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Miniaturization of Microstrip Yagi Array Antenna Using Metamaterial

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Abstract—An approach of miniaturizing planar Yagi array using metamaterial is presented in this paper. In this methodology, metamaterial structures are incorporated in the antenna in place of directors. An investigation in reflection and radiation characteristics of the antennas is done, and the findings are presented. The metamaterial loaded antenna shows improved directivity and efficiency of 16.3% and 2.95% with respect to the microstrip Yagi antenna while achieving a noticeable size miniaturization of 33.3%. Also, a better matching, compared to Yagi antenna, is observed in this proposed design. The fabrication and measurement of metamaterial loaded structure have been performed. The measured result shows an acceptable extent of agreement with the simulated ones.

1. INTRODUCTION

Recently with the development of wireless communication the requirement for highly directive antenna has been elevated. The main radiation beam of a directive antenna should be towards a particular direction in order to attain a better communication. As well known, Yagi-Uda antennas have high directivity [1–3], thus they are popularly used in directive wireless application. Nowadays, microstrip Yagi array, a hybrid of microstrip antenna and Yagi-Uda antenna, has become very popular due to low profile, compatibility with planar component, simple and inexpensive manufacturing process and high directivity [4]. This kind of antenna was first introduced by Huang and Densemore in [5]. A typical microstrip Yagi antenna consists of a driven patch element and a few parasitically coupled reflector and director patch elements [5]. It is a well-established fact that the directivity of microstrip Yagi antenna greatly depends on the number of directors [6]. Various attempts have been made to enhance the gain of Yagi antenna by incorporating more than a single director [7–9]. Also, the gain of series-fed two-dipole array antenna and log-periodic dipole array antenna can be improved using multiple directors as mentioned in [10] and [11], respectively. All these attempts result in an increment in the size of the antenna as well. Moreover, as the induced current decreases progressively on the more extreme directors, the efficiency and gain of the antenna do not improve progressively with the number of directors [4]. Alternatively, performance of the Yagi array antenna can be improved significantly by constructive interference of multiple microstrip Yagi structures in the place of a single Yagi antenna [12]. This, whatsoever, increases the overall configuration of the antenna.

In this paper, an approach to reduce the size of a Yagi antenna using a metamaterial structure as the substitute of directors is proposed. For that purpose, a meandered driven dipole with reflector patch is designed which is considered as the reference antenna. Director patches are added to the reference antenna to form a Yagi array antenna, resulting in enhanced directivity. Due to addition of directors, the size of the antenna increases by a significant amount. Alternatively, a new method has been proposed, to load the antenna with metamaterial unit cells instead of directors. This results in an increment in

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the directivity by 16.3% with respect to the microstrip Yagi array. Moreover, the size reduction of the metamaterial loaded Yagi antenna is 33.3% compared to the microstrip Yagi structure. Thus, by this approach, considerable size reduction of antenna is achieved while attaining enhanced directivity. The High Frequency Structure Simulator software (HFSS) is used to design these antennas. In this context, a metamaterial loaded Yagi antenna is fabricated. The measured result from the fabricated antenna shows acceptable agreement with the simulation one.

2. DESIGN OF METAMATERIAL BASED ON SPLIT RING RESONATOR STRUCTURE

Nowadays, artificially composed structures having negative values of permittivity and permeability, termed as metamaterial [13], have drawn attention of antenna designers for their unconventional properties such as negative refractive index and phenomena of left-handed propagation [14]. These exclusive properties of metamaterial depend on their transmission and reflection characteristics. It is known that the frequency, for which the metamaterial structure shows minima in reflection coefficient and maxima in transmission coefficient, depends upon the structure and dimensions. Adding metamaterial to the antenna allows the electromagnetic wave to propagate from the antenna to the structure due to matched resonance condition. Therefore, metamaterials can be used to guide the electromagnetic wave propagation in the desired direction resulting in enhanced directivity. In this article, the metamaterial slab design is based on Split Ring Resonator (SRR) unit cell, introduced by Cao et al. in [15]. The advantages for choosing SRR unit cell as metamaterial, as shown in Figure 1, are its simple structure, large capacitance and easy tunability of the resonant frequency by varying parameters W_{M3} and L_{M2}. For simulation in HFSS, the planes perpendicular to electric field are assigned to boundary condition of perfect electric conductor (PEC), and the planes perpendicular to magnetic field directions are assigned to boundary condition of perfect magnetic conductor (PMC). All the dimensions are described in Table 1.

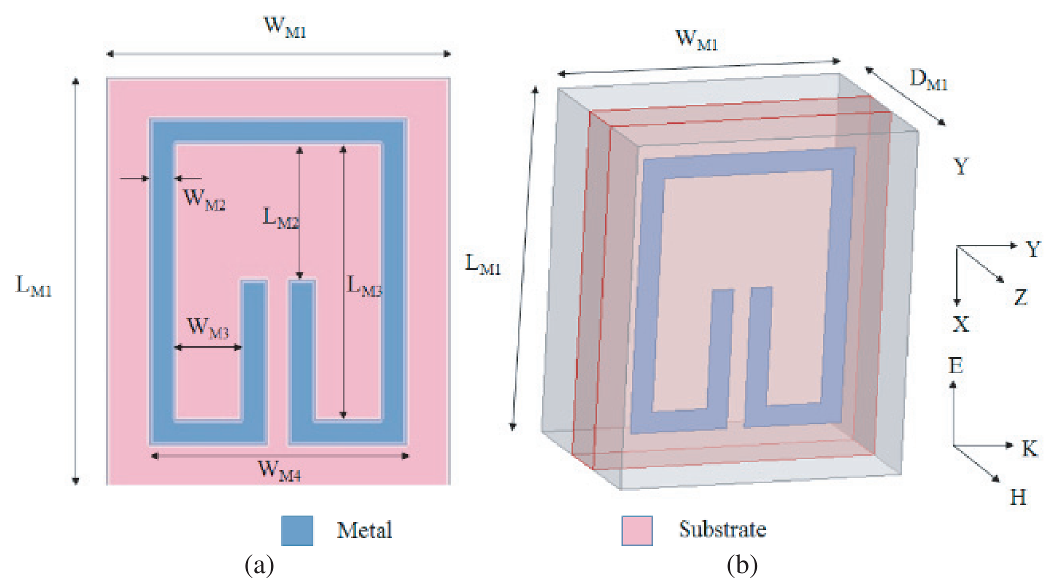

Figure 1. Simulation model of SRR unit cell. (a) Top view and (b) 3-D view.

Table 1. Dimensions of SRR unit cell.

Parameter	W_{M1}	W_{M2}	W_{M3}	W_{M4}	L_{M1}	L_{M2}	L_{M3}	D_{M1}
mm	8	0.6	1.55	6	10	3.35	6.8	6

3. DESIGN OF YAGI ARRAY ANTENNA USING SRR STRUCTURE

In this paper, three different antennas are considered to give an insight of the proposed approach for miniaturization of Yagi structures while attaining improved directivity. To design the antennas, Duroid is used as the antenna substrate with relative permittivity of 2.2, substrate thickness of 1.58 mm and dielectric loss tangent of 0.0009. Initially, a meandered driven dipole antenna with reflector is designed and referred to as the reference antenna. Consequently, director patches are added to the reference antenna to design the microstrip Yagi antenna. Afterwards, the reference antenna is loaded with SRR unit cells to achieve miniaturization and enhanced directivity compared to microstrip Yagi array.

3.1. Design of Meandered Driven Dipole Antenna with Reflector

The geometry of the designed meandered dipole antenna with reflector is shown in Figure 2. It consists of a driven dipole and reflector. The arms of the dipole are on two opposite sides of the substrate. The arm on the top face of the substrate is directly connected to the signal path, and the other arm on the bottom face is an extension of the metal layer (ground). All the dimensions corresponding to the reference antenna are provided in Table 2.

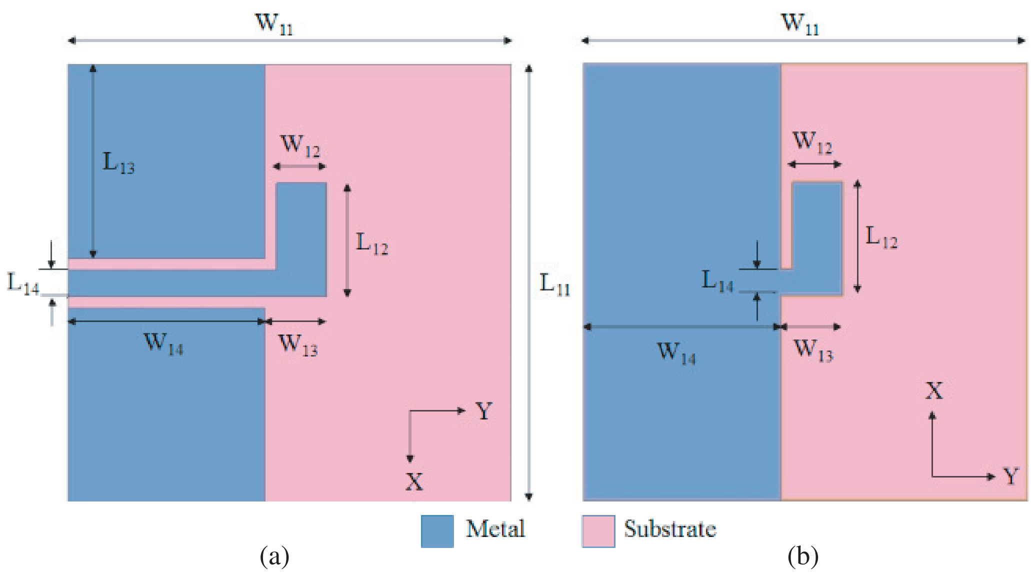

Figure 2. Design of reference antenna. (a) Top layer and (b) bottom layer.

Table 2. Dimensions of reference antenna.

Parameter	W_{11}	W_{12}	W_{13}	W_{14}	L_{11}	L_{12}	L_{13}	L_{14}
mm	80	9	11.2	35.5	80	20.7	35.5	4.9

3.2. Design of Microstrip Yagi Array

The design of the microstrip Yagi array, shown in Figure 3, is based on adding director patches to the reference antenna keeping the driven element and the reflector unchanged. Incorporation of directors to the antenna has led to size increment. Director patches are added on the both surfaces of the substrate. However, it has been ensured that addition of directors does not shift the resonant frequency significantly by choosing dimensions appropriately as in Table 3. The microstrip Yagi antenna contains four directors, each on both layers of the substrate.

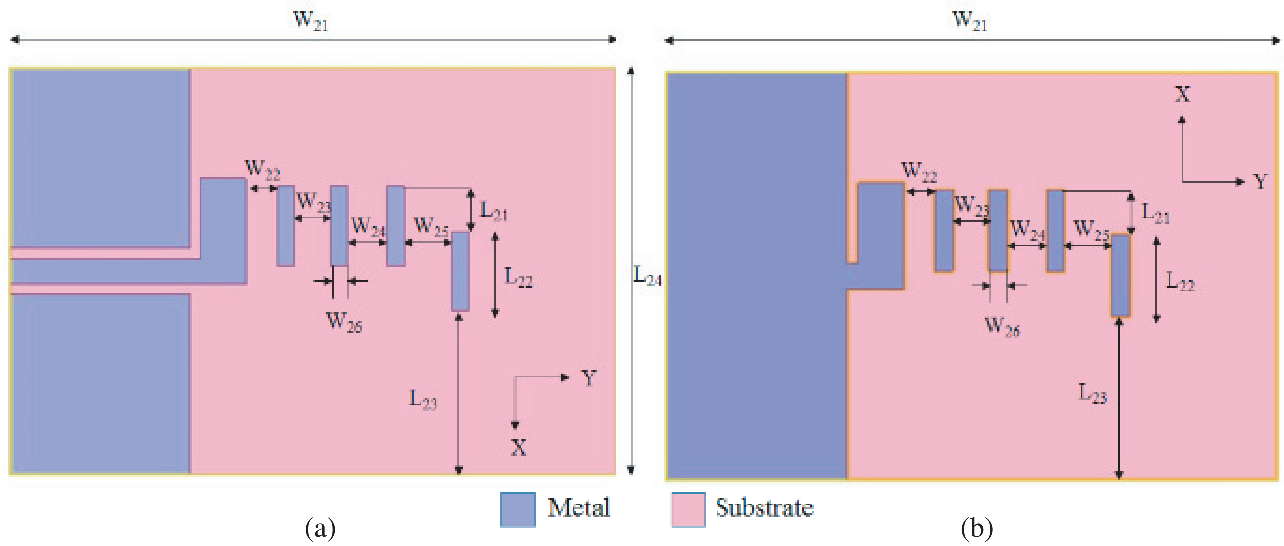

Figure 3. Design of microstrip Yagi array. (a) Top layer and (b) bottom layer.

Table 3. Dimensions of microstrip Yagi array.

Parameter	$\mathbf{W_{21}}$	$\mathbf{W_{22}}$	$\mathbf{W_{23}}$	$\mathbf{W_{24}}$	$\mathbf{W_{25}}$	$\mathbf{W_{26}}$	$\mathbf{L_{21}}$	$\mathbf{L_{22}}$	$\mathbf{L_{23}}$	$\mathbf{L_{24}}$
mm	120	6.2	7.3	7.8	9.4	3.4	8.9	15.8	32.1	80

3.3. Design of SRR Loaded Antenna

In order to achieve size shrinkage with higher directivity than the microstrip Yagi array, metamaterial structures are introduced to the antenna in the place of multiple directors, as depicted in Figure 4. The antenna consists of total four SRR unit cells, two structures on each layer of the substrate. The parameters W_{M3} and L_{M2} of SRR unit cell, as in Figure 1, are chosen so that the resonating frequency of the unit cell corresponds to that of the reference antenna. At the resonating frequency, most of the input power from the driven element is available at the output of the SRR structures. The SRR unit cells provide the best matched condition when the electric field is in the XY plane and the magnetic field in the Z direction as shown in Figure 1. To ensure the best resonance condition, the orientation of the metamaterial in the antenna is as shown in Figure 4. The corresponding dimensions are tabulated in Table 4.

Table 4. Dimensions of SRR loaded antenna.

Parameter	$\mathbf{W_{31}}$	$\mathbf{W_{32}}$	$\mathbf{W_{33}}$	$\mathbf{L_{31}}$	$\mathbf{L_{32}}$
mm	8	0.6	1.6	10	3.4

4. RESULTS AND DISCUSSION

The transmission and reflection characteristics of the SRR unit cell, based on simulation, are shown in Figure 5. $|S_{11}|$ and $|S_{21}|$ of the SRR structure are about -50 dB and 0 dB respectively at 2.89 GHz. Thus, the SRR unit cell, described by Table 1, is resonant at 2.89 GHz.

Simulated return loss characteristics for all the designed antennas, as described in the previous section, as well as the measured S_{11} for the fabricated SRR loaded antenna, are exhibited in Figure 6.

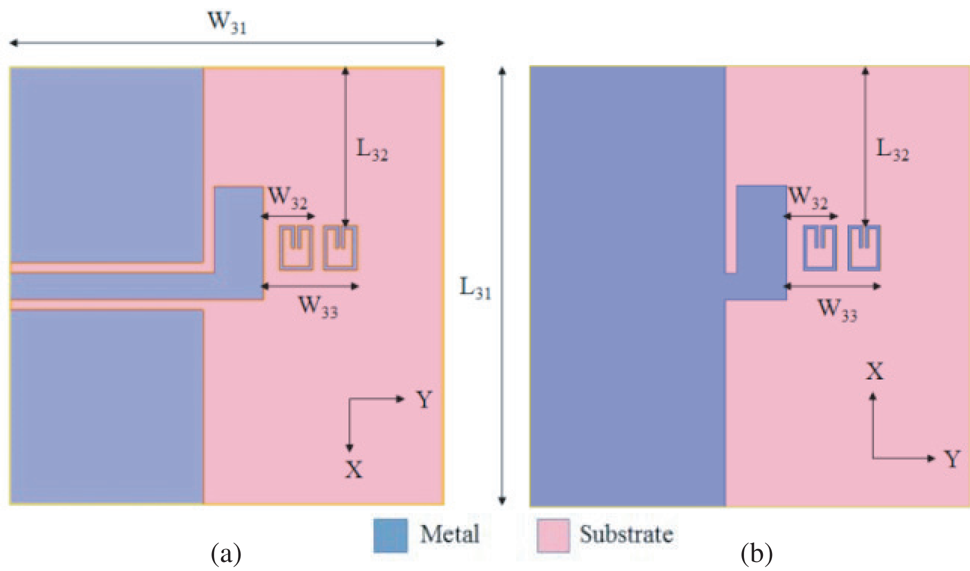

Figure 4. Design of SRR Loaded Yagi antenna. (a) Top layer and (b) bottom layer.

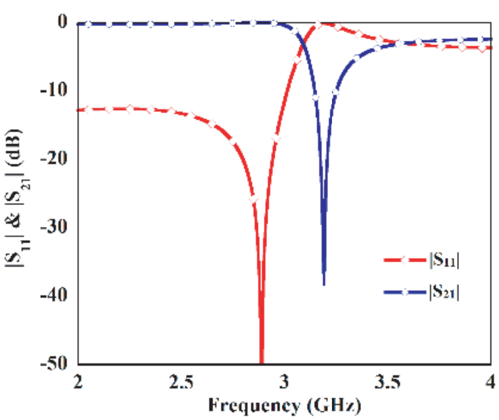

Figure 5. S parameters for SRR unit cell.

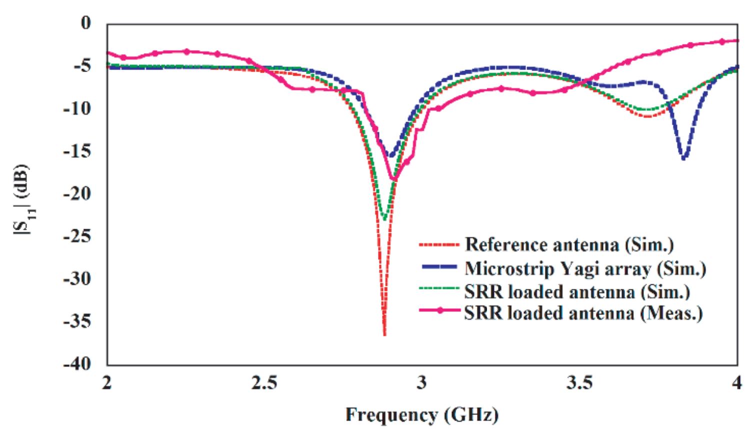

Figure 6. Return loss characteristics for designed antennas.

The reference antenna shows a return loss of -37.8 dB at 2.89 GHz with a -10 dB bandwidth of 7.2%. The design of microstrip Yagi array is made in such a way so that the resonant frequency remains unaltered. For loading the reference antenna with directors, the return loss characteristics of -15.38 dB and bandwidth of 5.2% are observed, as depicted in Figure 6. This degradation is due to the coupling loss among the directors. Loading the reference antenna with SRR structures, as substitute of directors, also does not lead to frequency shifting, and S_{11} value of -22 dB along with a bandwidth of 6.9% is obtained. A better matching of reflection coefficient is obtained for the SRR loaded Yagi antenna compared to microstrip Yagi array due to the impedance matching of the SRR unit cell. The prototype of the fabricated SRR loaded antenna is depicted in Figure 7. Consequently, the measured result for fabricated antenna suggests that $|S_{11}|$ is -18.24 dB at 2.91 GHz, and -10 dB bandwidth is 6.5% as shown in Figure 6. Thus, improved matching and bandwidth characteristics are achieved in SRR loaded antenna compared to the Yagi antenna.

In Figure 8(a), 2-D directivity patterns for different designed antennas are shown. As the reference antenna contains driven element as well as reflector patch, there is less back radiation with a directivity of 2.94 dB along the X axis ($\theta = 90^\circ$ and $\phi = 90^\circ$). By adding directors to the reference antenna, i.e.,

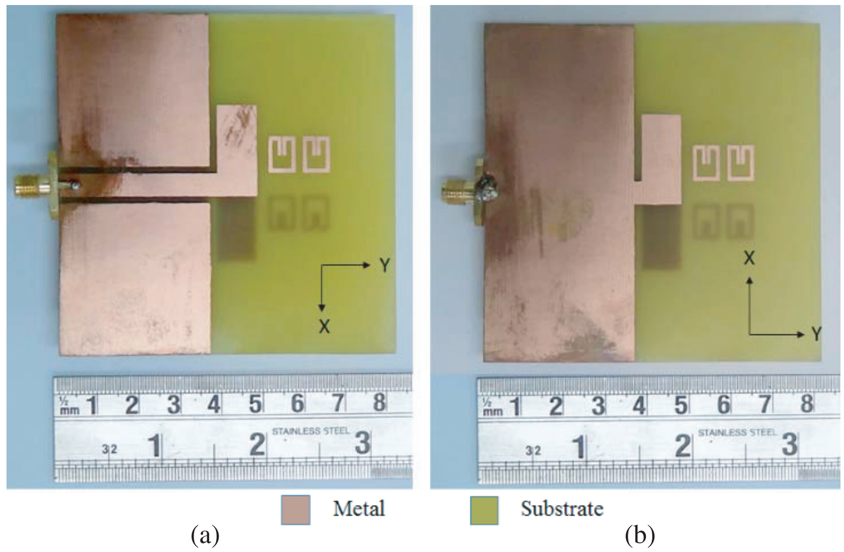

Figure 7. Fabricated prototype of SRR loaded Yagi antenna. (a) Top layer and (b) bottom layer.

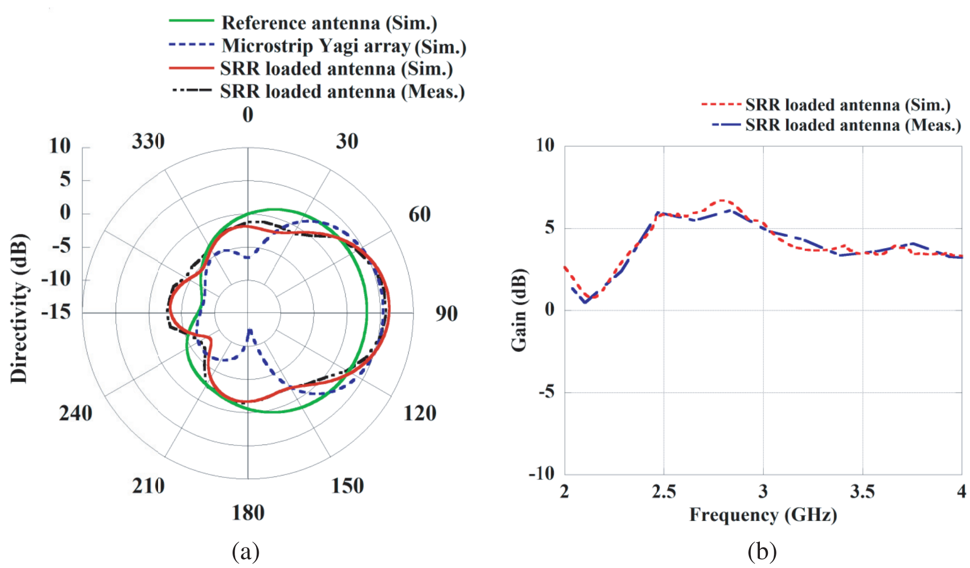

Figure 8. (a) Comparison of antenna's radiation characteristics. (b) Measured and simulated gain versus frequency plot of the SRR loaded Yagi antenna.

in the microstrip Yagi array, the directivity along the X axis increases to 5.4 dB with enlargement of the antenna size. Loading the reference antenna with SRR structures results in a directivity of 6.28 dB towards the direction $\theta = 90^\circ$ and $\phi = 90^\circ$ which is 0.88 dB more than the directivity of the microstrip Yagi antenna along the same direction. The measured directivity of the SRR loaded antenna is also shown in Figure 8(a), and it is 5.9 dB. In Figure 8(b), the measured and simulated gains versus frequency plot of the SRR loaded antenna is shown. The measured gain of the proposed antenna is 5.6 dB at the resonance frequency.

The Wheeler cap method [16] has been used for determining the efficiency of the fabricated SRR loaded antenna. The measured efficiency for the SRR loaded antenna is 93.3%, while the corresponding simulated efficiency is 94.1%. The loss in this case is due to the finite conductivity of ground plane and substrate dielectric loss, surface-wave loss, and edge currents on the ground plane.

A comparison between different parameters of the reference antenna, microstrip Yagi array and the

Table 5. Comparison of different antenna parameters.

Antenna	**Size (mm^2)**	**Resonance Frequency (GHz)**	**Return loss (dB)**	**Impedance bandwidth (%)**
Reference (Sim.)	80 × 80	2.89	−37.8	7.2
Microstrip Yagi (Sim.)	80 × 120	2.89	−15.38	5.2
SRR loaded (Sim.)	80 × 80	2.89	−22	6.9
SRR loaded (Meas.)	80 × 80	2.91	−18.24	6.5
Antenna	**Half-power beamwidth (Degree)**	**Gain (dB)**	**Directivity (dB)**	**Efficiency (%)**
Reference (Sim.)	172	2.82	2.94	97.3
Microstrip Yagi (Sim.)	96	5	5.40	91.4
SRR loaded (Sim.)	55	6.02	6.28	94.1
SRR loaded (Meas.)	62	5.6	5.9	93.3

SRR loaded antenna is demonstrated in Table 5. It is evident that incorporation of director patches to the reference antenna results in degraded size, return loss characteristics, bandwidth and efficiency with respect to the reference antenna in spite of improved half-power beamwidth, directivity and gain. However, loading the reference antenna with SRR unit cell results in better matching characteristics, directivity, half-power beamwidth, bandwidth, efficiency and gain compared to the Yagi array. It is important to note that incorporation of SRR structure reduces the size of the antenna significantly compared to the Yagi antenna.

5. CONCLUSION

In this paper, a simple technique, for reducing overall configuration of the planar Yagi antenna using metamaterial instead of directors, is demonstrated. Loading the antenna with SRR structures results in 16.3% directivity enhancement compared to microstrip Yagi array while achieving 33.3% size shrinkage. Moreover, a better matching condition is also achieved by loading the antenna with metamaterial structures rather than directors. The proposed approach has potential application in miniaturizing antenna system used in wireless mode of communication.

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