Multiple Split Ring Resonator Inspired Dual Band Microstrip Patch Antenna Array

Chirag Arora[1], Shyam S. Pattnaik[2], R. N. Baral[3]

Abstract - **A shorted-pin, dual-band, metamaterial-inspired microstrip patch antenna array has been discussed in this paper. Under the unloaded conditions, the traditional patch antenna array resonates at 5.8 GHz with gain of 9.8 dBi and bandwidth of 540 MHz. However, when each patch of this traditional array is loaded with Multiple Split Ring Resonator (MSRR) and a metallic via hole is made on the patch, the same antenna array also produces an additional resonant frequency at IEEE 802.11 b/g/n 2.45 GHz Wi-Fi band with bandwidth and gain of 290 MHz and 5.7 dBi, respectively. However, the initial resonant frequency (i.e. 5.8 GHz) gets shifted to IEEE 802.11a 5 GHz Wi-Fi band, providing the gain and bandwidth of 11.2 dBi and 510 MHz, respectively. The proposed antenna array has been fabricated and measurements are done to validate the proposed array.**

Keywords - **Wi-Fi, MSRR, Permeability, Shorting pins.**

I. INTRODUCTION

In order to accomplish the demand of two most commonly used Wi-Fi bands, i.e. 802.11a 2.45 GHz and 5 GHz, a single, dual band antenna is desirable, as it squeeze the resonant dimensions of antenna. To achieve multi-band operation, several traditional approaches have been reported in the literature. These techniques include- introduction of perturbation by cutting slots into the radiator [1], using reconfigurable antennas [2], by truncating the ground plane [3], by stacking two structures together [4], by use of stubs [5] etc. Most of these techniques increase the size of antennas and make them bulky. In order to overcome the drawbacks, faced by using these conventional techniques, recently, due to their peculiar properties, antenna researchers worldwide have been attracted by the artificially engineered single/double negative metamaterials, also called zero index materials, for the size reduction and performance enhancement of antennas [6-18]. These artificial materials are characterized by either dispersion relations or by constitutive electromagnetic parameters. In 1968, Veselago, in his paper [19], first time gave the theoretical explanation on materials with simultaneous negative permittivity and permeability and also predicted some peculiar phenomena obtained from them. After a long time in 1990s, Pendry et al. demonstrated electric plasma (negative permittivity) from wire structures [20] and then magnetic plasma (negative permeability) from ring shaped structures [21]. In [22], Smith et al. were the first to experimentally demonstrate the double negative metamaterials.

Since then, due to their novel properties, these materials have been deeply studied as a potential artificial material for large number of applications in the microwave and optical region [23–24]. They exhibit unusual and useful phenomena due to their controllable electric and magnetic responses [19], as a result of which, by loading the conventional antennas with metamaterials, they are capable to match the impedance at frequency which is lower than the initial resonant frequency of their conventional counterparts, generate sub-wavelength resonances due to modifications of the modes, act as reflective surfaces etc. These interesting anomalous electromagnetic features result in size reduction and performance improvement of conventional antennas at no extra hardware cost and size.

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II. REVIEW OF PAST WORK

In the past literatures, various techniques to load the microstrip patch antennas with different types of metamaterials have been reported, which include use of Electromagnetic Band Gap (EBG) Structures [6-8], embedding single/double negative metamaterials with conventional antenna [8-12] or using them as superstrate/substrate [13-15] or by directly connecting them with traditional antennas [16-18].

In [6], B. P. Smyth et al. covered the conventional patch antenna with an EGB metamaterial. The proposed antenna provided the gain within 1 dB of the conventional antenna at 2.45 GHz, while at frequency of 5.2 GHz gain is 2.7 dB below the conventional patch antenna gain. Thus it is observed that the improvement in gain is not much significant. In [7], W. Cao et al. deigned an EBG based multi-frequency patch antenna. Three frequency modes, one with mono-pole pattern and two with patch antenna like radiation patterns, are obtained. However, the -10 dB bandwidth obtained in each mode is considerably low. J. G. Joshi et al., in [10], embedded the SRR into the slot of a slotted patch antenna to match the impedance at the desired frequency band. In [11], C. Arora et al. loaded the feed line of the patch antenna array with split ring resonators to enhance the bandwidth of its conventional counterpart. The same group, in [13], designed a metamaterial superstrate to improve the gain of patch antenna array. These artificially engineered materials can also be directly connected to the antenna for size reduction and enhancement of gain and bandwidth, like in [16], where M. Palandoken et al. directly connected the unit cell of left handed metamaterial to the dipole antenna to obtain the broadband performance and in [17], where G. Du et al. connected the modified S-shaped resonator directly to the monopole antenna to achieve the multiband operation. However, the gain obtained by this modified S-shaped resonator is lesser than 2 dBi at all the resonant frequencies.

III. Need for Problem Formulation

Though these metamaterial inspired single patch antenna provided considerable gain and bandwidth, however there are certain requirements, such as satellites, radars etc, where the performance obtained by single patch antenna is not sufficient to achieve the desired goal. In such cases, the arrays of antenna are used to achieve the desired antenna performance. But the arrays increase the physical dimensions of the radiator. Therefore, to minimize the size of antenna array, a method is to be devised in which an antenna array can provide high performance with requirement of minimum number of patch elements. Loading of metamaterials to the conventional microstrip patch antenna array is one such method where size reduction and performance improvement of antennas can be achieved at no extra hardware cost and size. However, to the best knowledge of the authors, till date, research has been limited to the metamaterial loading of the single patch and no much research has been conducted in the direction of loading the arrays by metamaterials. Therefore, to contribute in this region, in [11-15], authors have integrated the metamaterials to the conventional patch antenna arrays in various ways, for their performance improvement such as, by using them as superstrates. However, this technique improves the performance of the antenna array, but destroys the planarity of the array structure.

To cope-up with this situation, in this paper, authors have directly connected an MSRR to each patch of a conventional 4-element microstrip patch antenna array to obtain dual band operation at IEEE 802.11a 5 GHz and IEEE 802.11b/g/n 2.45 GHz Wi-Fi band, with considerable gain and bandwidth while maintaining the size and planarity of the proposed antenna array same as that of its conventional counterpart. A metallic via hole is introduced on each patch to tune the resonant frequency. This dual band behaviour results in the size reduction of the proposed antenna array, apart from its performance improvement.

As compared to some latest published literature [7, 10, 17], the proposed antenna array is novel because this MSRR loaded antenna achieved considerable gain enhancement and size miniaturization without any extra hardware cost and size, in contrast to its conventional counterpart. Moreover, the two-dimensional structural planarity of the antenna array is maintained, thus providing the ease to integrate it with various communication devices.

This communication is organized into eight different sections. Introduction, literature review and need for problem formulation are discussed in first three sections of the paper. The detailed geometrical structure and design of conventional and proposed antenna array is presented in section IV. In section V, the measured and simulated results of conventional and proposed antenna array are presented and analyzed. Characterization of metamaterial unit cell using effective medium theory is done in section VI. Analytical analysis of the proposed antenna array is presented in section VII. Finally, the paper is concluded in section VIII.

IV. Antenna Array Design

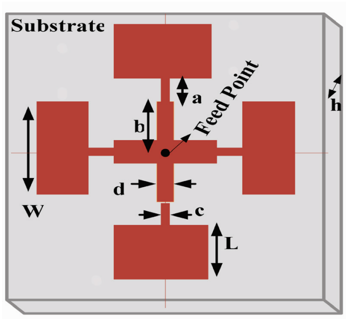


Fig. 1. Four element conventional microstrip patch antenna array

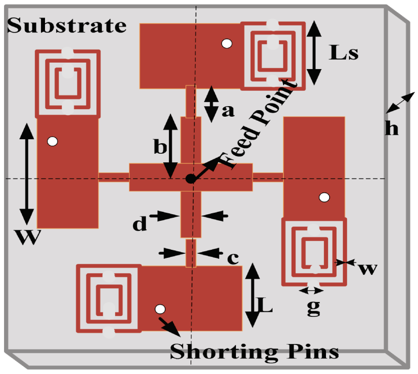


Fig. 2. Geometric sketch of MSRR loaded shorted- pin dual band antenna array

Fig. 1 presents the geometrical structure of a probe fed conventional 4-element microstrip patch antenna array and fig 2 shows the proposed dual band, MSRR loaded shorted-pin, microstrip patch antenna array. Initially, the array is designed to resonate at 5.8 GHz. The length (L) and width (W) of the patch required to produce this resonant frequency is calculated using Eqs. (1) and (2) [25-26]

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r + 1}{2}}}, \quad (1)$$

$$L = L_{eff} - 2\Delta L, \quad (2)$$

where, $L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}}$,

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)},$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}},$$

where c is speed of light, f_o is the resonant frequency of the patch antenna, ε_r is the dielectric constant of substrate and h is the thickness of substrate. These dimensions are found to be 11.95 mm and 15.88 mm, respectively. A corporate feed network is designed to probe feed the antenna array. As calculated from [25-26], the resonant input resistance (R) of the patch antenna is calculated using Eq. (3) and is found to be 238.5 Ω

$$R = 90\left[\frac{\varepsilon_r^2}{\varepsilon_r - 1}\right]\left(\frac{L}{W}\right)^2. \quad (3)$$

A quarter wave transformer of 109.2 Ω is used to match the rectangular patch with 50 Ω line. As calculated from [27], the length of quarter wave transformer and fifty ohm line is calculated as a = 7.55 mm and b = 8.00 mm, respectively. Also, their widths are determined as c = 0.5237 mm and d = 2.8758 mm, respectively. The length of quarter wave transformer is given by Eq. (4)

$$\text{Length of quarter wave transformer} = \frac{\lambda_0}{4\sqrt{\varepsilon_{reff}}}. \quad (4)$$

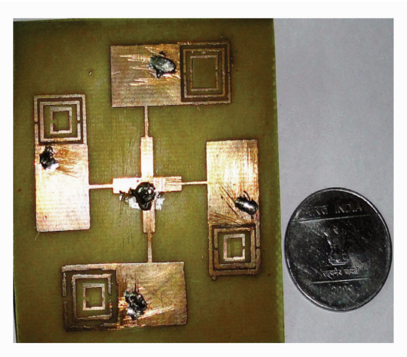


Fig. 3. Photograph of fabricated proposed antenna array

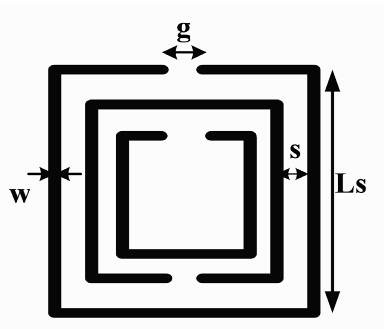
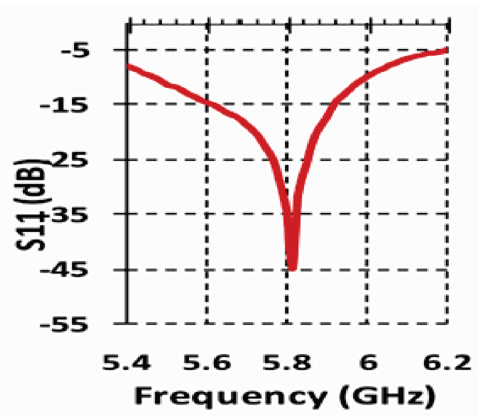


Fig. 4. Geometry of proposed MSRR unit cell

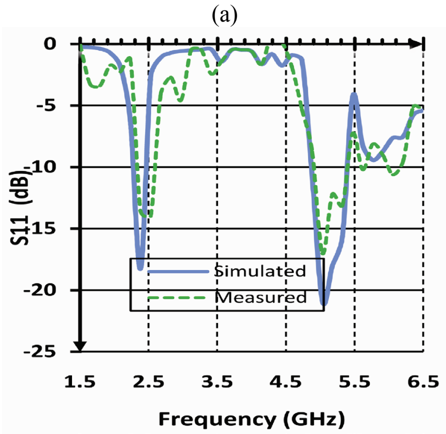
Now to obtain the subwavelength resonance, a split ring resonator is directly connected to each patch of the conventional patch antenna array. However, on loading this conventional microstrip patch antenna array with MSRR, the original resonant frequency (5.8 GHz) gets shifted to IEEE 802.11a 5.02 GHz and an additional resonant frequency is obtained at 2.3 GHz. As this additional resonant frequency does not possess much industrial applications, shifting of this frequency to some desired value is required. Therefore, to shift this resonant frequency to the desired value of IEEE 802.11b/g/n 2.45 GHz Wi-Fi band, a metallic via hole of radius (R) 0.5 mm is symmetrically introduced on the diagonal of each patch of the array. The photograph of this proposed dual band, shorted-pin, MSRR loaded microstrip patch antenna array is presented in Fig. 3. The structure of MSRR unit cell is depicted in Fig. 4.

The dimensions of this MSRR unit cell are: total number of split rings = 3, length of outer split ring (Ls) = 11.95 mm, ring width (w) = 0.2 mm, split gap (g) = 0.3 mm and gap between two split rings (s) is set to as 1 mm. The dimensions of MSRR unit cell are chosen in such a way that the size of conventional antenna array does not increase at all. FR-4 substrate of thickness (h) = 1.48 mm, dielectric constant (ε_r) = 4.3 and loss tangent = 0.01 is used to design the antenna array and is fed by a 50 ohm SMA coaxial connector. Finite Element Method (FEM) based commercial software, Ansoft HFSS, is used to design and simulate this antenna array.

V. Results and Discussion



(a)



(b)

Fig. 5. Return loss characteristics of (a) Conventional patch antenna array (simulated), and (b) Proposed antenna array (simulated and measured)

This section presents the simulated and measured results of the conventional antenna array and the proposed antenna array. Fig. 5*a* presents the simulated and Fig. 5*b* presents the simulated and measured return loss characteristics (S_{11}) of the conventional antenna array and the proposed dual band antenna array designed with metallic via holes and MSRRs, respectively. The location of via holes on the microstrip patch has been tuned in such a way that the 2.3 GHz band gets shifted to 2.45 GHz band.

As depicted from return loss characteristics (Fig. 5*a* and *b* and radiation patterns (Fig. 6, Fig. 7*a* and *b*), the unloaded antenna array resonates at 5.8 GHz band with gain of 9.8 dBi and bandwidth of 540 MHz. However, when each patch of this antenna array is directly connected to a split ring resonator, the initial resonant frequency gets shifted to 5.02 GHz, providing the gain and bandwidth of 11.2 dBi and 510 MHz, respectively, along with an additional resonant frequency band at 2.3 GHz.

But this additional resonant frequency band at 2.3 GHz does not possess much industrial applications. Therefore, to shift this resonant frequency to IEEE 802.11b/g/n 2.45 GHz Wi-Fi band, a metallic via hole is inserted on the diagonal of each MSRR loaded patch. Due to the addition of this extra inductance, this additional resonant frequency (i.e. 2.3 GHz) gets shifted to IEEE 802.11b/g/n 2.45 GHz Wi-Fi band, providing bandwidth and gain of 290 MHz and 5.7 dBi, respectively. Hence, it is observed that apart from the development of the additional resonant frequency, the gain of the proposed antenna also increases by 1.6 dB at 5.02 GHz. Thus, it is concluded that development of this dual band antenna by loading the conventional antenna array (which initially resonates at a single band) with MSRRs and metallic via holes, results in size miniaturization and gain improvement. Moreover, this has been achieved without incorporating any additional hardware and hence, at no extra cost and size.

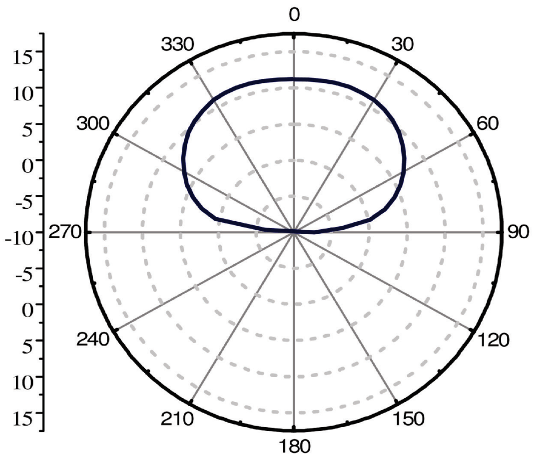
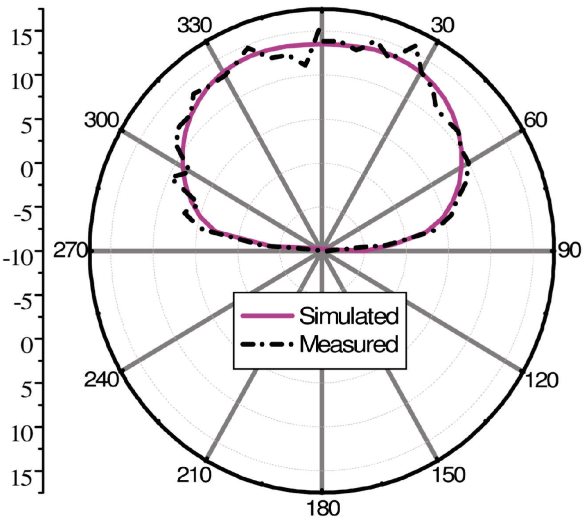


Fig. 6. Elevation plane radiation patterns of conventional patch antenna array at 5.8 GHz (simulated)

(a)



(b)

Fig. 7. Elevation plane radiation patterns of proposed antenna array at (a) 2.45 GHz (b) 5.02 GHz (measured and simulated)

Table 1 shows the comparison of this proposed dual band antenna array with some other multiband antennas discussed in the literature. It is observed from this table that the proposed MSRR loaded antenna array achieved the maximum gain for the smallest patch size.

TABLE 1

COMPARISON OF PROPOSED ANTENNA WITH OTHER EXAMPLES DISCUSSED IN THE LITERATURE

Ref.	Operating Freq (GHz)	Bandwidth (MHz)	Gain (dBi)	Patch Size (mm)	Features	Substrate Permittivity
[1]	3.7/4.95/5.5	340/300/200	8.2/8/7.9	35.5 x 26	Planar	1
[6]	2.45/5.2	20/40	2.6/6.6	28.2 x 21	Planar	3.0
[8]	1.08/1.94/2.4	0/8/30	1.9/0.6/6.2	44 x 44	Stacked	2.2
[17]	2.46/3.45/5.39	100/680/1110	0.76/0.86/1.58	20 x24	Planar	9.5
Proposed Antenna	2.45/5.0	290/510	5.7/11.2	15.8 x 11.9	Planar	4.3

Fig. 8 presents the view of experimental set up to measure the return loss characteristics of the fabricated proposed antenna array. The anechoic chamber, along with the experimental setup, to measure the radiation patterns is depicted in Fig. 9. Anritsu Vector Network Analyzer, model no. MS2028C, frequency range 5 KHz to 20 GHz and spectrum analyzer, model no. Anritsu MS2719B, operating over the frequency range of 9 KHz to 20 GHz is used to test this proposed antenna array. Some mismatch between measured and simulated result is observed due to the inaccuracy occurred while fabricating the proposed antenna array and the use of FR-4 substrate, which has lossy characteristics but cheaper in cost, and hence good for preparing such prototypes.

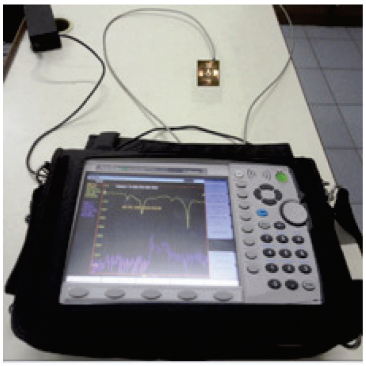


Fig. 8. Experimental set up to measure return loss characteristics of the proposed antenna array

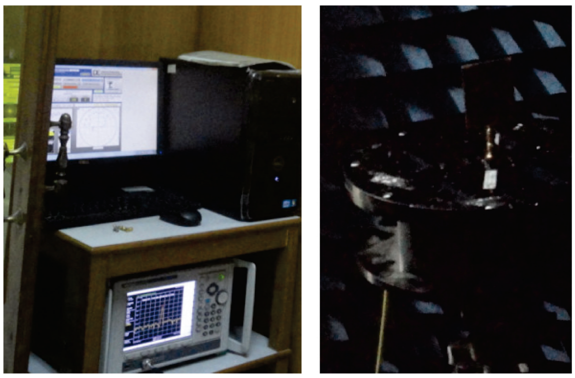
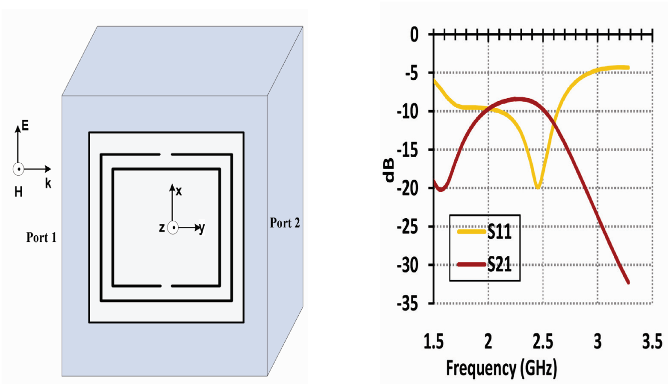


Fig. 9. Measurement of radiation patterns inside an anechoic chamber

VI. METAMATERIAL UNIT CELL CHARACTERIZATION USING EFFECTIVE MEDIUM THEORY

To determine the effective parameters of the MSRR, the unit cell is placed in a waveguide in such a way that the incident electromagnetic wave is polarized with propagation vector (k) along y axis, the magnetic field is along z axis, whereas the electric field is along the x axis. The arrangement of the proposed MSRR inside the wave guide is shown in Fig. 10*a* and the S-parameters determined from it are shown in Fig. 10*b*.



(a) (b)

Fig. 10. (a) Metamaterial unit cell placed inside the waveguide, (b) Reflection and transmission characteristics of the metamaterial unit cell

Nicolson-Ross-Weir (NRW) method [28] is used to obtain the effective magnetic permeability of MSRR unit cell, the equations of which are as following:

$$\mu_r = \frac{2}{jk_o d}\frac{1-V_2}{1+V_2} \tag{5}$$

$$\varepsilon_r = \frac{2}{jk_o d}\frac{1-V_1}{1+V_1} \tag{6}$$

where k_0 represents wave number, d is substrate thickness, V_1 and V_2 are obtained from Eqs. (7) and (8) [28]

$$V_1 = S_{21} + S_{11}, \quad (7)$$

$$V_2 = S_{21} - S_{11}. \quad (8)$$

Now, by using Eqs. (5) to (8), the metamaterial characteristic of MSRR unit cell is verified. From Fig. 11 it is observed that the magnetic permeability of the MSRR unit cell is negative from 1.95 GHz to 3.4 GHz, implying that the structure exhibits metamaterial characteristic at the frequency of interest.

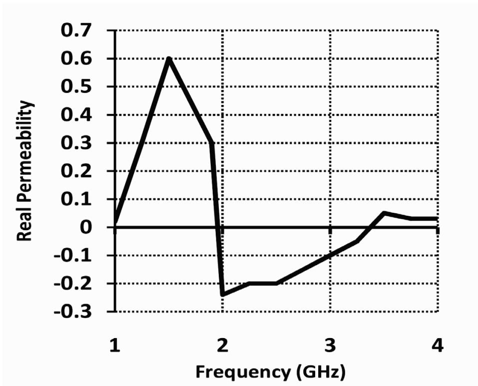


Fig. 11 Magnetic Permeability characteristic of MSRR unit cell

VII. Analytical Analysis

Operation of the proposed microstrip patch antenna array is based on the excitation of MSRR with patch antenna field. When the patch antenna array is excited by a corporate feed network, electric current flows along the outer split ring of each MSRR. Due to electromagnetic induction, current gets induced in the inner split ring. As a result of it, a huge electric field is induced across the gap capacitance at splits and mutual capacitance between the split rings. The inductance of each patch and the equivalent capacitance of each MSRR form the LC resonator circuit of the loaded antenna array and this result in generation of the additional resonant frequency at 2.3 GHz, which further gets increased to 2.45 GHz by introduction of a shorting pin, as it inserts an extra inductance in the circuit.

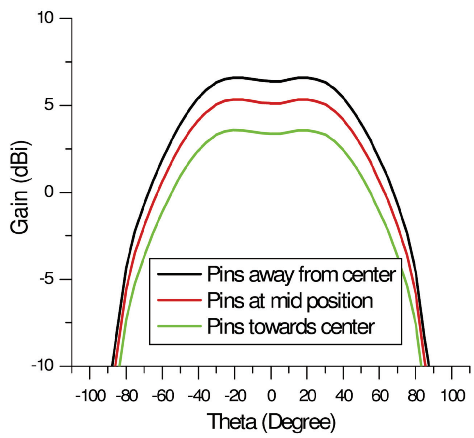


Fig. 12 Variation of the gain of the proposed antenna array as the function of location of shorting pins

Thus, it is observed that the metamaterial unit cell also act as a radiation source along with the exited patch antenna. The electric dipole moments (**p_e**) and magnetic dipole moments (**p_m**) of these radiating unit cells are expressed in terms of their surface current densities J_e and are represented by Eqs. (9) and (10) [14].

$$\vec{p}_m = \frac{\mu_o}{2} \int_s \vec{r} \times \vec{J}_e(r') ds' \quad (9)$$

$$\vec{p}_e = \frac{j}{\omega} \int_s \vec{\nabla}.\vec{J}_e(r') \vec{r} ds' \quad (10)$$

where μ_o is permeability of free space, r is the displacement vector, r' is current element position and ds' is differential current carrying surface element. In addition to frequency shifting, introduction of the shorting pins also have an additional effect of gain enhancement by 1.6 dB at 5.02 GHz. This enhancement of gain results due to increase in effective area of the array caused by the shunt inductive effect of the shorting pins. These shorting pins largely disturb the electric field under the patch. Due to this perturbation of field, overall area of the patch gets increased, resulting in gain enhancement of this devised array. The inductance of each shorting pin is given by Eq. (11) [29]

$$L_P = \frac{\mu_0}{2\pi}\left[p \ln\left(\frac{p + \sqrt{p^2 + R^2}}{R} \right) - \sqrt{p^2 + R^2} + \frac{p}{4} + R \right], \quad (11)$$

where μ_0 is the permeability in vacuum, p is the height of each pin and R is the radius of each pin. As these pins starts to move close to each other towards the center of patch, along the diagonal, their effect on the field distribution tends to decrease, resulting in the reduction of gain and resonant frequency. Fig. 12 shows this variation in gain of the proposed array at 2.45 GHz as a function of different positions of pins on the diagonal of the patch. As observed from Fig. 14, the gain decreases from maximum value of 5.7 dBi to 4.8 dBi and further to 2.7 dBi when pins are moved inwards, towards the centre of patch.

VIII. Conclusions

In this paper, a novel approach to design a dual band antenna array with enhanced gain at no extra hardware cost and size has been proposed. For this purpose, each patch of a coaxial fed four-element patch antenna array is directly connected to MSRR and a shorted metallic pin is introduced on it. The integration of MSRRs to the conventional array has been done in such a way that the overall size of the proposed array is same as that of the unloaded antenna array. Based on the working of MSRR and shunt inductive effect of shorting pins, the working of the proposed array has been discussed and it has been concluded that (i) The composite structure of MSRR and microstrip patch forms the LC resonant circuit, resulting in the generation of an additional resonant frequency band (ii) The MSRR unit cell also acts as the radiating source (iii) Introduction of via holes introduce an extra inductance in the structure (iv) These shorting pins increase the overall area of the antenna, resulting in enhancement of the antenna array gain. The proposed array has been fabricated and tested to validate the design and it is observed that the simulated and measured results quite well agree with each other. The proposed antenna array will find the applications in all the wireless devices operating at IEEE 802.11 b/g/n 2.45 GHz and IEEE 802.11a 5 GHz Wi-Fi band. Depending on specific requirements and applications, in future, the number of patch elements can be increased to obtain the enhanced performance. Moreover, some other substrate with lower dielectric constant and larger thickness can also be used.

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