Circular Split Ring Resonator (C-SRR) Array Integrated Frequency-Notched Horn-Filtenna With Wide and Strong Rejection Band

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ABSTRACT Linear-array of circular split ring resonators (C-SRR) integrated wideband notched filtering horn antenna with very strong rejection-band is proposed in this article. The linear C-SRR array, consisting of 3-sub arrays each having 4 identical C-SRR-elements, is printed on a dielectric substrate and is integrated into the throat or waveguide-section of the standard X-band horn (Narada 641). Staggered arrangement of the multiple C-SRRs based in-line filter contributes to the wideband notch filtering response with measured rejection band ($S_{11} < 3\text{-}dB$) of 315 MHz in proposed horn-filtenna. The realized horn-filtenna yields co- and cross-polar peak gain suppression of 35.42 dB and 24.6 dB at and around the centre of notch-band (9.8 GHz) while at the pass band of the C-SRR filter, the proposed antenna inherits the impedance and radiation characteristics of the standalone horn antenna. The proposed technique is simple, easy to integrate and can be used to eliminate adjacent band noise/interference for faithful reception of data without using any additional filter section.

INDEX TERMS Split ring resonator (SRR), horn, filtenna, frequency notch, co- and cross-polar gain.

I. INTRODUCTION Mitigation of noises and/or interferences from adjacent channels/bands is one of the key requirements in any practical receiving system for improved efficiency, increased signal-to-noise ratio and overall performance. Frequency-notched wide/UltraWide Band (UWB) antenna, thanks to its in-built notch-filtering functionality, is a potent solution for this purpose [1], [2]. Various notchting techniques, such as, i) employing shaped slots, ii) embedding parasitic resonators adjacent to the radiators, iii) integrating (SRR) along the feedline, and iv) combination of (i)-(iii), have been adopted over last few years to realize single/multi-notched UWB antenn [3]–[16]. Most of these designs use printed monopole as the reference radiator for realizing frequency notched UWB response [3]–[7]. Frequency notched antennas with horn and tapered slot as the radiator is proposed in [12]–[17]. A substrate-integrated waveguide cavity based horn filtenna with integrated filtering response is demonstrated in [6].

Horn antennas of various families and its planar version, tapered slot antenna (TSA), are an attractive choice as receiving antenna elements due to high gain, directional nature along with wide operating bandwidth. Horn antenna also severs as the key element in, i) point-to-point communication, ii) satellite and radar communication, and iii) feed-element of reflector antenna in the receiving station. Block diagram of ground station receiver system is shown in figure 1. Performances of the receiver in most of our practical communication systems are often affected by broadband co- and adjacent channel interfering signals. To eliminate these interferences a filtering-section can be deployed in the front end of the communication system. Such filtering sections are normally placed before the Low Noise Amplifier (LNA) to ensure that undesired inter-modulation products do not populate the desired spectrum. Moreover, such arrangement protects the LNA from getting saturated /damaged due to strong out-of-band interfering signal. Conventional design of such receiver front-end can be made more simplified by integrating the antenna and filter section in a single module, named as filtenna. Such arrangement also eliminates the need of separate...
In this paper, a horn-filtenna with integrated frequency notch characteristics having a wide rejection band of 315 MHz with very strong suppression of both co- and cross-polar gain in the notch-band is proposed. As shown in Fig. 2, a linear C-SRR array, consisting of 3-subarrays each having four identical elements and embedded in the throat-region of a standard gain horn (NARDA 641), contributes to the wide rejection band with notched-band peak gain suppression of 35.42 dB, and 24.6 dB for co- and cross-polar radiation respectively. The dimensions of the C-SRRs are varied slightly to achieve little varied resonance frequency, which in turn yields a wider rejection band. Since the C-SRR section is integrated near the throat i.e. W/G section of the horn, the proposed horn-filtenna contributes almost unperturbed radiation over its impedance bandwidth excepting the desired notched band. Main contribution of the article can be summarized as,

i. realization of a band notched horn filtenna with wide and strong rejection band using C-SRRs of varying dimension is sub-arrayed configuration

ii. systematic design and finalization involving computation, analysis, simulation and experimental verification for the finalized prototype

Moreover, the proposed concept can be easily extended and extrapolated to any other bands and/or horn antenna(s) of other types for suppressing the adjacent channel noise/interference. The rest of the paper is organized as follows: Section 2 describes the filtering response of C-SRR array, loaded inside the rectangular waveguide. Simulated and measured impedance and radiation characteristics of the proposed horn-filtenna are discussed in Section 3. Conclusions are presented in Section 4.

II. DESIGN OF C-SRR INTEGRATED WAVEGUIDE FILTER

Figure 1(a) shows the schematic diagram of the proposed frequency-notched horn filtenna. A linear C-SRR array comprising 3-sub arrays, each having four identical C-SRR elements, is printed on Rogers-5870 laminate ($\varepsilon_r = 2.33$, tan $\delta = 0.0012$) having an overall dimension of $68 \times 12.62 \times 0.508 \text{ mm}^3$ and later on integrated in the throat of the horn antenna. Choice on the number of sub-arrays, C-SRR elements in the sub-arrays and the dimension of the C-SRRs are optimally decided based on, i) centre frequency in the rejection band, ii) rejection bandwidth and iii) amount of gain suppression targeted by the in-line filter when integrated with the horn antenna. Fig. 1(b) and (c) shows the detailed geometrical parameters of the individual C-SRR-elements. To verify the performance of the C-SRR filter and ensure an optimal design, the same is loaded (parallel to the narrow wall of the W/G and perpendicular to the broad-wall of the WG) along a rectangular W/G excited in its dominant TE10-mode. Such arrangement constitutes a waveguide based frequency notched filter [18]–[21]. The C-SRR, thanks to its magnetic resonance frequency, contributes to a strong rejection band around its resonance frequency.
A. DETERMINING DIMENSION OF C-SRR

Dimension of C-SRR array in the proposed notched horn filtenna is determined based on theoretical estimation of C-SRR resonance frequency originally proposed in [21], followed by verification through eigen-mode solver of Ansys High Frequency Structure Simulator (HFSS) [22]. Resonance frequency of the C-SRR yielding the notch at its resonance, using the closed form expressions can be expressed as,

\[
   f_{0-CSSR} = \frac{1}{2\pi \sqrt{L_T C_{eq}}}
\]

where \( L_T \) is the total inductance of the C-SRR structure and \( C_{eq} \) is the total equivalent capacitance of the structure. This total equivalent capacitance \( C_{eq} \) can be evaluated as in [3] and [20],

\[
   C_{eq} = \frac{C_0 + C_g}{2}
\]

where, \( C_g \) indicates the gap capacitance in the C-SRR. \( C_1 = C_2 = C_0 \) indicates the distributed series capacitance [20].

The gap capacitance can be approximately represented as,

\[
   C_g = \frac{\varepsilon_0 c t}{g}
\]

where \( t \) is the metal thickness of the strip conductor. The distributed capacitance \( C_1 = C_2 = C_0 \) are also function of the split-gap dimension \( g \) and the average ring radius \( r_{avg} \) and is governed by,

\[
   C_0 = \frac{\pi r_{avg} - g}{C_{pul}}
\]

and \( C_{pul} \) is the per unit length capacitance and is calculated as [3] and [20],

\[
   C_{pul} = \sqrt{\varepsilon_r C_0 Z_0}
\]

where \( c_0 \) is the velocity of light in free space and \( Z_0 \) is the characteristic impedance of the line given as in [23].

\[
   f_{0-CSSR} = \frac{1}{2\pi \sqrt{L_T C_{eq}}}
   = \frac{1}{2\pi \sqrt{L_T \left[ \frac{1}{2} \pi r_{avg} - g C_{pul} + \frac{\varepsilon_0 c t}{2 g} \right]}}
\]

where, the total equivalent inductance \( L_T \) is governed by [24], and \( L_T \) is the total equivalent capacitance governed by [24].

\[
   L_T = 0.0002 l (2.303 \log_{10} \frac{4l}{c} - \gamma) \mu H
\]

where, the constant \( \gamma = 2.451 \) for a circular loop. The evaluation of the wire length \( l \) is straight forward and given by,

\[
   l = 2\pi r_{ext} - g
\]

B. C-SRR BASED WIDEBAND NOTCHED RESPONSE

Using the closed form expression of (3), outer radius of the C-SRR are gradually changed with subtle variation keeping all other geometrical parameters (\( c_1 = 0.5 \text{ mm} \), \( d_1 = 0.2 \text{ mm} \) and \( g_1 = 0.2 \text{ mm} \)) of the C-SRR unaltered to achieve three close-by resonances which effectively contributes to a wideband notch. As indicated in Table-1, the theoretically obtained resonance frequency is in good match with the resonance frequency obtained from HFSS eigen-mode solver [22]. Further, to enhance the strength of frequency notches a staggered arrangement of these C-SRRs having four elements of each of the three C-SRRs, totaling \( 3 \times 4 = 12 \), C-SRRs are printed on a dielectric substrate. The subtle variation in the analytically estimated resonance frequency with that of practically measured notch frequencies can be attributed to, i) edge/diffraction effect in the finite array, ii) fabrication tolerance and iii) assembly tolerance while affixing the SRR-strip in the throat of the horn.

Figure 3 shows the simulated \( S_{11} \) and \( S_{21} \) response of the C-SRR loaded W/G-filter with an inset diagram, clearly indicating the positioning and resonance-excitation of the SRR with axial magnetic field (\( H \)) and SRR-gap-oriented electric field (\( E \)). The axial magnetic field in SRR produces magnetic flux which induces an oscillating current yielding a strong magnetic resonance. As revealed from the simulated reflection and transmission coefficient plots, the proposed C-SRR loaded waveguide filter exhibits a very strong rejection band with \( S_{21} < -60 \text{ dB} \) for \( f = 9.62 \text{ GHz} \) to 9.87 GHz. This strong wideband rejection is due to the multiple resonances of three different sub-arrays with varying \( r_{ext} \) values. It can also be noted from the plot of Fig. 3, that the realized WG based C-SRR filter exhibits very low pass-band loss (less than 1.8 dB) and sharp transition from pass-band to stop band. The rejection band of the proposed SRR filter can be tuned to any desired frequency by changing the SRR dimensions.

III. REALIZATION OF C-SRR-BASED FILTENNA

The C-SRR array based notched-filter is integrated in a commercial X-band dual exponentially tapered horn antenna (Narada 641) having dimension, \( a = 28.5 \text{ mm} \),
TABLE 1. Comparison of resonance frequency of C-SRR $f_{0C-SRR}$ (GHz)

| $r_{ext}$ (mm) | Resonance Frequency $f_{0C-SRR}$ (GHz) |
|---------------|--------------------------------------|
| 1.86          | 10                                    | 9.91       |
| 1.88          | 9.84                                  | 9.74       |
| 1.9           | 9.66                                  | 9.54       |

FIGURE 4. Gain vs frequency characteristics for different SRR loading with different set of sub arrays ($3 \times 1, 3 \times 2, 3 \times 3, 3 \times 4$) and compared with unloaded structure for wide band of frequency.

$\frac{b}{a} = 12.62 \text{ mm}, a_1 = 97.2 \text{ mm}, b_1 = 72.8 \text{ mm} \text{ and } L = 160.2 \text{ mm}$. This standard horn, having a square flange with WR112 standard dimension, is connected to waveguide to co-axial adaptor, with identical WR112 flange to excite the horn. The proposed C-SRR loaded horn filtenna is designed and simulated in Ansys HFSS [22].

C-SRRs of varying dimensions ($r_{ext} = 1.86, 1.88$ and $1.9$ mm, keeping $c = 0.5$ mm, $d = 0.2$ mm and $g = 0.2$ mm) are deployed in sub-arrayed configuration to activate multiple resonances with nearby resonance frequency, which in turn contributes to a wideband rejection. Total number of sub-arrays and number of C-SRR elements in these sub-arrays along with the dimension of C-SRR elements are decided through systematic theoretical computation and EM simulation targeting for a wideband rejection with highly suppressed gain over the entire notch band. Figure 4 shows simulated maximum realized gain of the proposed horn filtenna for various combination of C-SRR loading (no loading, $3 \times 1, 3 \times 2, 3 \times 3$ and $3 \times 4$). As indicated in Fig. 4, with increase in the number of C-SRR elements in each sub-array, peak gain of the antenna is more suppressed in the notch-band while the gain outside the notch band is minimally impacted. After systematic investigation, case-iv, with $3 \times 4 = 12$ C-SRRs loading, is used in present design. As the C-SRR array comprises sub-wavelength resonators, the overall dimension of the CSRR filter section is still quite compact ($6.61 \text{ cm} \times 1.26 \text{ cm} \times 0.0508 \text{ cm}$). Moreover, since the CSRR filter section is integrated in the throat region of the horn, antenna radiation aperture is not directly impacted. For practical measurement, the fabricated C-SRR filter is precisely integrated in to the throat region of the horn. Since width of the SRR strip is same as that of W/G narrow dimension ($b$) of the horn, the SRR strip got affixed without much mechanical difficulty. To ensure precise positioning without any undesired tilting especially for radiation pattern measurement, index matched glue was applied for affixing the C-SRR filter. After affixing C-SRR inside throat region of the horn, a waveguide to coaxial adaptor (WCA) is connected to the horn. Standard horn and WCA are connected using screws inside the flange holes. SMA coaxial cable is connected to WCA for further measurements.

Figure 5 shows the simulated and measured $S_{11}$ characteristics of the proposed horn antenna with and without C-SRR loaded filter-section. The standalone horn antenna exhibits very good matching for the entire frequency range ($S_{11}$ below $-15$ dB for the entire frequency range of 7.5 to 10.2 GHz). The same antenna when loaded with C-SRR
filter, exhibits a wideband frequency-notched response with very good overall correspondence between simulated and measured $S_{11}$ plots. As indicated in the plots, the obtained notch-band is very strong with simulated $S_{11}$ stronger than $-1\,\text{dB}$ for the most of notched-band. The measured $-3\,\text{dB}$ rejection band, as revealed from the plot, is $315\,\text{MHz}$ spanning from $9.635\,\text{GHz}$ to $9.95\,\text{GHz}$. The radiation pattern measurement of C-SRR based filter integrated horn is carried out at Compact Antenna Test Facility (CATF). As shown in Fig. 6, filter integrated horn mounted on a circular zig acts as the receiving antenna while electromagnetic signal is transmitted by a standard source and reflected by the CATF reflector to generate parallel ray in the horn mounting plane. The measurement set up is very accurate and quiet zone of the CATF range is having amplitude imbalance lesser than $0.5\,\text{dB}$. Proposed frequency notched horn is moved horizontally to get E-plane pattern and moved vertically to get H-plane pattern. Four sets of measurement are carried out for each frequency and each radiation plane; i) standard gain horn co-pol pattern without SRR, ii) standard gain horn co-pol pattern with integrated C-SRR filter, iii) standard gain horn cross-pol pattern without SRR, and iv) standard gain horn cross-pol pattern with integrated C-SRR filter.

Figure 7 shows the measured normalized E- and H-plane co- and cross-polar pattern of the proposed horn antenna with and without the C-SRR based notched filter section at $9.2\,\text{GHz}$, $9.4\,\text{GHz}$ and $10.05\,\text{GHz}$, respectively, all selected in the pass-band of the filter. As can be noted from the plot, filter integrated antenna exhibits almost identical pattern as that of standalone antenna at $9.2$ and $9.4\,\text{GHz}$ while at $10.05\,\text{GHz}$ a slight fall in gain, close to $1.5\,\text{dB}$ is observed.

| Ref. | Notching technique used | Notch centre freq (GHz) | Notch BW ($S_{11}<-3\,\text{dB}$) (MHz) | Gain suppression |
|------|-------------------------|-------------------------|------------------------------------------|-----------------|
| [12] | Square split ring resonator | 9.84 | 220 | 25 dB |
| [12] | Two Square split ring resonator for dual band | 9.38 | 174 | 24.5 dB |
| [14] | Two open square rings (Position varied) | Tunable | 50 to 100 | 16 dB |
| [15] | Two quarter wavelength slots | 9.4 | 50 to 200 (for $S_{11}<10\,\text{dB}$) | Not mentioned |
| [16] | Open square ring Single square ring Multiple SRR | 10 10 10 | 310 220 140 | 22 dB 27 dB 24 dB |

**TABLE 2.** Comparison between proposed horn filtenna with existing frequency notched horn designs.
Such slight falls of gain in antennas with SRR integrated in the feed-line, is quite common and can be attributed to the post-resonance loss of the SRR [17]. To quantify the frequency notching performance of proposed C-SRR based horn filtenna, its radiation performance is further investigated at the centre of the notch-band (9.8 GHz) and is compared with the stand-alone antenna. As revealed in the plots of Fig. 8, the C-SRR loaded horn filtenna exhibits drastically reduced co- and cross-polarized gain both in E- and H-plane for the entire space angles over the stand-alone antenna.

The plots in Figure 9 shows maximum realized co- and cross-polar gain of the proposed C-SRR array loaded frequency-notched horn filtenna along with maximum realized gain of the antenna without the C-SRR filter section. As revealed from the plot, throughout the notch-band, proposed antenna yields a drastically reduced co- and cross-polar gain due to the C-SRR filter section while for rest of the band, proposed antenna exhibits gain-frequency profile almost identical to the stand-alone antenna. It can be noted that, at the centre of the notch-band (9.8 GHz), the antenna offers co- and cross-polar gain suppression of 35.42 dB and 24.6 dB respectively. TABLE-2 portrays a consolidated summary of the important figure of merits of various designs of frequency notched horn antennas available in open literature [12], [14]–[16], and that of the proposed horn-filtenna.

It can be noted that, SRR loaded techniques, thanks to high-Q resonance of the SRRs, contributes to much stronger notches over that obtained by other techniques. As clearly revealed from the TABLE-2, the obtained gain suppression of the proposed horn-filtenna is much higher than reported value of (23–25) dB in [12], and to the best of author’s knowledge it is not reported till date. Thus the advantages of the proposed work can be summarized below.

1) Higher gain suppression (more than 35 dB) is achieved with the proposed feed. This ensures attenuation of interfering signal and thereby restricting them to enter the channel.
2) Also, the bandwidth of the notch-band with 315 MHz measured rejection band, reported in this article, is higher than that of other techniques.
3) Since, the filter section design is independent of the radiator without adding any additional cost and constrain to the radiator, the proposed concept can be easily applied for horn antennas of other geometry/profile.
4) Moreover, the notch-band can be adjusted by using C-SRR of proper dimensions.

IV. STUDY OF DIFFERENT NON-IDEAL CASES AND TOLERANCE ANALYSIS

Study of different non ideal cases and assembly tolerance have been carried out and reported here. Insight on assembly tolerance of the C-SRR filter section is accomplished by performing a systematic study on impact of various practical issues, like, i) angular tilt while posting the CSRR filter section in the waveguide, ii) impact of air gap and iii) lateral offset and iv) longitudinal offset. Various cases of the practical tolerances are pictorially illustrated in Fig.10. Figure 11 plots the $S_{11}$ response of the proposed horn-filtenna for various cases of intrinsic tolerances. As it can be seen from the plot, the proposed design is not over sensitive to the assembly tolerance and yield reasonably good performance even with positional mismatch and air-gap etc. up to a certain level. However, some intrinsic minimal loss in gain of the SRR strip loaded horn filtenna, contributed by dielectric loss, conductor loss, imperfect assembling etc., might be unavoidable. Overall measured loss in the gain in the proposed design is less than 0.3 dB at mid frequency.
V. CONCLUSION
In this article, design and realization of C-SRR based frequency notched horn-filtenna is presented. Systematic studies and realization of the WG-based filter section, followed by the integration of the same in the throat region of a standard gain horn reveals a very strong rejection band of 315 MHz spanning from 9.635 GHz to 9.95 GHz. Proposed design is not over sensitive to the assembly tolerance and yields reasonably good performance even with positional mismatches like angular tilt, air gap etc. The proposed filtenna configuration is very simple and can be easily extended for various other practical horn antennas. Very strong and wide rejection band (315 MHz) and huge gain suppression in the notch band, 35.42 dB and 24.6 dB for co- and cross-polar radiation, of the proposed antenna can be extremely effective in satellite/wireless communication to eliminate interference from adjacent frequency band without using an additional filter section.

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