

Miniaturization and Bandwidth Enhancement of a CPW-Fed Annular Slot Antenna Using RIS

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Abstract—In this paper a CPW-fed annular slot antenna is miniaturized with enhanced impedance bandwidth using a reactive impedance surface (RIS) substrate. The RIS is realized by patterning 3×3 array of circular elements over an inexpensive FR-4 substrate which is backed by a circular metallic plane. Due to the compensation of electric and magnetic energy stored by antenna and RIS substrate respectively, the antenna resonance frequency is shifted by 53.6% compared with a simple annular slot antenna. By the inclusion of such reactive surface, input impedance of the antenna is reduced, and a remarkable improvement in impedance bandwidth from 11.66% to 64.26% is also noticed. Therefore, both miniaturization and bandwidth enhancement are achieved simultaneously with the present loading technique. The directivity of the RIS loaded antenna is increased further by loading a concentric metallic ring over the RIS loaded structure at a height above the RIS plane. The Ring & RIS loaded structure is fabricated for measurement purpose. A good agreement is obtained between the simulated and measured results for both RIS loaded and Ring & RIS loaded configurations. The ring loading over the RIS antenna provides improvement in directivity about 5 dB. The peak gain and bandwidth are measured at -1.03 dBi and 58.62%, respectively.

1. INTRODUCTION

The topic of compact printed antennas with enhanced bandwidth is becoming an essential choice to the wireless system designer. However, reduction in antenna dimension in general affects the impedance bandwidth and radiation characteristics. The easiest way to miniaturize the antenna size is placing the radiating element over a higher permittivity substrate. But the uses of high dielectric material are less effective for the printed slot antenna as the antenna suffers from surface wave excitation.

Terminating the two ends of a slot radiator by slotted spiral line minimizes the near-field coupling of inductive loads and also shrinks antenna dimension [1]. Loading of inductive slits [2] and vertical wires [3] on either side of the rectangular slot compensates the capacitive reactance of a simple slot antenna and reduces the size. In [2], placement of a backed metallic plate at very large distances, for enhancement of gain, may increase the overall volume of the structure. Recently, a probe-fed annular ring slot antenna [4] is miniaturized by several conductive vias where matching is improved by backing the structure with a ring cavity. Due to the size reduction of the antenna, impedance bandwidth has been adversely affected owing to the increased quality factor of the radiator. The narrow-band nature of the antenna used in [1] is enhanced further by folded slot/wire/complementary configurations [5]. This folded mechanism enlarges the physical aperture of the radiator which in turn increases the radiation conductance that helps to match the input impedance over a large frequency range. A tapered slot antenna (TSA) provides a wide operational bandwidth, but the complex feeding structure and necessity of large taper's opening make the design more challenging. To ease the feeding

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arrangement, a microstrip line feed has been used in [6, 7] where, corrugated and folded fin structure was adopted for miniaturization. In [8], an open-ended slot is utilized for size reduction of a UWB antenna while inverted feeding section maintains the impedance bandwidth. Recently, a very small size UWB antenna has been designed by half-cutting method [9]. Amongst the techniques adopted in [6–8] for designing of a UWB slot antenna, dimensions of the structure are rarely reduced. A printed wide-slot antenna with enhanced bandwidth has been realized by a microstrip line fed tuning stub [10], CPW-fed asymmetric slot [11], rotated square slot [12] and mono-pole fed structure [13]. It is found that wide-slot antenna contributes to large bandwidth [10, 12] whereas narrow-band slot antenna provides very small bandwidth [1]. Parasitic patches have been used along the feed line to further enhance the impedance bandwidth of the rotated square slot antenna in [14]. The narrow bandwidth of a cavity backed slot antenna has been improved by inserting a via-hole above the I-shaped slot [15]. The enhancement of ultra-wide bandwidth of a circle-like slot antenna has been achieved in [16] by using trident-shaped feed line and two L-shaped stubs on the back of the substrate, respectively. Recently, a ring slot antenna has been miniaturized by single and multiple interdigitated slits inside a ring structure [17].

In this paper, a CPW-fed annular ring slot antenna is miniaturized by the reactive impedance surface substrate [18]. The design of reactive impedance surface and its effect was first demonstrated in [18]. RIS-based compact microstrip patch antenna has also been proposed in [19, 20] where meta-resonator in the form of CSRR and CSR was added for further miniaturization. The effect of mutual coupling with the source and image is reduced due to the distribution of image current in space for the impedance surface. The RIS is realized by the unit cell structure with a proper periodic boundary condition applied to its walls. In our design, an annular slot antenna is miniaturized without modifying the slot and ground plane structure. The reference annular slot antenna shows capacitive behavior below the resonance frequency, whereas in the same frequency range RIS provides pure inductive impedance. With the introduction of such inductive surface below the radiator, input impedance of the antenna is decreased, which in turn aids in impedance matching over a large frequency range. The RIS loaded antenna provides a 53.6% size reduction with 57.1% impedance bandwidth. The directivity of the RIS loaded structure is improved by using a metallic ring above the antenna at a minimum height. Reduction of metallic losses over the circular ground plane and consecutively excitation of large surface current on the conducting ring has increased the directivity of the slot antenna. The ring loading technique provides about 10 dB improvements in FBR compared with the reference case.

2. CPW-FED ANNULAR SLOT ANTENNA DESIGN

In this work, a conventional annular slotted structure is employed as the reference antenna. Geometry of the annular slot antenna with a CPW-feed line is shown in Figure 1(a). In general, a microstrip slot antenna is very popular due to its compact, low-profile and easy to integrate with monolithic microwave integrated circuit. It is known that a narrow slot antenna exhibits narrow band operation, whereas wide slot antenna renders inadequate cross polar isolation. However, the annular ring slot antenna may be a

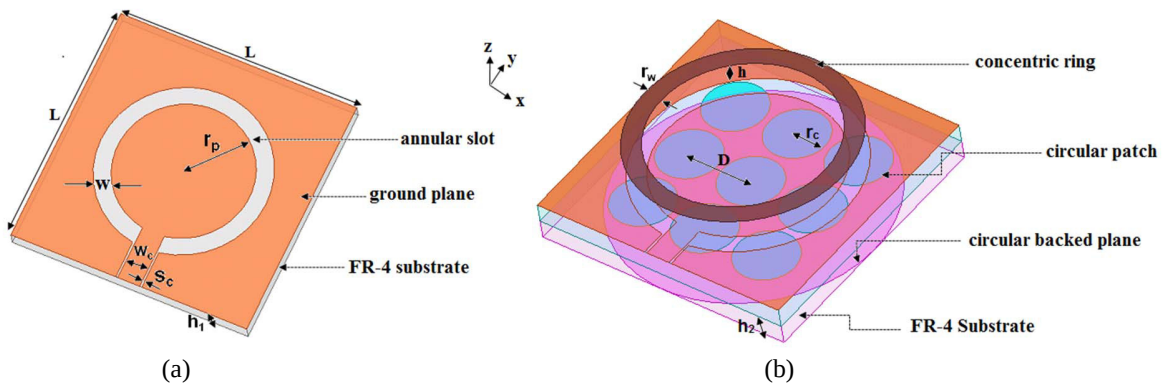


Figure 1. Antenna structure. (a) Simple annular slot antenna. (b) Ring & RIS loaded slot antenna.

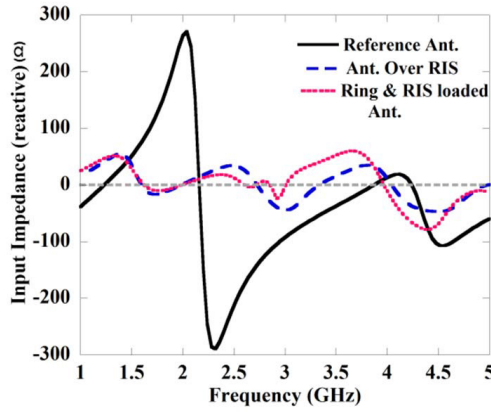


Figure 2. Reactive part of input impedance of slot antenna.

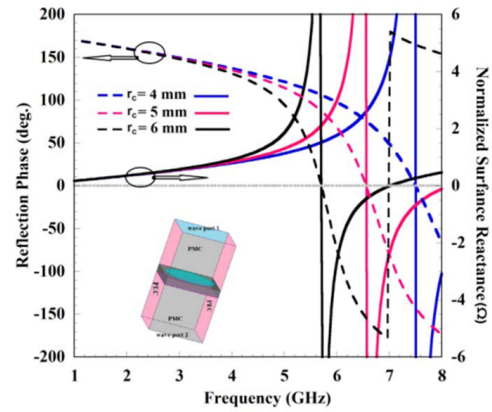


Figure 3. Reflection phase and surface impedance characteristics of unit cell structure.

better choice to accomplish both good cross-polar isolation and improved bandwidth. In the structure, annular slot with an average radius of r and slot width of w is etched from a $(L \times L)$ sized ground plane. The average radius can be calculated by equation (1) where r_p is the inner radius of the slot. A one-sided FR-4 substrate is used for the above design with the thickness h_1 of 1.6 mm, permittivity of 4.4 and loss tangent of 0.02. A CPW line with the trace width of w_c and the gap spacing between the signal strip and the coplanar ground of s_c is employed as the feed line of the slot antenna. The uses of CPW line as a feeding medium is ease the fabrication and reduced the losses. The structure exhibits capacitive behaviour below the resonance frequency and is shown in Figure 2. Thereafter, a reactive impedance surface substrate is placed below the antenna substrate to miniaturize the antenna size and widening the impedance bandwidth. Generally, RIS exhibits pure reactive surface impedance below the resonance. Due to such reactive nature of the surface, antenna image current is distributed in sinusoidal form rather than concentrated at the image point at the complex vertical plane. Fields of the antenna image at the source point itself can be minimized by the proper choice of surface reactance. Thus, capacitive reactance of the antenna is cancelled out by the inductive reactance of RIS and hence antenna is miniaturized with enhanced impedance bandwidth. Here, to achieve the reactive surface behavior, unit cell analysis is performed where circular elements with a radius of r_c and periodicity of D are placed above another FR-4 substrate which has a metallic layer on the back side. To maintain the periodic behaviour of the unit cell, PEC and PMC boundary is applied to

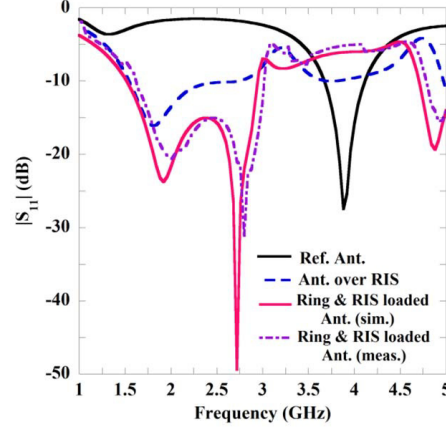
$$r = r_p + \frac{w}{2} \quad (1)$$

the four faces of the unit cell with the excitation port assigning on top and bottom surfaces. The unit cell simulation set up is shown in the inset of Figure 3. The dimension of the unit cell is chosen in such a way that its null phase frequency is beyond the resonance of the reference antenna. The unit cell exhibits inductive surface reactance below of its resonance which compensates the capacitive reactance of the reference slot antenna. Thickness, permittivity and loss tangent are retained same for both antenna and RIS substrate. 3×3 finite periodic circular array elements are used to realize the total surface impedance that helps to minimize the reactance produced by the antenna.

From the radiation pattern shown in the next section, the directivity of the RIS loaded antenna is reduced due to more back side radiation. To enhance the directivity of the miniaturized antenna a concentric conducting ring [21] with the width of r_w is placed above the antenna at a height of h . It is worth to mention that the width of the conducting ring is selected same as the width of the annular slot. Loading of the ring over an antenna is a very simple and inexpensive technique for enhancement of directivity compared to [2, 17]. The Ring & RIS loaded miniaturized antenna is displayed in Figure 1(b), whereas the fabricated structure is photographed in Figure 8. The dimension of the antenna is tabulated in Table 1.

Table 1. Different parameters of the proposed slot antenna (All units are in mm).

L	w	w _c	s _c	r _p	h ₁	r _c	r _w	D	h ₂	h
43	3	4	0.37	14.5	1.6	5	3	11	1.6	3

**Figure 4.** Return loss characteristics of reference and loaded slot antennas (simulated and measured).

3. RESULTS AND ANALYSIS

The return loss behaviour shown in Figure 4 depicts that the reference slot antenna is resonated at 3.88 GHz with an impedance bandwidth of 11.55%. It is also observed from the impedance plot shown in Figure 2, that the simple antenna provides input impedance in the form of pure capacitive reactance from 3.86 GHz to 2.16 GHz. By following the image current methodology used in [18] to minimize the near field coupling of the antenna current and its image currents, a circular RIS has been introduced in this work. The unit cell described in the last section is analyzed here to observe the reflection phase characteristics and surface impedance behaviour. From Figure 3 it is seen that the unit cell resonates at 6.55 GHz and exhibits a pure inductive surface impedance below the resonance frequency. From the parametric analysis conducted in Figure 3 for different patch radius, it is found that for a large circular patch, unit cell resonates at lower frequency whereas for small patch size the null phase point shifted upwards. In this design the radius of the unit cell patch elements are chosen as 5 mm taking into account the compact cell size and surface reactance value.

Next, the S_{11} characteristic of the RIS loaded slot antenna is exhibited in Figure 4. The resonance frequency of the antenna is now shifted down to 1.8 GHz with an acceptable impedance matching. As a consequence, the antenna provides 53.60% miniaturization compared with the reference case. Also, the fractional impedance bandwidth is calculated as 57.10%, which is enhanced by more than four times compared with the reference antenna. The radiation characteristics of the antenna are depicted in Figure 5 for both radiation planes.

From the radiation characteristics, it is apparent that at the resonant frequency the RIS loaded antenna has larger back lobe gain than the front lobe gain in both radiation planes. Radiation efficiency of the miniaturized antenna is only 3% less than the reference antenna whereas peak gain is -5 dBi, which is 6.14 dBi less than the reference antenna. The reduction in gain for the RIS loaded case can be explained by the surface current distribution over the antenna and the circular ground plane. It is apparent from Figure 6 that at the resonance, electric surface current is maximum around the slot and over the edges of the circular ground plane. As a consequence the backing plane of RIS produces some losses on the antenna that reduces both gain and directivity.

Both gain and directivity of the RIS loaded antenna are improved by taking into account the ring loading effects on the resonance frequency and impedance bandwidth. A concentric metal ring with the strip width of r_w is placed over the RIS loaded structure at a height h . From Figure 4, it is

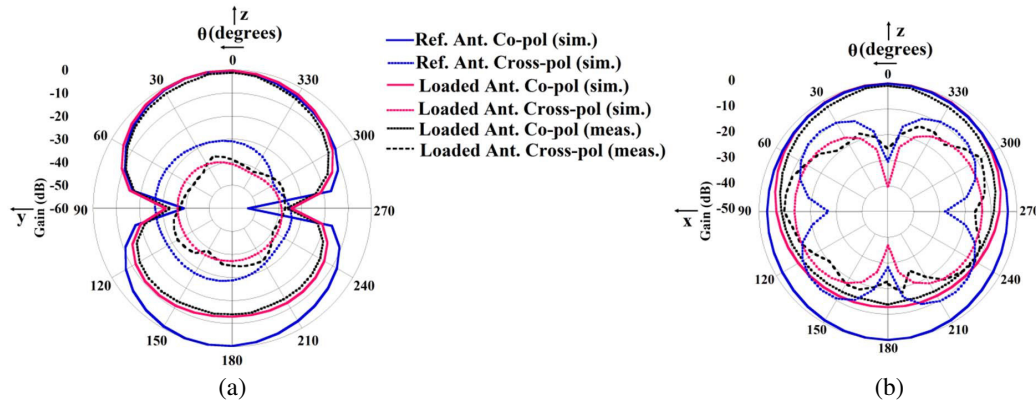


Figure 5. Radiation characteristics of Ring & RIS loaded slot antenna and reference slot antenna. (a) E -plane gain pattern, (b) H -plane gain pattern.

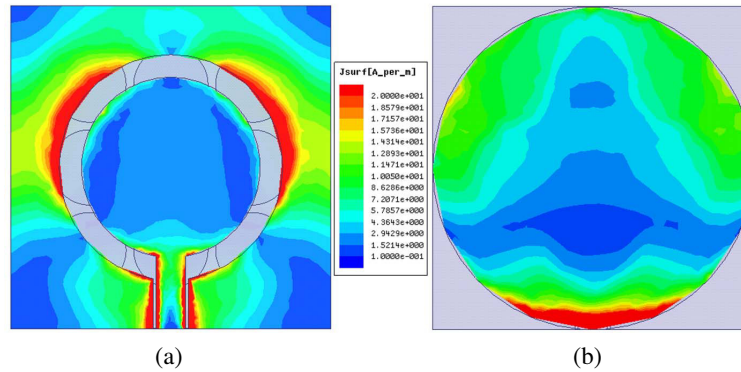


Figure 6. Electric surface current distribution for RIS loaded slot antenna. (a) Over the slotted ground plane. (b) Over the back plane of RIS substrate.

observed that the ring-loaded RIS antenna exhibits very good impedance matching with a bandwidth of 64.26%, but the resonance frequency is right shifted to 1.92 GHz from 1.8 GHz. As an outcome, the ring loading increases the antenna size by 6.5% compared with previous case, while it conversely enhanced the impedance bandwidth by 13.3%. From Figure 5 it is observed that back radiation is reduced and peak gain enhanced by the conducting ring placed above the RIS loaded structure. The reason behind such a phenomenon is the fall of electric surface current on the circular ground plane that also reduces metallic losses and excites the concentric conducting ring. The surface current distribution over the slot antenna, circular ground plane and concentric ring are displayed in Figure 7. Different simulated radiation parameters for all three configurations are summarized in Table 2. The following tabulated result also suggests the effects of loading over the reference slot antenna by the RIS and then RIS & Ring structure.

The fabricated prototype of Ring & RIS loaded structure is exhibited in Figure 8, where two substrates are assembled using a low-loss dielectric adhesive. Return loss characteristic of the proposed structure is measured using Anritsu MS2025B vector network analyser in our lab. The two-peak resonance of the proposed antenna is measured at 2 GHz and 2.8 GHz with a calculated impedance bandwidth of 58.62%. The measured and simulated normalized radiation patterns at the best matched resonance point are exhibited in Figure 5 for both y - z and x - z planes. The peak gain at boresight direction is measured at -1.03 dBi, which is slightly less than the simulated value. In both E & H polarization planes, measured co-pol pattern is very much similar to the simulated pattern with a negligible reduction in the gain. Isolation between co-pol and cross-pol in both E -plane and H -plane is measured at more than 30 dB at the broadside radiation. The calculated front-to-back ratio (FBR) of the measured ring loaded RIS antenna is above 10 dB.

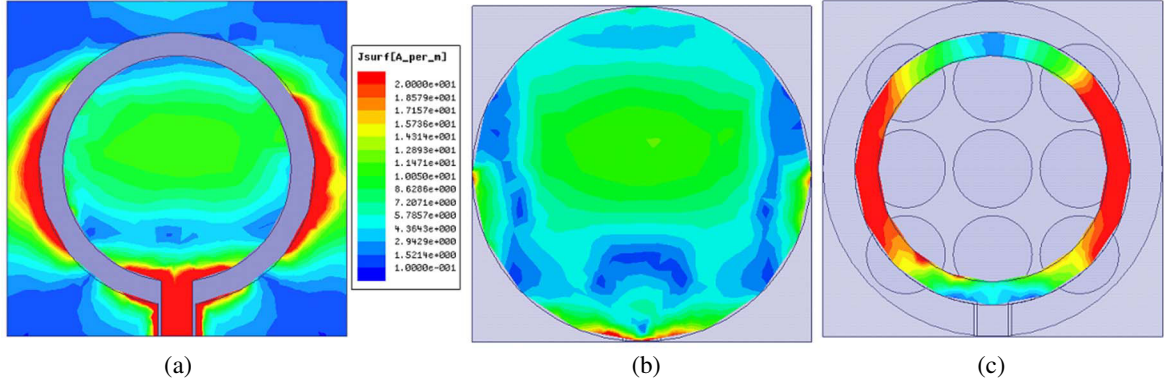


Figure 7. Electric surface current distribution for Ring & RIS loaded slot antenna. (a) Over slotted ground plane. (b) Over RIS backed plane. (c) On circular metallic ring.

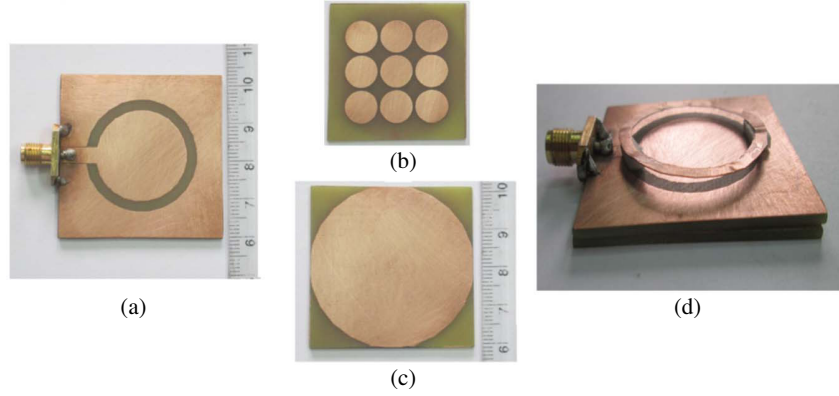


Figure 8. Fabricated Configurations. (a) Reference slot antenna. (b) Front side of RIS structure. (c) Back side of RIS structure. (d) Ring & RIS loaded slot antenna.

Table 2. Simulated radiation parameters for slot antenna (with and without loading).

Ant. Type	Resonance Freq. (GHz)	Imp. Bandwidth (%)	Matching (dB)	Peak directivity (dB)	Front-to-back ratio (dB)	Efficiency (%)
Ref. Slot Ant.	3.88	11.55	-27.45	1.57	1.37	90.6
Slot Ant. Over RIS Only	1.8	57.10	-16.43	-4.47	-4.51	88.15
Slot Ant. over RIS with Ring loading	1.92	64.26	-23.76	-4.70	-3.51	90.70
	2.72		-49.39	0.83	12.98	81.94

4. CONCLUSION

In this paper, a CPW-fed annular slot antenna is miniaturized by reactive impedance substrate. The RIS is realized with the array of circular metallic elements which are printed over a back-sided metal substrate. With the help of such meta-surface, more than 50% size reduction is achieved. A notable improvement in impedance bandwidth is obtained from the narrow slotted structure without altering the slot geometry. Both miniaturization and bandwidth enhancement are achieved at the cost of reduced gain and directivity by such reactive loading. Front-to-back radiation and directivity of the slot antenna are improved later by loading a circular metallic ring over the slot at an optimized height. The ring width is kept equal to the slot width for exciting the copper ring by the energy produced in the slot

antenna. At the resonance frequency, more energy is coupled from the slot to the overhead ring which results in improvement in front-to-back ratio about 17 dB. A good co-pol and cross-pol isolation about 30 dB is observed from the measured radiation pattern along with a FBR above 10 dB.

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