Progress In Electromagnetics Research M, Vol. 72, 97–104, 2018

Miniaturize Negative Index Metamaterial Structure Loaded Filtenna

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Abstract—In this article, a negative index metamaterial (NIM) superstrate is designed and cooperated with the filtenna to produce miniaturize communication front end for gain enhancement without any substantial increase in the profile of the whole structure. A finite array Double H Split Ring (DHSR) of 11×9 unit cells has been designed on a dielectric substrate to form the NIM metamaterial superstrate. The proposed superstrates and filtenna have an overall dimension of $0.67\lambda_o \times 0.54\lambda_o \times 1.19\lambda_o$ at 10.16 GHz with 10.6 dB total broadside gain in simulation and 9.8 dB in measurement at 10.22 GHz ($\lambda_o = 30$ mm). This miniaturized communication front end which consists of a filter, an antenna and a gain enhancer affords smaller size with the overall volume of $0.43\lambda_o^3$ in the context of using a metamaterial superstrate for gain enhancement reported in the earlier literature.

1. INTRODUCTION

Recently, the researchers are looking forward to the miniaturization and reliability of the communication front end. Radiating elements and filters are very important devices in most communication and radar systems. In those systems, filters are used to reject out-of-band noise and interference while conveying in band signals. Resonator filters based on the substrate integrated waveguide (SIW) [1], waveguide cavities [2], and dielectric resonators [3] are preferred over planar structures because of their lower insertion loss, which is the main factor that helps enhance the system efficiency.

One of the most assuring devices in order to achieve miniaturization is Substrate Integrated Waveguide (SIW) Technology. By utilizing rows of metallic vias built into a dielectric substrate that electrically connect two parallel metal plates, the SIW is realized similar to a waveguide structure [4]. The embedded laminated waveguide was the first generation of SIW structure fabricated using conventional Printed Circuit Board (PCB) [5]. Since the invention, a diversity of filters with varying topology have been created by using SIWs [6, 7] which are more compact than a conventional waveguide filter.

Conventionally, filters and antennas are integrated into a system by using standard 50 Ω ports between them such as coaxial connectors or transmission lines. However, bulkiness and difficulties in fabrication and incorporation with other electronic circuits are their major drawbacks. By integrating a filter and an antenna into an unseparated unit, the 50 Ω transition between the two structures is removed which contributes to a more compact and efficient system [8–10]. To realize smaller and efficient communication front end, radiating element is another important device that needs to be considered. Antennas with low profiles and small sizes are extremely needed for installation especially in military applications. Patch antennas are highly utilized in this application with their efficient broadband radiation, and they can work within close proximity of a ground plane. In addition, patch antennas have other attractive properties such as low cost, light weight and ease of fabrication.

Received 28 May 2018, Accepted 26 July 2018, Scheduled 21 August 2018

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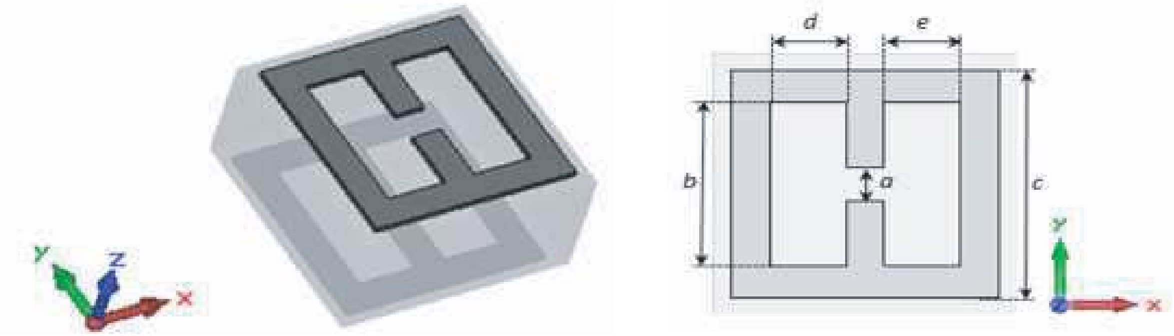
Several studies have initiated investigation on the possibility of enhancing the performance of patch antenna applications by incorporating metamaterial superstrate structures. Some of them are placed on top of the microstrip patch antenna [11] resulting in significant improvement of the directivity and gain of their antennas. At higher frequency, bigger dimension superstrates are also used to enhance the gain of the antenna, and size of the antenna is much smaller than the superstrates [12]. Unfortunately, the design method inevitably has enlarged the size of the communication front end.

In this article, our approach is to design a miniaturized communication front end that utilizes metamaterial structures loaded filtenna for X-band application. The miniaturization is achieved by using smaller overall lateral dimension of superstrate structures. The compact filtenna also contributes to the miniaturization of the overall module [13]. Besides using inseparable filter and antenna, a substrate integrated waveguide (SIW) bandpass filter is chosen due to its smaller size than conventional waveguide filter. In this work, a novel negative index superstrate using Double H-shape Ring (DHSR) unit cell is designed for gain enhancement of filtenna. The unit cell is designed to have negative refraction index at the resonance frequency of the filtenna. The designed superstrate along with the filtenna is numerically simulated and measured, and the effect of superstrate on gain, filtering response, and radiation pattern of the filtenna is investigated.

2. DESIGN METHODOLOGY

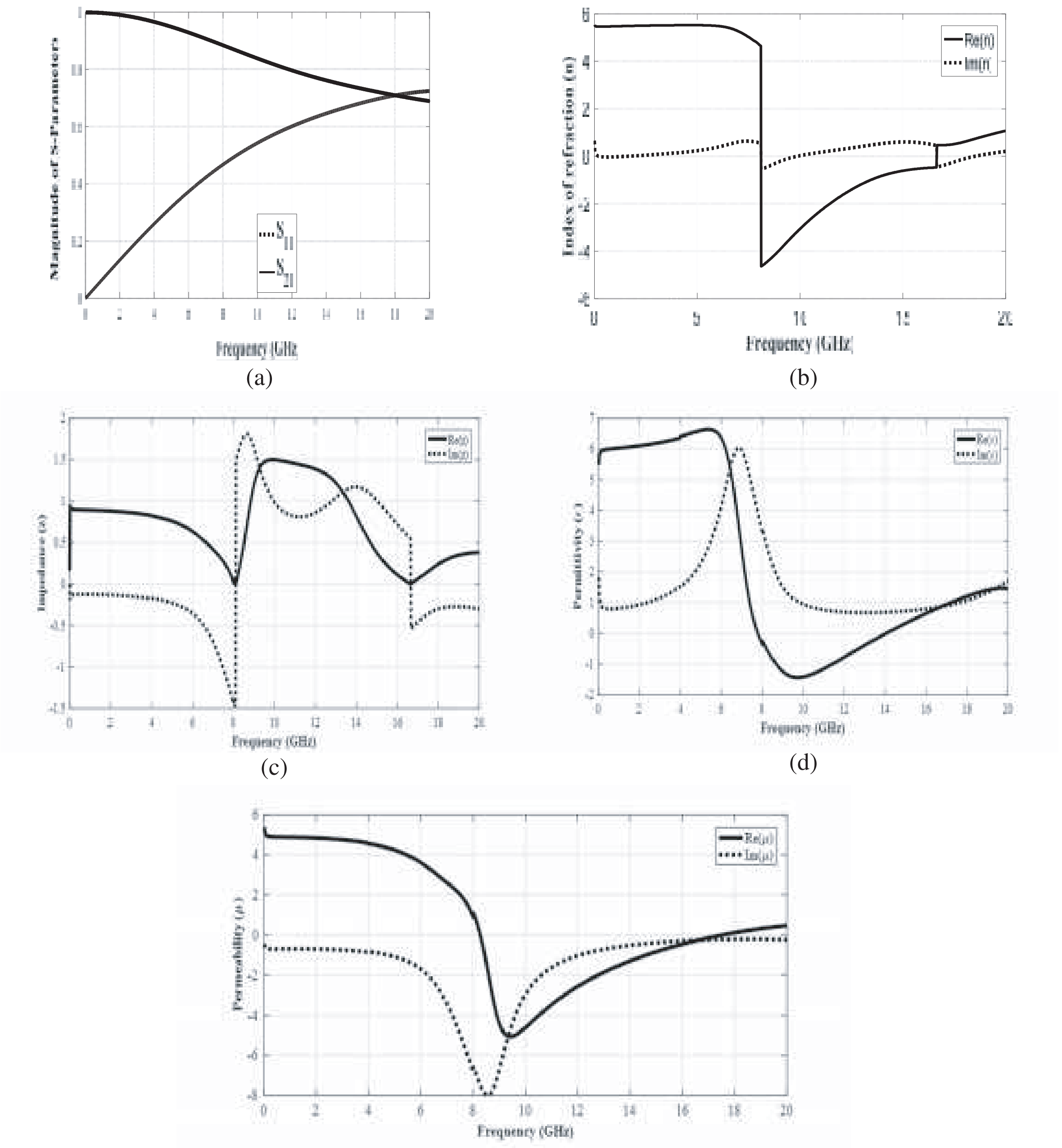
At this point, a unit cell of DHSR with negative effective permeability and negative effective permittivity is designed. An optimized dimension of the DHSR unit cell is designed in order to give both negative permeability and negative permittivity with a frequency range matched with the frequency response of the filtenna. This will enable the achievement of maximum beam focusing when an array of DHSR is incorporated with the filtenna. Each side of the DHSR unit cell is a copper layer with thickness t of 0.035 mm designed on both sides of a Rogers Duroid 5880 dielectric substrate with relative permittivity ε_r of 2.2 ($\tan\delta = 0.0009$) and thickness h of 0.787 mm. The DHSR unit cell is designed as in Figure 1 using the CST Microwave Studio [14] to have a negative refraction index at 10.16 GHz with dimension parameters $a = 0.2$ mm, $b = 1.0$ mm, $c = 1.4$ mm, $d = 0.4$ mm and $e = 0.4$ mm. The effective parameters of the DHSR unit cell are obtained by using boundary conditions where the electric field is polarized in y-direction and the magnetic field polarized in x-direction. Figures 2(a)–2(e) show the S-parameters, refractive index, impedance, permittivity and permeability of DHSR unit cell. The real part of refractive index, permeability and permittivity of the unit cell are negative within the operating frequency, 8–12 GHz. The predesigned DHSR unit cell structure is used to develop a periodic structure with lateral dimension equal to the lateral dimension of the filtenna with 20 mm × 16 mm, for miniaturization purposes. An array of 11×9 unit cells is constructed in a single layer metamaterial (MTM) superstrate.

A designed substrate integrated waveguide of three-pole cavity filtenna integrated in vertical orientation is chosen [13] due to its smaller footprint than the conventional waveguide filter. The structures of the filter are shown in Figure 4. The overall system has three resonators which consist



(a) (b)

Figure 1. Geometry of the proposed Negative Index Metamaterial (NIM) unit cell DHSR. (a) Perspective view and (b) top view.



(a) (b)

(c) (d)

(e)

Figure 2. Metamaterial unit cell performances. (a) S-parameter, (b) index of refraction, (c) impedance, (d) permittivity, (e) permeability.

of two cavity resonators and one resonant bow-tie patch antenna with the thicknesses of 1.567 mm and 0.787 mm, respectively. The sidewalls of resonator 1 and resonator 2 from the bottom of the designed are formed by closely-spaced metallic vias to form artificial waveguide also known as substrate integrated waveguide. The gap between the vias is $\sim$ 0.7 mm which is small enough compared to wavelength. The substrate used for all three layers is Roger RT/Duroid 5880 ($\varepsilon_r = 2.2$; $\tan\delta = 0.0009$). A bow-tie antenna is chosen which can be easily attached with the vertically stacked band-pass filter and also easy to fine tune to produce the expected result. The bow-tie antenna consists of three elements: a strip and two side wings of the bow-tie. This antenna is built on the 0.787 mm Rogers Duroid which also acts as a resonator.

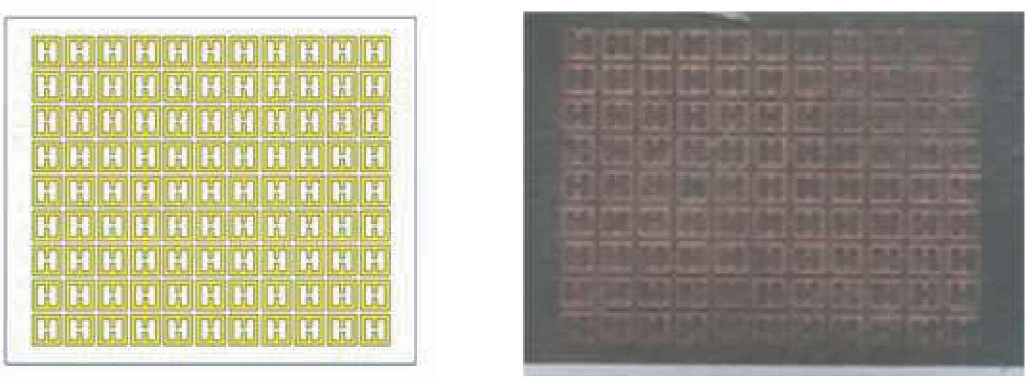
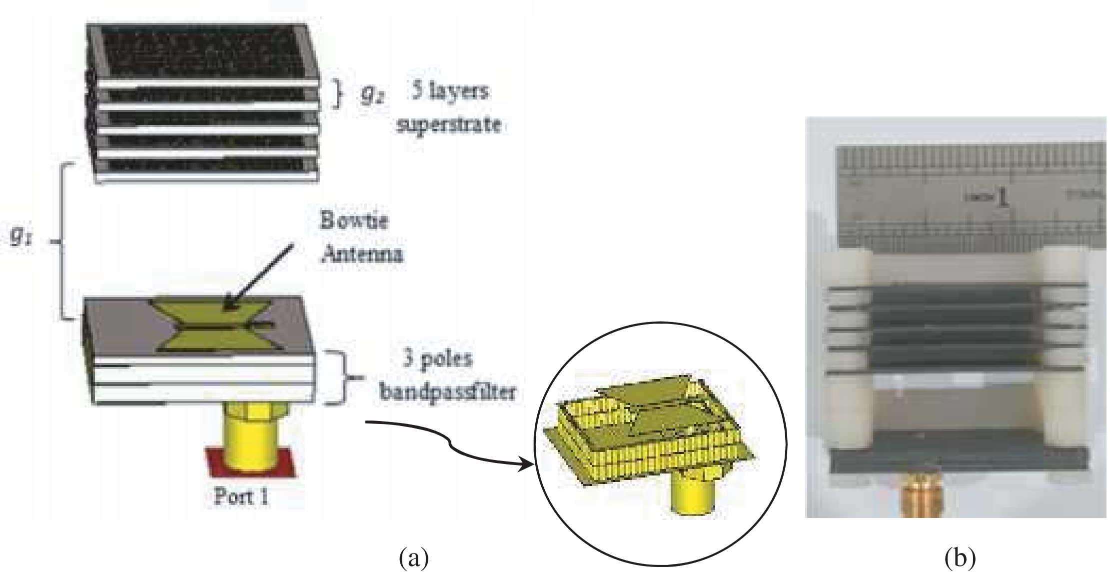

(a) (b)

Figure 3. Superstrate is composed of the 11 × 9 unit cells of the NIM DHSR. (a) Schematic of a superstrate. (b) Photograph of a superstrate.



(a) (b)

Figure 4. The structure of the proposed module. (a) Schematic of DHSR superstrate loaded filtenna. (b) Photograph of DHSR superstrate loaded filtenna.

3. METAMATERIAL SUPERSTRATE LOADED FILTENNA

A layer by layer NIM superstrate is incorporated with the designed filtenna to enhance the antenna gain of the broadside without affecting the filtering response. Each layer of the superstrate consists of 11 by 9 DHSR unit cells in x- and y-directions respectively as shown in Figure 3. The distances between the filtenna and the first superstrate layer and between the superstrates have been optimized to obtain an optimum filtenna response. The distance from the filtenna to the bottom copper of the first layer superstrate is $g_1 = 15\,\mathrm{mm}$ at $\lambda_o/2$, where λ_o is the free space wavelength at the resonance frequency of the filtenna. Different superstrate layers are separated with air gaps of $g_2 = 3\,\mathrm{mm}$. At this distance, the near-field coupling between the superstrate and filtenna is not significant. In addition, the effect of the MTM superstrate layers on the filtenna parameters have been studied, and the frequency response of the filtenna with a 5-layer superstrate is shown in Figure 5 and Figure 6. The capacitive and inductive couplings between H-rings periodic structures have significant effect on the filtenna input impedance that can vary the filtenna return loss, bandwidth and gain which is the main reason of the impact of MTM structure on the filtenna matching.

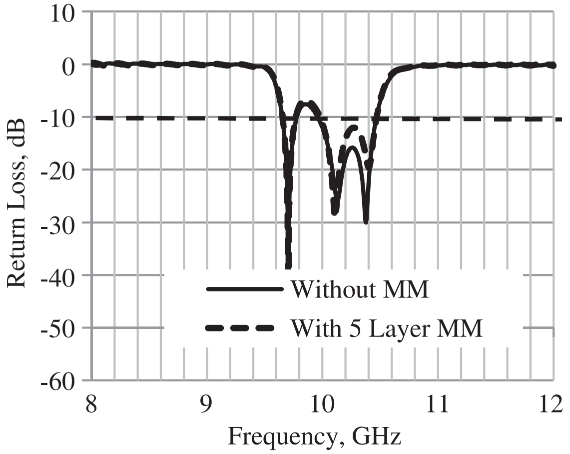


Figure 5. Return loss, S_{11} (dB) of filtenna without and with 5 layers superstrate.

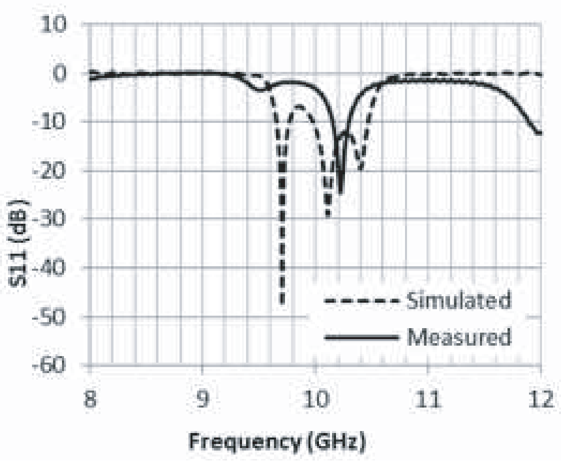


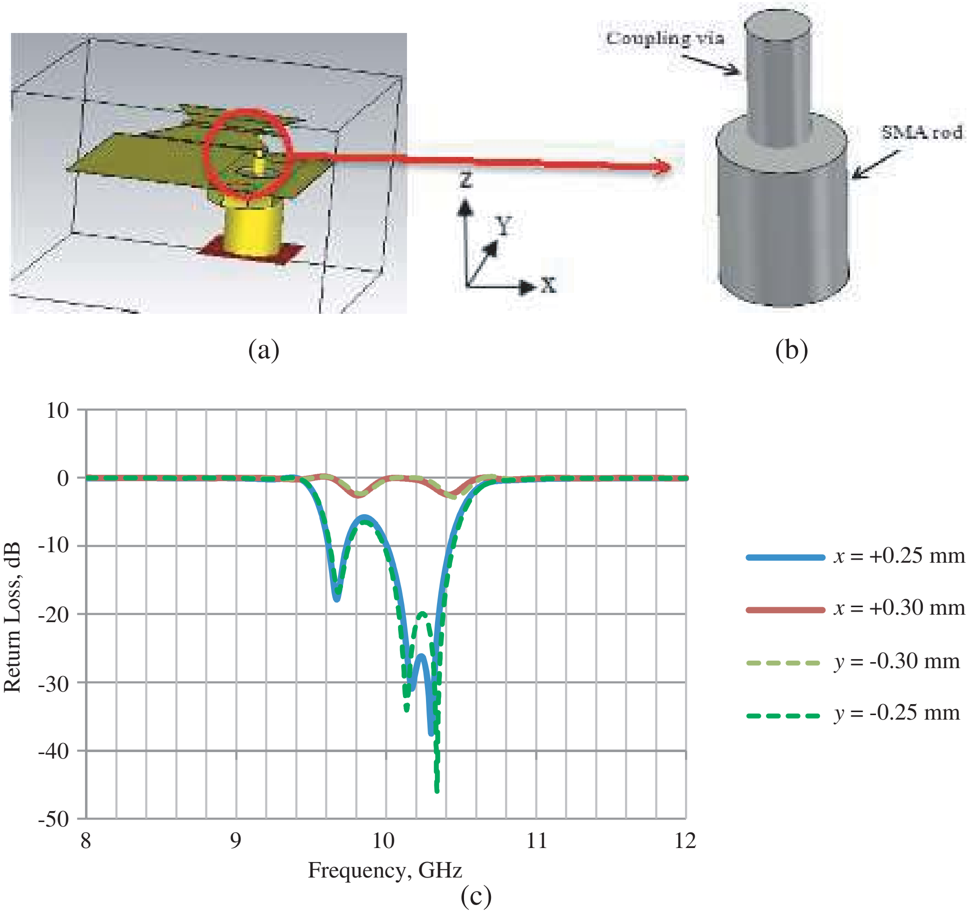
Figure 6. Return loss, S_{11} (dB) of filtenna with 5 layers superstrate.

Figure 5 shows the simulated frequency responses of the 3-pole bandpass filtenna $S_{11} = -29.2\,\mathrm{dB}$ at 10.16 GHz, and the bandwidth increases from 6.9% to 7.4% with the use of the 5-layer metamaterial superstrate. The shape of the 3-pole bandpass filter response is almost unchanged. The frequency response of the filtenna incorporated with the 5-layer superstrate is shown in Figure 6, where the solid and dashed lines denote the measured and simulated results, respectively. The resonance frequency varies between 10.16 GHz and 10.22 GHz in simulated and measured results with return losses −29.2 dB and −25.1 dB, respectively. There is a frequency shift in the responses of approximately 0.06 GHz between the simulated and measured responses. This is mostly due to the fabrication tolerances, and the tolerance in the dielectric constant of R/T Duroid 5880 is ±0.02 at 10 GHz.

Furthermore, the measured 3-pole bandpass filter responses have small deviations from the measured responses in each usage of different layers of superstrates. All deviations are due to manual mechanical assembly of three resonators and all layers of the superstrates. Asymmetric shape of the measured results indicates that the resonators do not resonate at the same frequency due to imperfect fabrication between coupling via and middle cavity. The coupling between the middle cavity and the antenna is realized by the coupling via short-ended with an SMA rod. The diameters of the coupling via and SMA rod are 0.627 mm and 1.16 mm, respectively, which are too small for manual assembling. Moreover, the coupling via is positioned almost 45 degrees from x-direction on the SMA rod which is not exactly at the center of the SMA rod as shown in Figure 7(a) and Figure 7(b). Frequency responses of random positions of coupling via on the SMA rod is shown in Figure 7(c), which shows that the position of the coupling via on the SMA rod is too sensitive to the overall frequency response. It also shows that the frequency response is changed drastically from optimized position to the positive x-directions compared to negative y-directions.

As the simulated and measured results revealed as shown in Figure 8 the 5 layers of superstrates show more significant anticipated improvement in gain than the filtenna without or with single superstrate. Since metamaterial is an artificially engineered material, the properties of the actual substrate can be manipulated. Metamaterial with negative refraction index is able to focus a diverging wave. An array of DHSR is able to focus details smaller than wavelength of light; therefore, combination of the two will enhance the gain. The optimized filtenna works at 10.16 GHz with a simulated gain of 10.6 dB, 3.39 dB higher than the original filtenna, and the corresponding measured gain for this antenna with a 5-layer superstrate at resonance is achieved as high as 9.8 dB. The overall gain for the filtenna with a 6-layer superstrate is decreased to 9.97 dB and 8.1 dB for simulated and measured results, respectively.

The radiation pattern for filtenna with and without 5-layer MTM superstrate for y-z plane (H-plane) and x-z plane (E-plane) is obtained by using CST Microwave Studio [14], and the radiation pattern measurement of the filtenna is carried out inside an anechoic chamber. The filtenna radiation patterns are plotted in Figures 9(a) and (b). It is shown clearly from the plot that loading the filtenna



(a) (b)

(c)

Figure 7. (a) The structure of the proposed module with hidden substrates and array of vias. (b) Enlarged view of coupling via and SMA rod. (c) Frequency response with various position of the coupling via on the SMA rod.

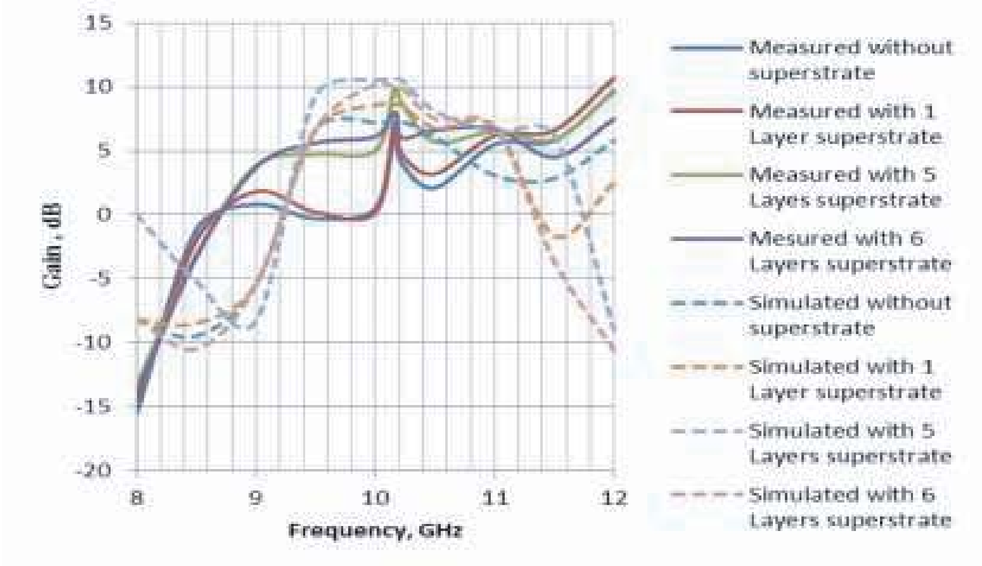
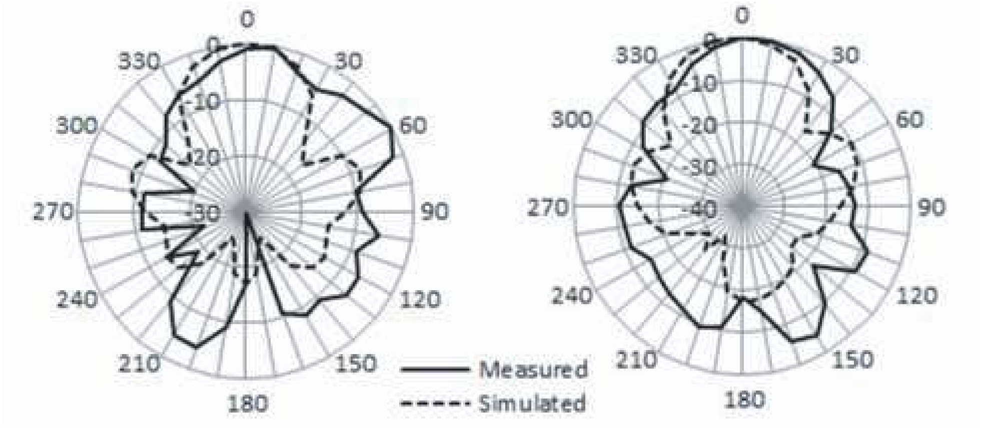


Figure 8. Gain for filtenna without superstrate and different layers of superstrate.



(a) (b)

Figure 9. Simulated and measured radiation pattern for the filtenna with 5 layers metamaterial superstrates: (a) E-plane (x-z), (b) H-plane (y-z).

with the NIM superstrate focuses the radiation beamwidth and thereby increases the filtenna directivity. According to the NIM property of the MTM layers, the radiated Electromagnetic (EM) Wave from the filtenna is focused, and the beam becomes more directive. Filtenna gain and directivity have also been improved, and filtenna radiated power is managed with a reduced beam area.

4. CONCLUSION

The miniaturized communication front end module which consists of a filter, an antenna and a gain enhancer is introduced. The performance of the filtenna is improved through the incorporation with negative index MTM structures. The overall size including the MTM structures is $0.67\lambda_o \times 0.54\lambda_o \times 1.19\lambda_o$ with overall volume of $0.43\lambda_o^3$. The miniaturization is realized via compact filtenna utilizing substrate integrated waveguide resonators and microstrip antenna. Unseparated filter and antenna by removing $50\,\Omega$ transmission line between them is the main contribution to its compactness. The 3-pole bandpass filtenna covered with the new design of negative index MTM superstrate having equal lateral dimensions with the filtenna is numerically investigated and compared to the filtenna without superstrate. It is shown that the 3-pole bandpass filtenna at resonance frequency has gain enhancement from 6.2 dB to 9.8 dB when 5 layers of metamaterial superstrate is placed on the top of the filtenna. The radiation pattern of the filtenna is more directive, and it shows that layers of superstrate act as a focusing device where the beam becomes narrower, and the gain is increased in nature.

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