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SUBWAVELENGTH SPIRAL SLOTTED WAVEGUIDE ANTENNA

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Abstract—Integrating antennas into a load-bearing airframe structure has the potential for profound improvements in the capability of military and commercial airplanes, by allowing for substantially increased radiator and array size with reduced weight or drag penalties. Reducing the size of array elements can significantly improve the mechanical performance of the load-bearing antenna. The novel single element spiral slot cut in the broad-wall of a WR-90 rectangular waveguide proposed in this paper is smaller than a quarter of the operating wavelength (half of the size of a conventional rectangular slot). The small antenna element enables a slotted waveguide array to be realized without significantly degrading the mechanical performance in load bearing applications. The proposed spiral slot is compared with conventional rectangular slots and exhibits comparable performance in terms of total efficiency (representing coupling from waveguide mode to the slot) and peak realized gain. Total efficiency and peak realized gain of the spiral slot in travelling wave mode are significantly higher than those of a quarter wavelength rectangular slot element which has near zero radiation. The simulated results were validated by manufacturing the spiral slot placed on the broad-wall of a rectangular waveguide. Realized gain patterns of the spiral slot measured at the design frequency corroborate reasonably with the simulations.

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1. INTRODUCTION

The Slotted Waveguide Antenna (SWA) dates back to World War II [1]. Since then, SWAs have become popular in the communication, aerospace and aviation industry because of their simplicity, high power handling and relatively low profile. Most SWAs are resonant structures. An electrical short at the end of the waveguide creates a standing wave which excites the slots. The slots are approximately half a wavelength long and their centres spaced by approximately half wavelength. A comprehensive literature review on SWAs can be found in [1]. Slotted Waveguide Antenna Stiffened Structure (SWASS) integrates SWAs into load-bearing aircraft structures. The blade stiffeners in sandwich panels or top-hat stiffeners on skins serve the dual purpose of providing both structural stiffening and serving as radio frequency waveguides. SWAs can be produced by cutting slots through the outer skin and into the waveguides [2].

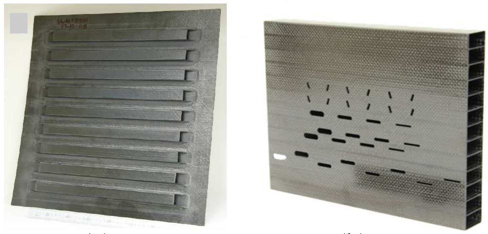
The mechanical performance of a SWASS under compression for single rectangular slot cut on WR-90 waveguides has been predicted using finite element analysis and measured experimentally in [3]. The results indicate a promising future for this concept. However, the slot-to-slot interaction in carbon fibre reinforced polymer (CFRP) laminates under compression degrades the overall strength of the structure. For circular holes with diameter being 25% of the spacing, the interaction is close to negligible and the structure behaves like a structure with one hole [4]. Therefore for SWASS, reducing the size of the slots from $\lambda_0/2$ to $\lambda_0/4$ (where λ_0 is the free space wavelength) can simplify the design and improve the mechanical performance of the structure. In addition, the maximum hole size (i.e., the diameter of a circle enclosing the slot) in aircraft panels to achieve airworthiness certificates without additional strengthening is a quarter of an inch, which is slightly less than $\lambda_0/4$ at 10 GHz. Aircraft skin panels are designed such that they (i) can be joined to other panels using mechanical fasteners of 1/4 inch diameter and (ii) can be repaired using bolted joints on mechanical patches.

Reducing the size of the traditional rectangular slots or circular holes from $\lambda_0/2$ to $\lambda_0/4$ is not a feasible solution because the coupling from the waveguide mode to a subwavelength slot is near zero. Transmission through subwavelength apertures is a classical problem in both microwave and optics regimes. The theory of diffraction by small holes was first developed by Bethe [5], which showed for circular holes much smaller than the wavelength the radiation transmitted through the hole is very small. Several techniques were investigated by researchers to overcome Bethe's limits. A review of these techniques is provided in [6].

Array of subwavelength slits [7], Split Ring Resonators (SRRs) [8, 9] and single particle resonators [10] were used to enhance the transmission through subwavelength apertures. In these methods the aperture is in a conductive plate and is illuminated by a plane wave propagating at normal incidence. The inclusion of additional elements is necessary to intensify the electromagnetic field in the vicinity of the aperture and consequently increase the transmission through the subwavelength aperture. Similarly, a single SRR was employed in a SWA in order to reduce the size of the slot resonator to $\lambda_0/4$ without significantly affecting the RF performance of the antenna. This can improve the mechanical performance of SWASS [11]. In [12], a 4-slot SWA array with SRR loading was developed from this concept. In [13] a wire element was used instead of the SRR beneath a $\lambda_0/4$ slot to improve the realized gain of the sub-resonant length slot. However, enhancing transmission through subwavelength apertures without the need for additional elements and resulting from single aperture geometry has not been reported.

The high stress concentration factor of rectangular slots also degrades the mechanical performance of the SWASS. In [14, 15], the stress concentration factor and compressive strength of spiral slots was investigated and was compared to circular and rectangular slots. It was shown that the mechanical performance of spiral slots is superior to that of rectangular slots for selected load-cases. Consequently, a spiral slot was used on the broad-wall of a rectangular waveguide for wideband operation [16]. However, the outer diameter of the employed spiral slot is in the order of the waveguide wall dimension (larger than half a wavelength).

This paper proposes a single element spiral slot in the broad-wall of a rectangular waveguide having a diameter slightly less than $\lambda_0/4$. The aim of this work is to reduce the size of the slots used in SWASS panels (Figure 1) to improve the load-bearing capability of such multifunctional structures without deleterious effects on its electromagnetic function. A circular hole with equal diameter or a rectangular slot with equal length to the outer diameter of this spiral slot both exhibit near zero radiation. The feasibility of using a small spiral slot in a waveguide wall has not been investigated before and is a novel solution for the SWASS concept. Among different possible slot shapes that can be used to resonate with overall size of $\lambda_0/4$, the spiral slot has been chosen for the SWASS application because of three main reasons. First, total efficiency (representing coupling from waveguide mode to the slot) and peak realized gain of this antenna are shown to be comparable to that of a conventional $\lambda_0/2$ rectangular slot (both



(a) (b)

Figure 1. Evolution of hat stiffeners in (a) aircraft composite panels to (b) SWASS concept [17].

in travelling and standing wave modes) and are far superior to a $\lambda_0/4$ rectangular slot. Second, compared with the techniques in [11–13], this new slot shape does not require additional components such as SRRs to enhance the gain. Third, the proposed slot can improve the mechanical performance of the SWASS by reducing a) the slot-to-slot interaction and b) the slot stress concentration. The theoretical radiation limit of rectangular slots and circular holes cut into the waveguide wall is discussed first. Then the simulation results and design criteria for a subwavelength spiral slot are presented, and validated by experimental measurements.

2. THEORY AND DESIGN

Bethe [5] theorised the diffraction through a single circular hole in a thin metallic film illuminated by an incident plane wave. Similarly, transmission through subwavelength apertures on waveguide walls is limited for apertures smaller than $\lambda_0/2$. Figure 2 illustrates the simulated total efficiency (radiated power divided by the input power) and peak realized gain of circular and rectangular slots on the broad-wall of a rectangular waveguide for different slot sizes (normalised to the wavelength). The results in Figure 2 were obtained by simulating a WR-90 waveguide with internal cross-sectional dimensions of $22.86\,\text{mm} \times 10.16\,\text{mm}$, and wall thickness of 0.5 mm (which is of the same order as hat stiffeners on skins or face-sheet separation in CFRP aircraft structures [2]) using the ANSYS HFSS$^{\text{TM}}$ software. The rectangular slot was designed to resonate at the centre frequency of 10 GHz with maximum efficiency and the circular slot diameter was set equal to the rectangular slot length. Then the size of each slot was reduced in incremental steps to obtain total efficiency and peak realized gain. Both total efficiency and peak realized gain decrease

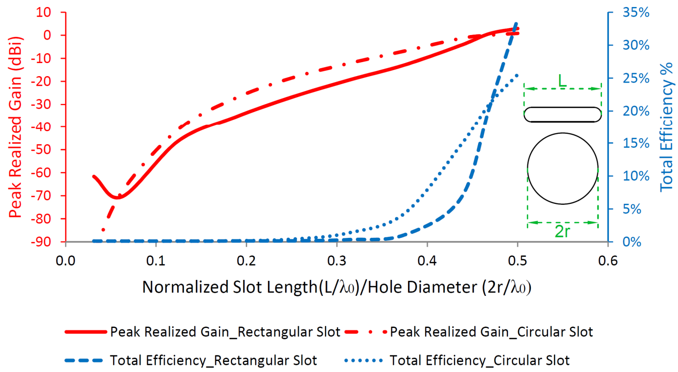


Figure 2. Total efficiency and peak realized gain of rectangular and circular slots on the broad-wall of a rectangular waveguide for different slot sizes normalized to the free space wavelength.

rapidly by reducing the slot size. This restricts the minimum slot size in SWASS, affecting its mechanical performance.

A spiral slot on the broad-wall of a rectangular waveguide is designed to radiate as a subwavelength aperture going beyond the existing transmission limits. Replacing rectangular slots with subwavelength spiral slots in SWASS can improve the mechanical performance by (i) reducing the size of the radiating element and hence reducing the slot to slot interaction [4], and (ii) reducing the stress concentration factor compared to conventional rectangular slots [14, 15]. Here, the spiral slot is a self-complementary equiangular spiral designed to be incorporated into the broad-wall of WR-90 rigid rectangular waveguides and operate at 10 GHz. The end of the spiral slot was terminated with a semi-circle in order to minimise the stress concentration [14, 15]. The spiral slotted waveguide antenna investigated in this paper was simulated using the ANSYS HFSS$^{\text{TM}}$ (version 15.0) software. Figure 3 shows the geometry of the spiral slot along with conventional $\lambda_0/2$ rectangular slot and $\lambda_0/4$ rectangular slot.

The design parameters for the spiral slot are shown in Table 1 and are illustrated schematically in Figure 4. The critical parameter in determining the resonant frequency of the spiral slot is the length of the spiral. The spiral resonates when its arm length is equal to approximately one wavelength at a particular frequency. The wall thickness also influences the operating frequency. Reducing the wall thickness increases the resonant frequency slightly. Here, the wall thickness was set to 0.5 mm to be similar to the wall thickness of CFRP

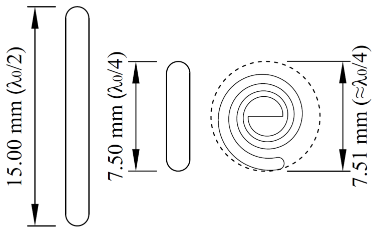


Figure 3. Geometry of the proposed spiral slot in comparison with $\lambda_0/2$ and $\lambda_0/4$ rectangular slots.

waveguides used in previous SWASS work [17]. The metallic flanges at the end of the waveguide were not included in the simulation to isolate the radiation characteristics of the spiral slot; therefore, it can be directly compared with traditional rectangular slots.

The coupling between the spiral and the field inside the waveguide can be adjusted by offsetting the spiral from the waveguide centerline similar to traditional rectangular waveguides. In addition, the coupling can be adjusted by changing the slot width angle. The total efficiency of the element (which represents the coupling to the slot) can be reduced by decreasing the slot width angle. The largest dimension of the designed spiral slot is slightly less than $\lambda_0/4$. A traditional $\lambda_0/2$ longitudinal broad-wall slot was also simulated as a reference. The rectangular slot was designed to resonate at 10 GHz and is operated in travelling wave mode. The slot is 15 mm long by 1.6 mm wide and its ends are rounded with 0.8 mm radius. The rectangular slot is offset by 6.5 mm from the centerline of the broad wall. The slot length was then reduced to $\lambda_0/4$ in order to be compared with the spiral.

The slot spiral, placed at the centre of waveguide broad wall, is excited by the electromagnetic wave travelling through the waveguide. As the electromagnetic field propagates through the waveguide the

Table 1. Design parameters of the spiral slot.

Parameter	Description	Value
Slot width angle (δ)	Determines width of spiral slot	π
Growth rate (a)	Determines spiral tightness	0.080
Number of turns (T)	Number of spiral turns	2.292 turn
Inner radius (r_{in})	Start of spiral curve	1.193 mm
Outer radius (r_{out})	End of spiral curve	3.757 mm
Initial growth angle (Φ_0)	Progressive growth angle at r_{in}	0

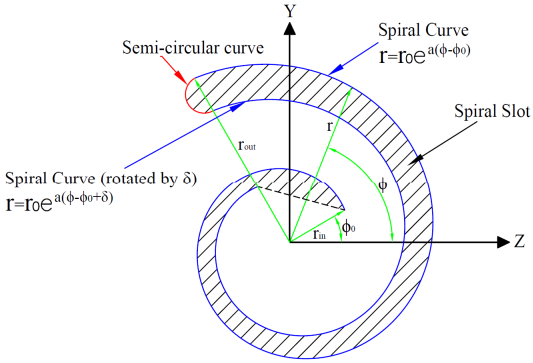


Figure 4. Design parameters of the spiral slot.

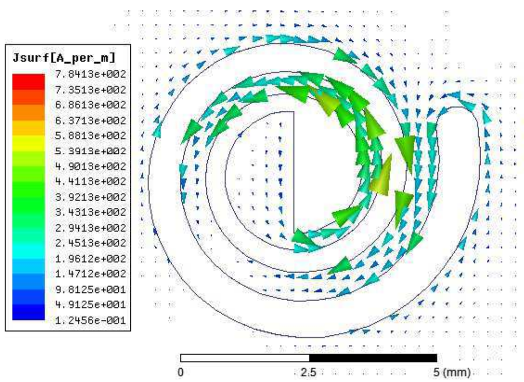


Figure 5. Surface current distribution for the subwavelength spiral slot on the broad wall of WR-90 waveguide at 10 GHz.

electric field induces a current on the edges of the spiral slot. In other words, the spiral slot cuts the current flow on the broad wall of the rectangular waveguide operating in the TE_{10} mode. Because of the unique geometry of the spiral, the current needs to flow in a longer path than a $\lambda_0/4$ rectangular slot. In contrast to rectangular slots, the spiral slot does not need to be offset from the centerline of the broad wall. The predicted surface current distribution for the spiral slotted waveguide at 10 GHz is shown in Figure 5. Because of the spiral geometry the magnitude and direction of the induced currents vary at different locations of the slot, resulting in a sinusoidal current distribution. The current on opposite edges of the slot are travelling in opposing directions along the slot edges; therefore, the total length travelled is longer than in a rectangular slot with the same size.

3. MEASUREMENT AND RESULTS

In order to validate the simulations, the subwavelength spiral slotted waveguide antenna was manufactured and measured. Figure 6 shows the spiral slot cut in the broad wall of a WR-90 waveguide. For the measurement of scattering parameters the two ends of the waveguide were connected to the two ports of the vector network analyser (VNA) in order to simultaneously measure the $|S_{11}|$ and $|S_{21}|$. The radiation pattern of the manufactured antenna was measured in an anechoic chamber. For the Gain measurement, one end of the spiral SWA was connected to an SMA-to-waveguide adapter (HP® X281A™) and the other to a waveguide termination (model 5985-99-527-1086) resulting in a traveling wave condition (similar to the condition used for the two port simulations). To generate a standing wave condition the waveguide termination was replaced with a sliding short (HP® X923A™) and the position of the short was adjusted to locate the field maximum under the spiral slot.

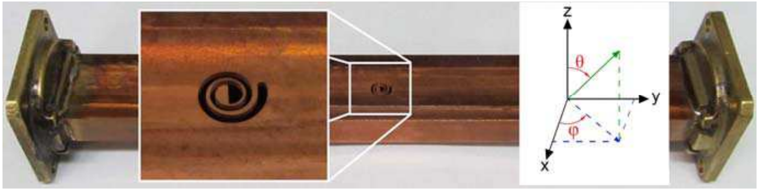


Figure 6. Spiral slot cut in the broad wall of a WR-90 waveguide.

3.1. Scattering Parameters

The simulated and measured scattering parameters of the spiral slotted waveguide antenna in travelling wave mode are shown in Figure 7. $|S_{21}|$ is the transmission from port 1 at one end of the waveguide to port 2 at the other end of the waveguide. The $|S_{11}|$ and $|S_{21}|$ for each design correspond to each other indicating the resonance at that frequency. The dip in the $|S_{21}|$ curves is primarily the result of radiation through the spiral slot and loss at the resonant frequency is negligible. The resonant condition can be confirmed by the change in the phase of the wave propagating in the waveguide at the resonant frequency seen in Figure 8. Measured results show acceptable agreement with simulations in predicting the resonance of the spiral slot. The shift in the frequency of the measurements is due to the dimensional tolerances in manufacturing the spiral.

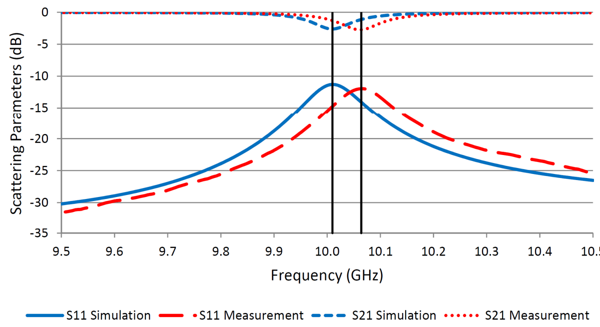


Figure 7. Measured and simulated scattering parameters (magnitude) of the spiral slot element.

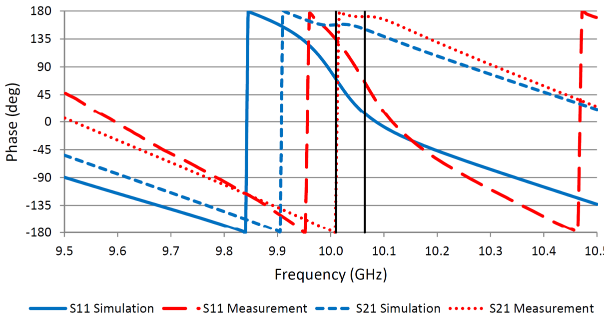


Figure 8. Measured and simulated scattering parameters (phase) of the spiral slot element.

3.2. Efficiency and Peak Realized Gain

The simulated and measured total efficiency and peak realized gain of the spiral slot are compared with that of a conventional rectangular slot in travelling wave mode in Figures 9 and 10, respectively. The total efficiency of a $\lambda_0/4$ rectangular slot which is the representative of the coupling from the waveguide to the slot is almost zero (as seen in Figure 9). However, the total efficiency of the spiral slot (of the same size) is more than 35%, which exceeds the total efficiency of the conventional $\lambda_0/2$ rectangular slot. The efficiency bandwidth of the spiral slot is smaller than the conventional $\lambda_0/2$ rectangular slot; however, this is not a limitation for narrowband SWA arrays. Realized gain was used as a metric to account for the reflected and transmitted power, which is a very important consideration for a single slot element.

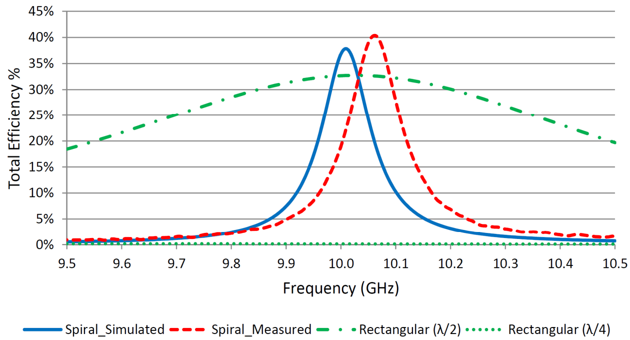


Figure 9. Comparison of simulated total efficiency for the conventional rectangular slot and the spiral slot on the broad wall of the WR-90 waveguide in travelling wave mode.

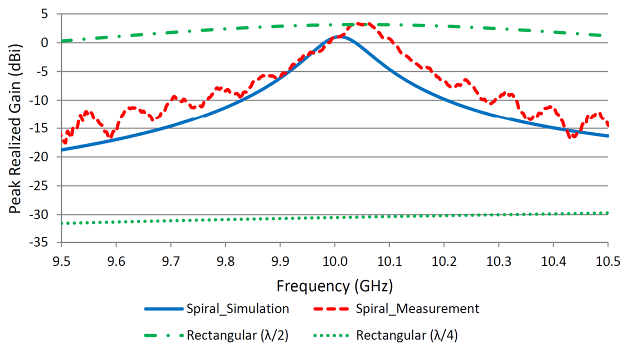


Figure 10. Comparison of simulated peak realized gain for the conventional rectangular slot and the spiral slot on the broad wall of the WR-90 waveguide in travelling wave mode.

In Figure 9, it is evident that the peak realized gain of the spiral slot is significantly higher than the $\lambda_0/4$ rectangular slot, and approaches the peak realized gain of the conventional $\lambda_0/2$ rectangular slot.

Total efficiency and peak realized gain of the spiral slot are compared with those of the rectangular slots in standing wave mode in Figures 11 and 12, respectively. The standing wave condition was simulated by replacing the second port of the waveguide with a metallic short. Both the total efficiency and the peak realized gain of the spiral slot are significantly higher than those of the $\lambda_0/4$ rectangular slot, showing extraordinary transmission similar to the travelling wave mode.

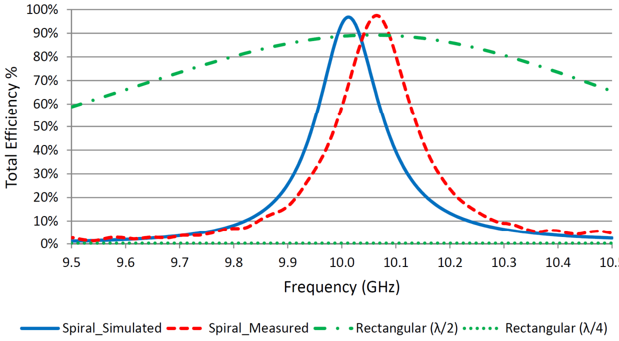


Figure 11. Comparison of simulated total efficiency for the conventional rectangular slot and the spiral slot on the broad wall of the WR-90 waveguide in standing wave mode.

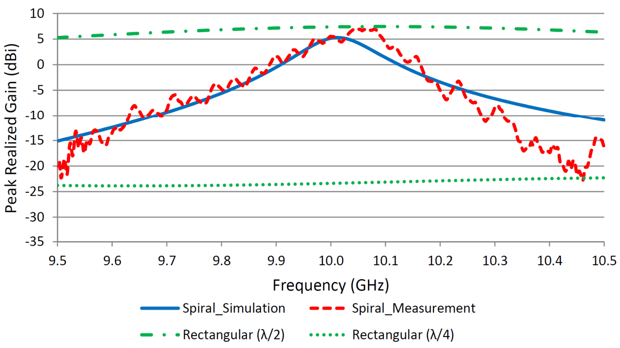


Figure 12. Comparison of simulated peak realized gain for the conventional rectangular slot and the spiral slot on the broad wall of the WR-90 waveguide in standing wave mode.

3.3. Radiation Pattern

The simulated and measured realized gain patterns of the spiral slot at two orthogonal planes ($\Phi = 65^\circ$ and $\Phi = 155^\circ$) at 10 GHz are presented in Figures 13 and 14. In order to avoid reflection from waveguide flanges during gain measurement they were covered with absorber material. The proposed spiral slot radiates linearly polarized wave at the polarization plane of $\Phi = 65^\circ$ (see Figure 6). The measured cross-polarization level is about -15 dB at bore-sight. The polarization plane can be adjusted by rotating the spiral around its centre relative to the direction of wave propagation in the waveguide (i.e., changing

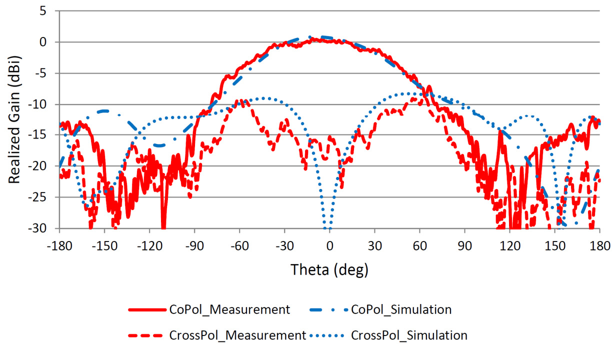


Figure 13. Realized gain pattern at 10 GHz ($\Phi = 65°$ plane).

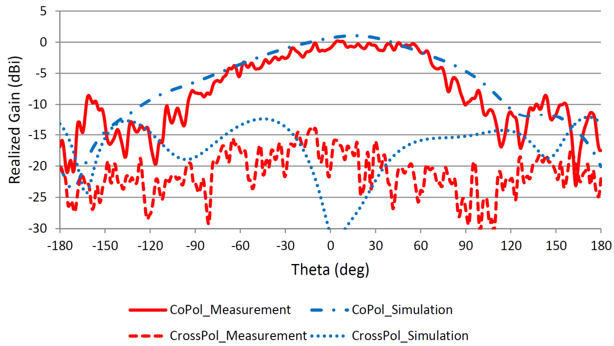


Figure 14. Realized gain pattern at 10 GHz ($\Phi = 155°$ plane).

the initial growth angle (Φ_0) shown in the Figure 4). Therefore, the spiral could be designed to resonate at a certain frequency and then could be rotated to achieve the desired polarization plane.

Measured results show reasonable agreement with the simulated results which confirm the radiation from the spiral slot at the resonance. The measured realized gain of the spiral slot is similar to those of traditional rectangular slots. The measured realized gain patterns and linear polarization of the spiral slot make it a suitable candidate for reducing the size of array elements in SWASS. The slight differences between measured and simulated results are due to various sources of error. The accuracy of the gain measurement in the anechoic chamber is about 0.5 dB. The loss in the SMA-to-waveguide adapter was measured as approximately 0.5 dB at 10 GHz. Overall, the measured results show good agreement with simulations and validate the design results in the previous sections.

4. CONCLUSION

In this paper, a single element spiral slot cut into the broad wall of a rectangular waveguide is proposed as a subwavelength slotted waveguide antenna. The spiral slot with a quarter wavelength outer diameter shows comparable performance to a conventional half wavelength rectangular slot in traveling and standing wave modes. The spiral slot radiates linearly polarized wave similar to the traditional rectangular slots. Total efficiency and peak realized gain of the spiral slot in travelling wave mode are significantly higher than those of a quarter wavelength rectangular slot element which has near zero radiation. This represents a markedly higher transmission through the aperture cut in the broad-wall of a rectangular waveguide. The presented results prove that this novel slot design couples effectively to the electromagnetic field inside the waveguide whilst coupling to a circular hole or a rectangular slot with equal size and without the need for additional elements is not feasible.

Simulated and measured scattering parameters and realized gain patterns of the manufactured spiral slotted waveguide antenna corroborate reasonably with each other. With its overall reduced size and thus enhanced mechanical attributes, the sub-wavelength spiral slot has been shown to possess equivalent electromagnetic properties to that of conventional rectangular slots when used in SWASS applications. Further study on the design and development of arrays from spiral slot elements is required to enable full potential of this concept. The design criteria, results and discussions presented in this paper provide primary design criteria for such array designs in the future.

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