Compact SRR Loaded UWB Circular Monopole Antenna With Frequency Notch Characteristics

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***Abstract*—This paper presents the design of a compact split ring resonator (SRR) loaded coplanar waveguide (CPW) fed ultrawideband circular monopole antenna having frequency notch characteristics. The electromagnetic coupling of the SRR with the CPW yields the frequency notch. Fabricated prototypes were measured and compared with simulations and good agreement was obtained. The impedance and radiation plots confirm the suppression of the desired notch frequency. A theoretical formulation to calculate the notch frequency is also proposed and validated.**

***Index Terms*—Circular monopole, split ring resonator (SRR), ultrawideband (UWB) antenna.**

I. Introduction

Mitigating interference between ultrawideband (UWB) antennas and other narrow band systems have spurred growth in designing UWB antennas with notch characteristics. Several design configurations have been proposed in the open literature using planar monopole antennas with modified radiator and/or ground plane to achieve this characteristic [1]–[16]. Notch characteristics with triple notch frequencies [1]–[6], dual notch frequencies [7]–[10] and single notch frequency [12]–[16] were achieved using various design configurations employed with planar monopole printed antennas. Triple notch frequencies over the band were obtained using multiple etched slots on the patch and split ring resonators (SRRs) coupled to the feed line [1], by inserting two I-shaped notched slots and an open-ended U-shaped slot on the edge of the radiation patch [2], by using three open-ended quarter-wavelength slots [3], by embedding an Omega-shaped slot on the radiating patch [4] and by using a pentagonal radiating patch with two bent slots [5]. A compact triple band notch UWB antenna featuring complementary co-directional split split-ring resonator (CSRR) arranged in the middle of the radiating patch close to the feeding strip was demonstrated in [6]. Similarly, dual band notch characteristic to reject undesired frequencies in UWB radiators was demonstrated in [7] where two C shaped slots were etched on a beveled rectangular patch. Another design by etching one quasi-complementary SRR in the feed line was shown in [8]. Several other designs, such as using a trapezoidal ground plane with a rectangular slot together with a modified complementary co-directional split ring resonator (SRR) etched on the radiating patch [9], by employing a U-slot defected ground structure in the ground plane and etching a split ring slot in the radiation patch [10], and by embedding a E-slot in the radiation patch and a U-slot defected ground structure in the feeding line [11], have also been used satisfactorily. Similarly, single band-notch characteristic was proposed in an antenna consisting of a patch with arc-shaped edge and a partially modified ground plane [12]. A single frequency notch characteristic was also realized by introducing a microstrip feeder with a tuning stub in [13], by utilizing a mushroom-type electromagnetic-bandgap (EBG) structure in [14], and also by using a coplanar waveguide (CPW) with two asymmetrical ground planes as demonstrated in [15]. An ultra-wideband planar monopole antenna with a tunable band-notch characteristic was also realized by loading an embedded resonant slot with a varactor as was demonstrated in [16].

This paper describes a novel and simple method to design a frequency notched UWB antenna by loading a pair of SRRs on the opposite surface of a CPW fed circular monopole antenna. The SRRs are placed symmetrically on the back side of the printed monopole antenna which results in a notch frequency determined by the SRR's geometrical dimensions. The suppression of the radiation at the notch frequency is due to the effect of a strong magnetic coupling of the propagating EM signal with the SRR. This coupling between the SRR and the propagating EM signal can be used to filter out undesired frequencies and avoid possible interference within the UWB (3.1 GHz to 10.6 GHz). By loading multiple SRR pairs with varying dimensions, multiple resonances can also be achieved. Fig. 1 shows the schematic of the proposed antenna. The circular monopole of radius R is fed by a CPW consisting of ground planes having widths W_1 and W_2, length Ls and a signal line having width S and length $Ls + t$. The slots between the ground planes and signal line have width, S_g. The antenna is printed on a substrate having thickness h and dielectric constant ε_r. Two square shaped split ring resonators having dimension "a_{ext}" which is half the dimension of the side-length of the SRR, conductor thickness "c," separation between rings "d" and split gaps "g_1" and "g_2" as shown in Fig. 1(c), are printed on the other side of the substrate with their centers coinciding with the slot lines of the CPW feed. Unlike in most of the previously presented designs described earlier, where most of the inclusions and slots were arranged on the radiating patch itself or the ground planes,

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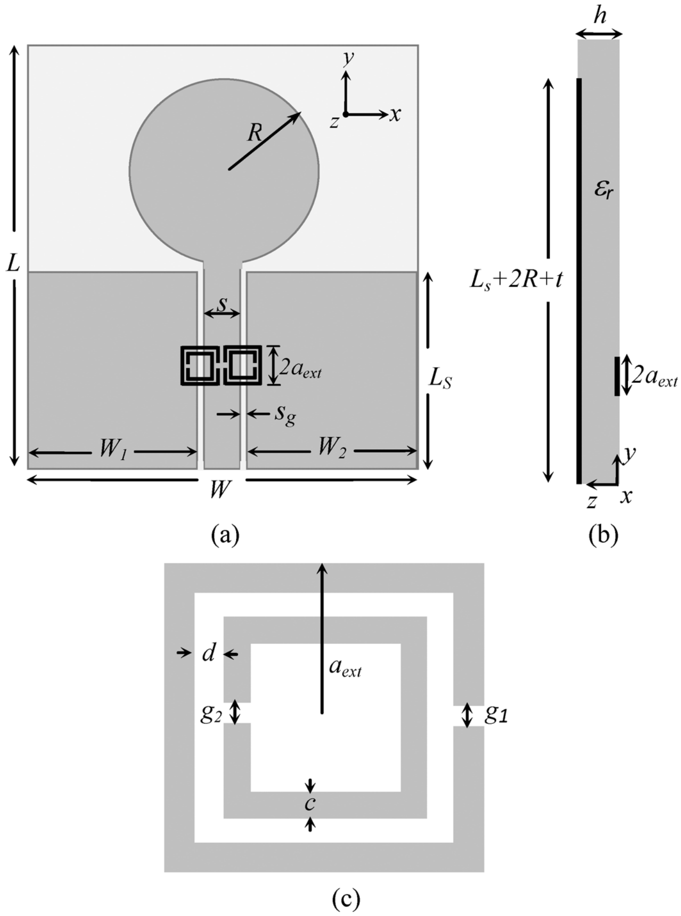

Fig. 1. Schematic of a CPW fed printed circular monopole antenna loaded with square SRR (a) Top view with a pair of SRRs (in darker shade) loaded on the back side. (b) Side view showing the printed SRRs separated by h from the CPW fed printed circular monopole. (c) Enlarged view of the square SRR printed on the back side of the CPW fed monopole antenna.

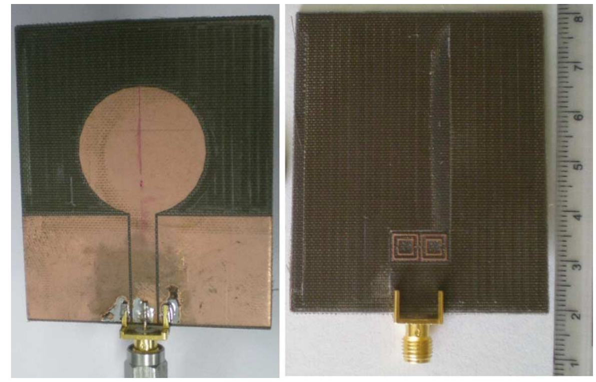

Fig. 2. Fabricated prototype of the CPW fed circular monopole loaded with SRR. Parameters as in Table I.

TABLE I
DESIGN PARAMETERS OF THE FABRICATED CPW FED CIRCULAR MONOPOLE ANTENNA LOADED WITH SRR PRINTED ON A DIELECTRIC SUBSTRATE HAVING THICKNESS, $h = 1.575$ mm, DIELECTRIC CONSTANT $\varepsilon_r = 2.33$ AND $\tan\delta = 0.0009$ (PARAMETRIC VARIABLES AS SHOWN IN FIG. 1)

Design Parameter	All are in (mm)
R	12.5
W	50
L	50
$W_1 = W_2$	22
S	5
S_g	0.5
Ls	22.4
t	0.2
a_{ext}	2.5
c	0.35
d	0.6
$g_1 = g_2 = g$	0.7

the novelty in our design is that it can be employed on any CPW fed planar monopole UWB antenna without tampering or changing the shape of the radiator or the ground plane.

II. The Antenna Design

The fabricated prototype of the SRR loaded circular monopole antenna is shown in Fig. 2. Table I shows the design parameters used for the prototypes. The circular monopole having diameter 25 mm is fed with a coplanar waveguide having ground plane length $L_s = 22.5$ mm, width $W = 50$ mm and feed gap dimension $t = 0.2$ mm. The antenna performance depends on the ground plane width W and the feed gap t, since the current is distributed along "W" and the ground plane serves as an impedance matching circuit [17]. The SRRs are printed on the back side of the CPW with dimension $a_{ext} = 2.5$ mm and other parameters as presented in Table I. The propagating EM signal along the CPW having its magnetic field oriented along the axis of the SRR induces an electro-motive force on the SRR which in turn induce currents oscillating between the two rings of the SRR. These oscillating currents between the two rings yield a resonance which is determined by the SRR's geometry and prohibits signal propagation at that frequency. This resonance frequency can be determined from the equivalent circuit approach demonstrated in [18] which involves calculation of distributed capacitance between the rings of the SRR and total inductance of the SRR. The SRR resonance frequency for related dimensions is calculated in the following section.

III. Calculation of SRR Resonance Frequency

The resonance frequency f_0 of the square SRR is given by [18]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{L_T C_{eq}}} \tag{1}$$

where C_{eq} is the total equivalent capacitance of the structure and can be evaluated by calculating the distributed capacitance between the two rings of SRR and the gap capacitance as

$$C_{eq} = \left(2a_{avg} - \frac{g}{2}\right) C_{pul} + \frac{\varepsilon_0 c t_m}{2g} \tag{2}$$

where, c and t_m are the width and thickness of the metallic rings, respectively and ε_0 is the free space permittivity. The split gaps are of identical dimensions $g_1 = g_2 = g$. The average ring dimension a_{avg} is given by

$$a_{avg} = a_{ext} - c - \frac{d}{2} \tag{3}$$

and C_{pul} is the capacitance per unit length and is calculated as

$$\mathrm{C}_{pul} = \frac{\sqrt{\varepsilon_e}}{c_0 Z_0} \tag{4}$$

where, $c_0 = 3 \times 10^8$ m/s, ε_e is the effective permittivity of the medium and Z_0 is the characteristic impedance of the line and are calculated as in [19].

A simplified formulation for the evaluation for the total equivalent inductance L_T for a wire of rectangular cross section having finite length l and thickness c is proposed as [20] as

$$L_T = 0.0002l\left(2.303\log_{10}\frac{4l}{c} - \gamma\right)\ \mu\mathrm{H} \tag{5}$$

where, the constant $\gamma = 2.853$ for a wire loop of square geometry. The evaluation of the wire length l is straight forward as

$$l = 8a_{ext} - g. \tag{6}$$

The resonance frequency of the SRR is determined using (1)–(6) which involves the SRR's geometrical parameters (a_{ext}, c, d, g_1 and g_2) and constitutive parameter (ε_r) of substrate on which the SRR is printed.

IV. Results and Discussions

Two working prototypes of the CPW fed circular monopole antenna, with and without SRR loading were fabricated on a Taconic substrate having thickness $h = 1.575$ mm, dielectric constant, $\varepsilon_r = 2.33$ and a loss tangent, $\tan\delta = 0.0009$. The prototypes were designed and simulated using a commercial EM Simulator [21] and validated with the measured results.

Fig. 3 shows the measured and simulated magnitude of the reflection coefficient (S_{11}) of the unloaded circular monopole antenna with design parameters presented in Table I. As can be seen from the figure, the simple CPW fed circular monopole without any SRR loading operates from 2.6 GHz to 10.8 GHz with resonance dip around 3 GHz corresponding to a quarter wavelength of the disc diameter. Subsequent resonance dips around 6 GHz and 9 GHz correspond to the higher order harmonics of the fundamental mode. Good agreement between the measured and simulated plots is envisaged from the figure. Fig. 4 compares the measured and simulated S_{11} of the SRR loaded circular monopole antenna. These SRRs are placed symmetrically on back side of the CPW fed planar monopole antenna with their axes coinciding with the slot between the signal line and ground planes of the CPW. The propagating EM signal excites the SRRs thereby prohibiting radiation around the SRR's resonance and hence yielding a notch in that frequency. For the SRR with dimensions as provided in Table I, a notch is obtained in the reflection coefficient at around 6.38 GHz for simulated and 6.39 GHz for measured results as shown in Fig. 4. This notch frequency corresponds to the resonance frequency of the printed SRR. The SRR's resonance frequency is determined and controlled by the geometrical dimension of the SRR and the material constitutive parameters of the host substrate. Ideally, the SRR axis should coincide with the centre of the two slots of the CPW for optimum coupling. The measured values of the first higher order resonance of the monopole

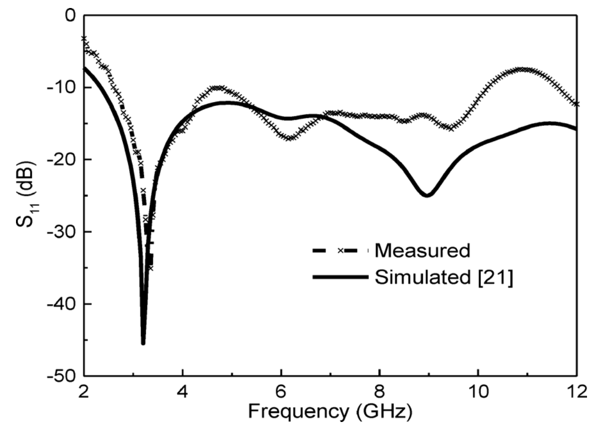

Fig. 3. Simulated and measured S_{11} characteristics of the fabricated prototype without SRR loading. Parameters as given in Table I (ignoring SRR parameters).

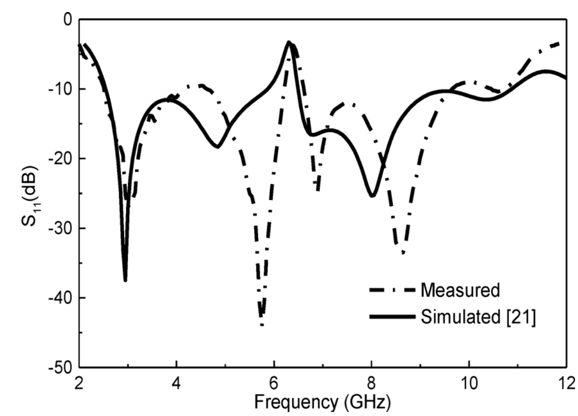

Fig. 4. Simulated and measured S_{11} characteristics of the fabricated prototype with SRR loading. Parameters as given in Table I.

antenna at around 5.9 GHz in both Figs. 3 and 4 show better impedance matching compared to the simulated values. The inclusion of SRRs enhances the impedance matching further as is evident from Fig. 4. This could be attributed to the coupling of the SRRs with the transmission line. The simulation plots in both the figures show reasonably good match with VSWR well below 2, which is acceptable for antenna applications. The impedance matching could be improved further with a choice of finer mesh size in the simulator but with the cost of higher computational overhead. The resonance frequency of the SRR is calculated using the design formulation proposed in Section III. The calculated inductance L_T and per unit length capacitance C_{pul} for the fabricated prototype of the SRRs having $a_{ext} = 2.5$ mm, $t_m = 35$ μm, $c = 0.35$ mm, $d = 0.6$ mm and $g = 0.7$ mm are 9.82 nH and 19.49 pF, respectively. This yields a theoretically resonance frequency of 6.28 GHz computed using (1), corresponding well with the measured and simulated values of 6.39 GHz and 6.38 GHz, respectively.

The radiation characteristic of the fabricated prototype was measured in a fully calibrated anechoic chamber with the antenna placed on an antenna mount as shown in Fig. 5. A part of the cable attached to the antenna was covered with ferrite rings to avoid unwanted currents on the exterior of the feed cable, which can significantly distort the back radiation of the antenna. A broadband pre-amplifier (Agilent 83051A) was used at the

Fig. 5. Fabricated prototype mounted in the anechoic chamber with cable covered with ferrite rings.

port feeding the transmitting broadband horn antenna during radiation pattern measurement. The measured and simulated radiation patterns in the $x-y$-plane and $x-z$-plane for the CPW fed planar monopole with SRR loading are presented in Fig. 6 for 3.1 GHz, 6 GHz and 10 GHz. The radiation patterns show good directive patterns for the $x-y$ –plane and omni directional pattern for the $x-z$-plane. The correspondence between the simulated and measured patterns in the $x-y$–plane from 0° to 180° is quite good. The measured and simulated peak gain values versus frequency of the SRR loaded prototype are illustrated in Fig. 7. The plot shows a reduction in gain at the notch frequency of operation whereas the gain for the rest of the band remains acceptable. The measured results yield a gain of -7 dBi at 6.39 GHz, whereas the simulated result yields a reduced gain of -8 dBi at the notch frequency of 6.38 GHz. The radiation efficiency was measured using the Wheeler cap method at 3.1 GHz, 6 GHz and 10 GHz using three different metallic enclosures of radiansphere dimensions. The results yielded around 92% efficiency at 3.1 GHz, 89% efficiency at 6 GHz and 86% at 10 GHz with an average error of 2%. The simulated efficiency calculated using HFSS yielded 96.1%, 91% and 90.6% at 3.1 GHz, 6 GHz and 10 GHz, respectively. The results indicate unperturbed antenna performance outside the resonance frequency of the SRR and very weak radiation at the resonance frequency of the SRR.

In Figs. 8 and 9, the control of the notch frequency by varying a_{ext} and g is demonstrated. Fig. 8 shows the simulated S_{11} characteristics for two different a_{ext} values of 2.2 mm and 2.6 mm yielding notch frequencies of 6.35 GHz and 4.8 GHz, respectively. With the increase in a_{ext} values, the total inductance L_T and the capacitance of the structure increase which in turn decreases the resonance frequency of the structure. Varying a_{ext} can be used as a variation parameter for wide range tuning of the notch frequency. Furthermore, Fig. 9 shows the simulated S_{11} characteristics for three different split gap dimension g values of 0.2 mm, 0.3 mm and 0.4 mm yielding notch frequencies of 4.3 GHz, 4.45 GHz and 4.8 GHz, respectively. The increase in g contributes to a slight decrease in the total inductance of the structure and the gap capacitance, which causes a shift in the resonance frequency of the SRR. Thus, the gap, g can be used as a tunable parameter for determining the notch frequency of the antenna. Multiple resonance frequency with multiple pairs of SRR loading with varying geometrical dimensions can be employed to achieve multi notch characteristics in the antenna design.

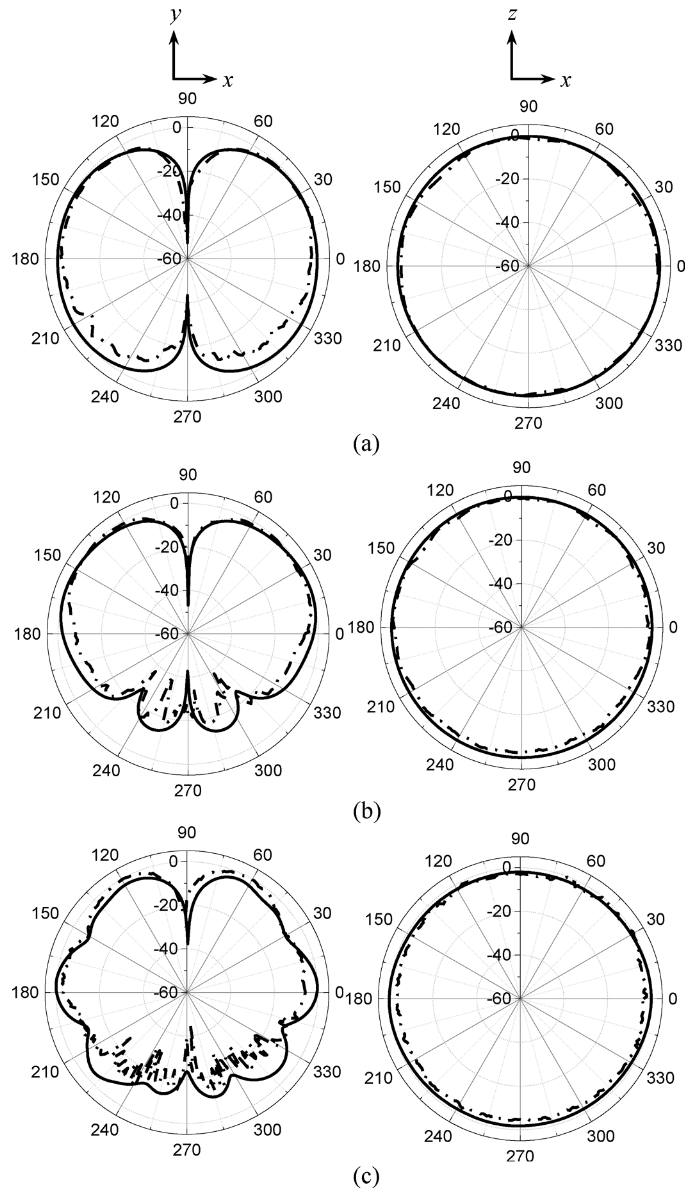

Fig. 6. Measured and simulated radiation patterns for $x-y$ plane (E-plane) and $x-z$ plane (H-plane) of the fabricated antenna, (Parameters as in Table I) for three different frequencies: (a) 3.1 GHz, (b) 6 GHz, (c) 10 GHz. (– · – · – [Measured], ——— [Simulated]).

The simulated surface current distribution at three different frequencies, 6.38 GHz, 3.1 GHz and 10 GHz of operation is shown in Fig. 10. It is clearly visible that at the frequency of interest that is at 6.38 GHz, corresponding to the resonance frequency of the SRR, the circular monopole is not excited resulting in suppression of radiation at that frequency.

V. Conclusion

A compact CPW fed circular monopole with an SRR with a frequency notch characteristic is proposed. The configuration

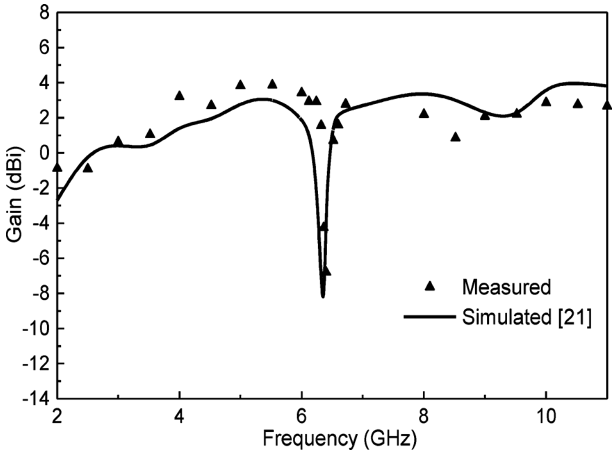

Fig. 7. Measured and simulated gain characteristics of the fabricated prototype with SRR loading. (Parameters as in Table I).

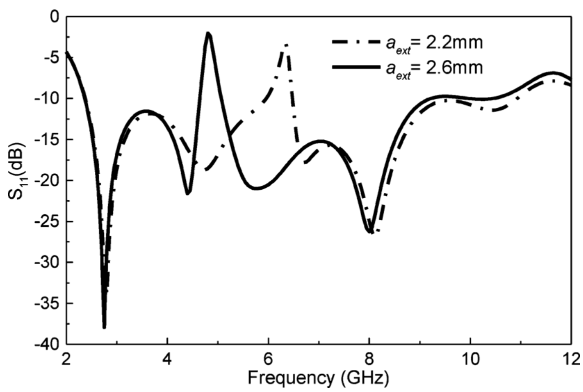

Fig. 8. Simulated S_{11} characteristic of the SRR loaded CPW fed UWB circular monopole antenna for different a_{ext} values. $c = 0.35$ mm, $d = 0.3$ mm, $g = 0.4$ mm, $h = 1.575$ mm, $\varepsilon_r = 2.33$.

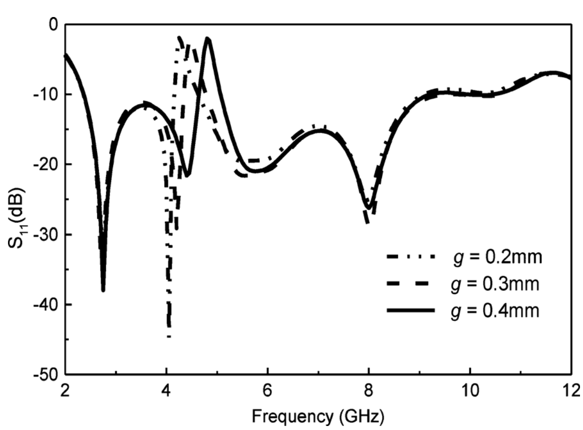

Fig. 9. Simulated S_{11} characteristic of the SRR loaded CPW fed UWB circular monopole antenna for different split gap dimension, $g\ (= g_1 = g_2)$, values. $a_{ext} = 2.6$ mm, $c = 0.35$ mm, $d = 0.3$ mm, $h = 1.575$ mm, $\varepsilon_r = 2.33$.

works with precise positioning of the SRR on the back side of the CPW. This design does not physically perturb the radiator or the ground plane. The electromagnetic coupling between the CPW and the SRR at the SRR's resonance frequency yields the desired notch. Since the antenna design and the SRR dimensions are independent of each other, the notch frequency can be customized to the desired value by changing the SRR dimensions.

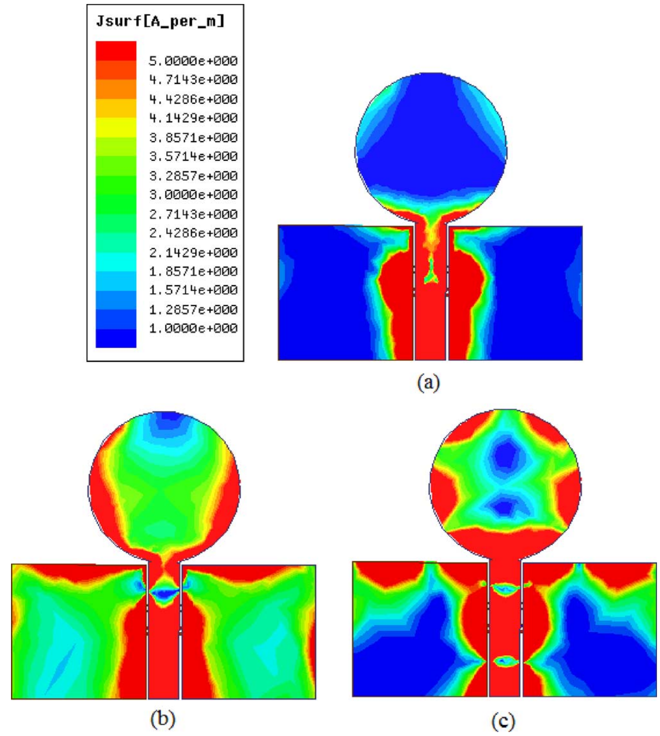

Fig. 10. Simulated surface current distribution of the CPW fed circular monopole with SRR loading (a) 6.38 GHz , (b) 3.1 GHz, and (c) 10 GHz (Parameters as in Table I).

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