Split-ring resonator loaded miniaturized slot for the Slotted Waveguide Antenna Stiffened Structure

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Abstract

The Slotted Waveguide Antenna Stiffened Structure (SWASS) utilizes conventional hat-stiffeners or blade stiffeners in sandwich structures as microwave waveguides. By machining slots through the outer skin and into the waveguide, large slotted waveguide antenna arrays may be integrated into the structure. Resonant slots are efficient radiators favored for high gain applications. However the length of a resonant slot, in the order of half a guided wavelength, can severely degrade the load-bearing capacity of the structure. This paper presents a metamaterial inspired design that achieves comparable gain from a miniaturized slot by means of a single split-ring resonator.

1. Introduction

Slotted waveguide antennas (SWA) date from the 1940s [1] and are still in popular use today. Their mechanical robustness and simple construction favor a variety of applications across the maritime and aerospace industry. Although aluminum and brass are perhaps the most common medium for SWA, such materials are unsuited for large scale arrays where thermal expansion and mechanical rigidity may necessitate the use of significant structural reinforcing. Metalized carbon fiber reinforced plastic (CFRP) has been used for the fabrication of space-based SWA [2] to achieve a significant weight saving with the required dimensional stability.

The potential advantages of the conformal load-bearing antenna structure [3] has inspired the Slotted Waveguide Antenna Stiffened Structure (SWASS) concept [4]. It was noted that the stiffener cross-section typical in hat stiffened skins, or skin-to-skin separation in sandwich panels, are similar to the waveguide dimensions for common military applications. Thus these structural features may be redesigned to act as waveguides. By machining arrays of resonant slots through the outer skin and into these stiffeners, a SWA may be integrated into the aircraft structure with very little weight and drag penalty. These slots may be filled with a low-loss dielectric to retain the aerodynamic performance of the panel or with a high dielectric to reduce their physical dimensions. Regardless, the structural impact of the slot is a significant issue that must be addressed in order to validate the SWASS concept [5].

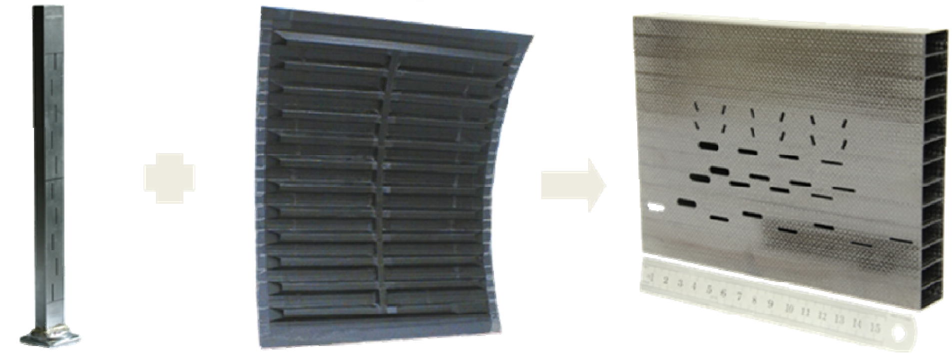

Slotted waveguide Antenna. Hat-stiffened panel. Representative SWASS concept

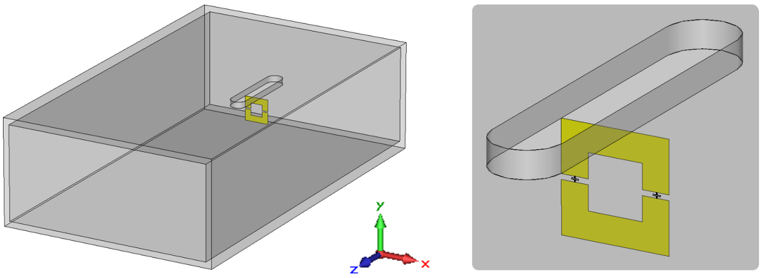
Fig.1. SWASS concept.

This paper presents a new metamaterial inspired method employing a single split-ring resonator (SRR) to couple energy through the slot in a resonant SWA. This allows for a significant reduction in the slot length therefore providing one approach to address the impact of slots on the strength of the SWASS without severely compromising the antenna performance.

2. SRR loaded sub-wavelength slot

The poor transmission of electromagnetic energy through a sub-wavelength aperture in an infinite metallic sheet is a classical problem that was first addressed by Bethe [6]. It remained a technical challenge until the experimental work of Ebbesen [7] and the theoretical analysis of Oliner and Jackson [8] established the role of surface plasmon polaritons in achieving enhanced transmission through a sub-wavelength aperture. However, the recent development of metamaterials inspired an alternative theoretical solution to the problem by Alu [9]. The practical issues regarding the experimental implementation of Alu's solution are discussed by Bilotti [10] who concluded with a resonant approach to the transmission enhancement problem.

This resonant approach to enhance the transmission employed a metamaterial constructed from magnetic inclusions such as the ubiquitous SRR. In [10], Bilotti demonstrated how such a metamaterial layer (with effective permeability of -1) fabricated with transverse dimensions similar to the aperture size, may significantly enhance the transmitted power. However, a seconded enhancement peak in the transmitted spectrum was observed and attributed to the resonance of the SRR. This suggested the possibility of achieving enhanced transmission with the very simple addition of a well placed SRR behind a slot in an infinite metallic sheet. Theoretical and experimental work on this mechanism for enhanced transmission has since been reported in [11] and [12] with the possibility to tune the enhancement frequency reported in [13]. This method of achieving enhanced transmission from a sub-wavelength aperture in an infinite metallic sheet may be extended to the slots in the SWASS. Reducing slot length reduces the adverse structural impact of both the individual slots and arrays of slots. The proposed slot and SRR geometry is presented in Fig. 2.



(a) (b)

Fig. 2. (a) SRR loaded slot in a rectangular waveguide and (b) detail of the geometry. Waveguide ports are located at either end of the guide with lumped capacitances located in the SRR gap regions.

The SRR captures a portion of the magnetic flux circulating down the waveguide. The strong localized fields induced in the SRR couple to the slot to achieve a significant improvement in radiated power compared to the unloaded sub-resonant length slot. In this work a square SRR with two splits, a mean ring dimension $d = 3$ mm and ring width of 0.5 mm orientated in a WR-137 waveguide as illustrated in Fig. 2, was considered. Each gap in the SRR was loaded with a capacitance of 0.25 pF such that the SRR resonance occurred at 6.5 GHz. The slot offset from the broadwall centerline was set to 25 % of the broadwall dimension and the slot width was fixed at 2.6 mm. The peak realized gain with and without the SRR loading was then determined numerically using the frequency domain solver in CST Microwave Studio. The slot length was varied in order to evaluate the effect of the SRR on antenna performance. The results are plotted in Fig 3.

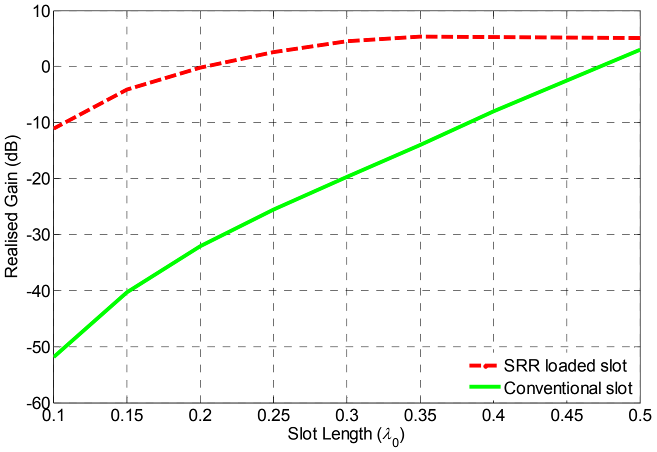


Fig. 3. Simulated peak realized gain for a conventional single slot and for the SRR loaded slot at 6.5 GHz. The plane of the SRR is located at the centre of the slot with the SRR axis parallel to the slot length.

Fig. 3 suggests a SWA with slot length of 0.25 λ_0 and SRR loading may exhibit comparable gain to a conventional SWA with resonant slot length of 0.496 λ_0 at 6.5 GHz in WR-137 waveguide. Since the slots in a resonant SWA are spaced half a guided wavelength apart, the greater separation between slots in the SRR loaded SWA would provide greater load-bearing capacity relative to the conventional SWA.

4. Conclusion

This paper presented a simple metamaterial inspired method to achieve acceptable gain from a miniaturized slot by utilizing the strong localized fields in the SRR. When applied to a conformal load-bearing antenna such as the Slotted Waveguide Antenna Stiffened Structure (SWASS), the reduced slot length enhances the load-bearing capacity of the structure. The experimental characterization of a SWA with and without SRR loading is underway with experimental results to be presented at Metamaterials 2011.

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