [3]. In addition to this, waveguide cavities have been used to adjust the field distribution in RLSA for single pattern operation, combining the excitation probes with some parasitic pins (see for example [7]).

In this section, we propose to use a hollow cavity coupled to the previously introduced RLSA by means of a centered circular slot in the antenna ground plane, to generate Σ and Δ patterns for monopulse operation (Fig. 4). Three cavity modes will be used to generate two different field distributions that will be excited simultaneously by means of two independent coaxial probes (K type air-line plug connectors). These modes, coupled to the PPWG above through the circular slot, will properly excite the symmetric and rotational fields needed to generate the Δ and Σ patterns respectively. The cavity will be implemented using groove waveguide technology [8].

Fig. 4. Exploded view of the proposed antenna, showing the coaxial probes, the cavity feed, the ground plane, the teflon substrate and the upper metallization with the slots

A. Design of the Monopulse Feed

As a first step, the dimensions of an ideal square cavity of $25.7\text{mm} \times 25.7\text{mm}$ with a height of $h = 4\text{mm}$ are selected with the aim of operating the TE_{330} for the symmetric field distribution, and a combination of modes TE_{140} and $TE_{410}|\pi/2$ for the rotating field distribution, in frequencies close to 24 GHz. Regarding the excitation of the modes in the cavity, the TE_{330} field is generated with a centered coaxial probe, and the rotating modes are excited by means of a single coaxial probe located close to a rectangular perturbation which is introduced to generate the 90° phase shift between the modes that compose that rotating field. Finally, the solid cavity is replaced by a bed of nails (BoN) with square pins to conform a groove gap-wave cavity. The pins dimensions and the gap were designed to introduce a bandgap between 18 and 32 GHz. The pins are located in a regular lattice. Three rows of pins were found to be sufficient to emulate the solid wall boundary condition.

Fig. 5 shows all the described elements (the PTFE substrate and the upper metallic plate with the slots have been removed for the sake of simplicity). It is worth mentioning that an homogeneous PPWG with no slots is used for the feed design at this point.

Fig. 5. Monopulse feed schematic detail

An optimization process was carried out with the described setup with the goal of achieving good matching in both ports, high isolation and a good response in terms of amplitude and phase for the generated sym. and rot. fields in the PPWG. Fig. 6 presents the phase for the vertical electric field component of both field distributions E_z achieved in the middle plane of the antenna substrate for a distance $R = 20\text{mm}$. Table I includes some quality parameters for those fields in terms of amplitude and phase ripple for the same distance. A least-squares straight line was used to best fit each phase and amplitude response for the errors estimation.

B. Simulation Results for the Monopulse RLSA

As a final step, the slots pairs were introduced in the PPWG structure. Neither the amplitude nor the phase distributions for E_z in the antenna substrate nor the S-parameters for

Fig. 6. E_z phase for sym. and rot. channels in the antenna substrate at 24 GHz ($R = 20\text{mm}$)

TABLE I
PHASE AND AMPLITUDE ERRORS FOR E_z IN THE PPWG FOR
WAVEFRONTS AT $R = 20\text{mm}$

Type	Max. Phase error (deg.)	Max. Amplitude error (dB)
Rot.	25	3.3
Sym.	6.1	0.9

the antenna ports changed substantially. According to the simulations, input matching for both ports and isolation are kept below reasonable levels in a narrowband centered at the selected frequency. Fig. 7 displays the radiation patterns of the achieved Σ and Δ channels at 24 GHz for different azimuth angles. These patterns are quite stable within a relative bandwidth of around 3%. For the Σ channel, it can be observed that strong sidelobes appear at $\Phi = 45^\circ$ and $\Phi = 135^\circ$. This could be related to the asymmetry introduced by the perturbation and the off-axis position of the exciting probe in the cavity, and has to be further investigated.

C. Preliminary measurements of the prototype

A prototype of the full antenna with the feed structure was manufactured and measured in terms of its S parameters. Fig. 8 shows the fabricated BoN cavity with the coaxial probes for both channels. The comparison of simulated and measured S parameters included in Fig. 9 shows a good agreement between them. The antenna is well matched at both ports and the isolation is better than 25dB in the band of interest. The characterization of the radiation patterns of the prototype is pending completion. From our previous experience, losses in the range of 1 dB are expected for this antenna in this frequency range.

V. CONCLUSION

A monopulse antenna based on a radial line slot array configuration, excited with a groove gap-waveguide feed is proposed in this paper. The application for this antenna is a space debris radar: this antenna is part of the global radar configuration and the complete design is in progress. This

Fig. 7. Simulated Σ and Δ patterns (Gain-LHCP) for different azimuth angles

Fig. 8. Manufactured BoN cavity showing the coaxial probes for both channels.

paper focuses mainly on the design of the monopulse feed and the integration in the slot array configuration.

The proposed groove gap-waveguide feed shows promising results when combined with a RLSA antenna for a monopulse radar application and is very simple and compact in comparison with classical feeds. Some design aspects of this kind of antennas have been described in the paper. A first prototype was manufactured and measured to investigate the fabrication limits of this technology. With respect the final design, simulated results show good response in terms of isolation and matching for both Σ and Δ channels, and stable and useful radiation patterns. In a second step, a prototype of the antenna at 24 GHz with the novel feed structure was fabricated. A good response in S parameters measurements

Fig. 9. Simulated (solid lines) and measured (dashed lines) S parameters of the manufactured antenna

was obtained. This antenna will be thoroughly tested, prior to its integration in the full radar system.

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