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Design of a Compact Planar Quasi-Yagi Antenna with Enhanced Gain and Bandwidth Using Metamaterial

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Abstract—In this paper, a compact planar quasi-Yagi antenna with enhanced radiation characteristics is presented. The proposed structure is designed by incorporating metamaterial unit cells in place of conventional directors. Here, the technique used for directivity improvement is that the refractive index of the metamaterial is lower than that of the antenna substrate, which acts as a regular lens for beam focusing. Loading the quasi-Yagi antenna with metamaterial results in directivity as well as gain enhancement at the end-fire direction compared to the quasi-Yagi antenna with directors. In addition, reduction in the overall size of the proposed quasi-Yagi antenna by 26.67% is achieved. An enhanced impedance bandwidth has also been noticed. The gain performance of the proposed antenna within the frequency band has been studied.

1. INTRODUCTION

In wireless communication systems, a planar Yagi antenna with directive end-fire radiation characteristics has been extensively used due to its small volume, low cost and simplicity in fabrication procedure [1]. After the evolution of the quasi-Yagi antenna by Qian et al. [2], several quasi-Yagi antennas have been investigated to improve radiation performances as well as size of the antenna configuration in the last two decades.

In general, the directivity of a Yagi antenna has been enhanced by adding more number of directors to the structure. In [3], a planar microstrip-fed quasi-Yagi antenna has been designed by using six directors to attain a promising gain and bandwidth. Then, to further enhance the performance, two rows of directors are introduced by replacing one row of directors with making an angle between the two rows [4]. Very recently, a quasi-Yagi antenna is designed by incorporating multistages of novel ladder-like directors for improving gain and bandwidth [5]. It might be noted that directivity of Yagi antenna does not increase significantly as the number of directors increases due to the gradual reduction in magnitude of the induced currents on the more distant directors [6]. Alternatively, higher gain can be achieved by incorporating multiple Yagi structures instead of a single Yagi antenna [7, 8]. However, all these attempts result in increment of the overall size of the antenna. Thus the challenge lies in reducing the overall antenna size while increasing the directivity to the end-fire direction. Previously, various approaches have been proposed to reduce the size of the Yagi antenna such as by reducing area of the feeding network [9], replacing radiating elements with artificial transmission lines (ATLs) [10] and modifying the parabolic reflector [11].

In this paper, a technique is proposed to design a compact high gain quasi-Yagi antenna by using metamaterial unit cells in the place of directors. Initially, a quasi-Yagi antenna with three directors is designed. Afterwards, the directors are replaced by metamaterial unit cells in the antenna configuration. The technique used for directivity improvement is that the refractive index of the metamaterial is lower than that of the antenna substrate, which works as a regular lens for beam focusing [12]. By this

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approach, the gain of the antenna is increased by 44.9% while attaining a size reduction of 26.67% of the overall antenna configuration. Moreover, efficiency and gain enhancement are observed. An improvement in impedance bandwidth of around 60% is achieved in comparison with the quasi-Yagi antenna with directors.

2. METAMATERIAL DESIGN

The schematic configuration of the metamaterial unit cell, inspired by [12], consists of a set of parallel lines, shown in Fig. 1. The unit cell is constructed on a TMM-4 substrate with dielectric constant of 4.5, loss tangent of 0.002 and thickness of 1.52 mm. The optimized parameters for this structure are shown in Table 1. A single unit cell with periodic boundary conditions is simulated to obtain reflection and transmission coefficients. The effective parameters are extracted from the scattering parameters by using the effective parameter retrieval method as mentioned in [13].

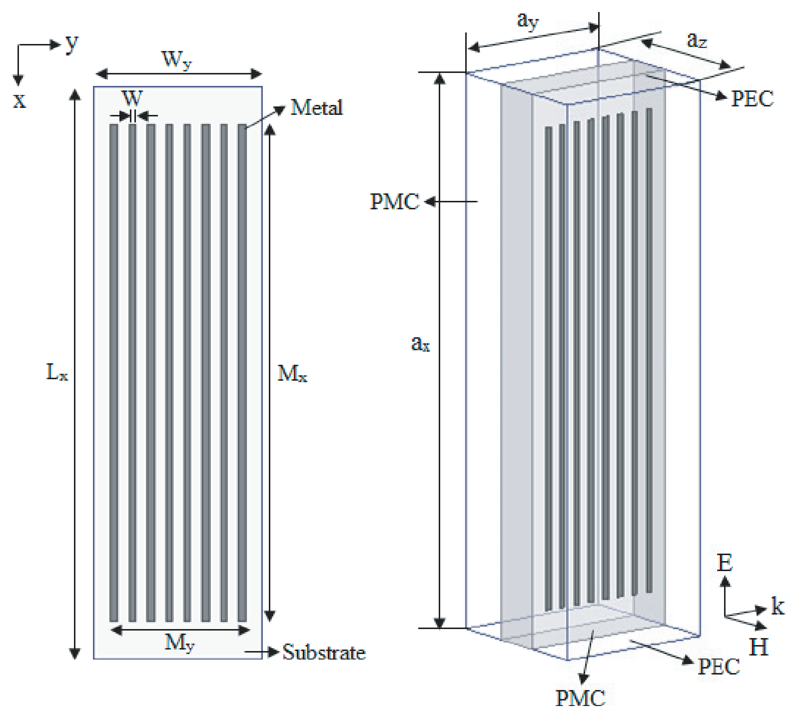


Figure 1. Metamaterial unit cell structure, (a) schematic configuration and (b) simulation model.

Table 1. Optimized design parameters of the metamaterial unit cell.

Parameters	(mm)	Parameters	(mm)
L_x	17.25	W	0.2
W_y	5	a_x	17.25
M_x	15	a_y	5
M_y	4	a_z	5

The scattering coefficients and effective parameters are presented in Fig. 2. The reflection coefficient is less than −10 dB and transmission coefficient near 0 dB in the frequency range 4.31–4.52 GHz as shown in Fig. 2(a). It is observed from Fig. 2(b) that over 4.41–5.26 GHz the magnitude of the effective refractive index value is less than that of the substrate refractive index. It can also be seen from Figs. 2(c) and 2(d) that the imaginary part of the effective permittivity and permeability is close to zero, which exhibits the low loss property of the designed metamaterial.

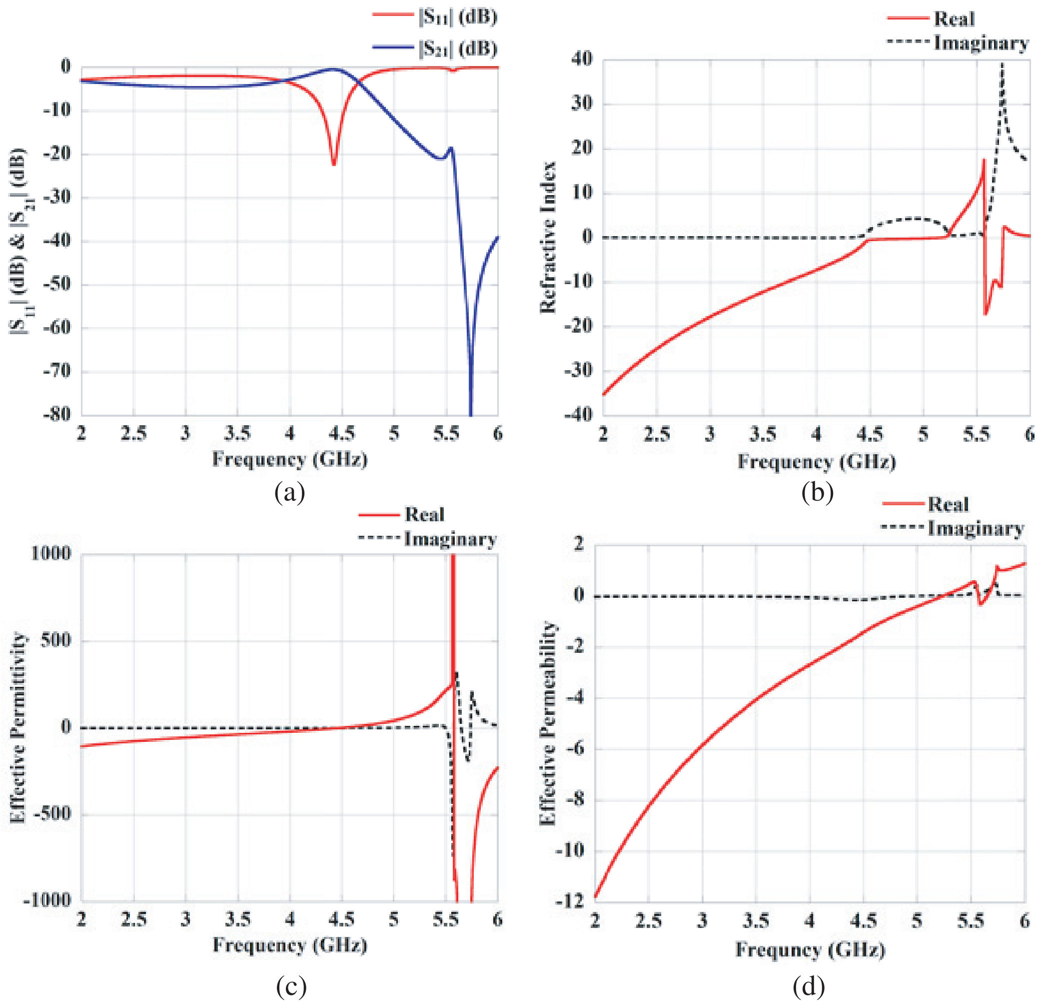


Figure 2. Simulated response of the metamaterial unit cell, (a) S-parameters, (b) refractive index, (c) effective permittivity and (d) effective permeability.

3. QUASI-YAGI ANTENNA DESIGN

In this work, quasi-Yagi antennas with directors and metamaterial are constructed separately in the following two sections. The antennas are realized on the same substrate as used to design the metamaterial unit cell.

3.1. Design of a Quasi-Yagi Antenna with Directors

The designed quasi-Yagi antenna based on [3] consists of five elements. There are one reflector, one driven element and three directors. The antenna topology is shown in Fig. 3. A monopole is used as a driven element. The monopole is excited through a microstrip-fed line. The simple feeding structure is utilized by the microstrip line without any transition, balun or being tapered. The total substrate area of the quasi-Yagi antenna with three directors is $50 \times 90\,\text{mm}^2$. The dimensions of this antenna structure are given in Table 2.

3.2. Metamaterial Loaded Quasi-Yagi Antenna as Substitute of Directors

In this section, the designed metamaterial structure is loaded with the quasi-Yagi antenna in place of the directors. The schematic configuration of the proposed metamaterial loaded quasi-Yagi antenna

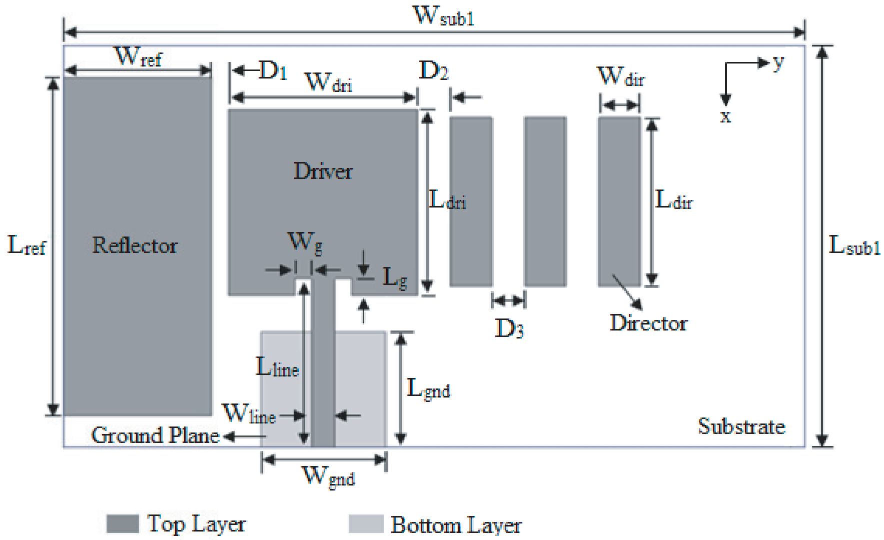


Figure 3. Geometry of the quasi-Yagi antenna using three directors.

Table 2. Optimized dimensions of the quasi-Yagi antenna with three directors.

Parameters	(mm)	Parameters	(mm)	Parameters	(mm)
L_{sub1}	50	L_{dir}	21	L_g	2
W_{sub1}	90	W_{dir}	5	W_g	2
L_{ref}	42	L_{gnd}	14.44	D_1	2
W_{ref}	18	W_{gnd}	15	D_2	4
L_{dri}	23	L_{line}	21	D_3	4
W_{dri}	23	W_{line}	2.88	–	–

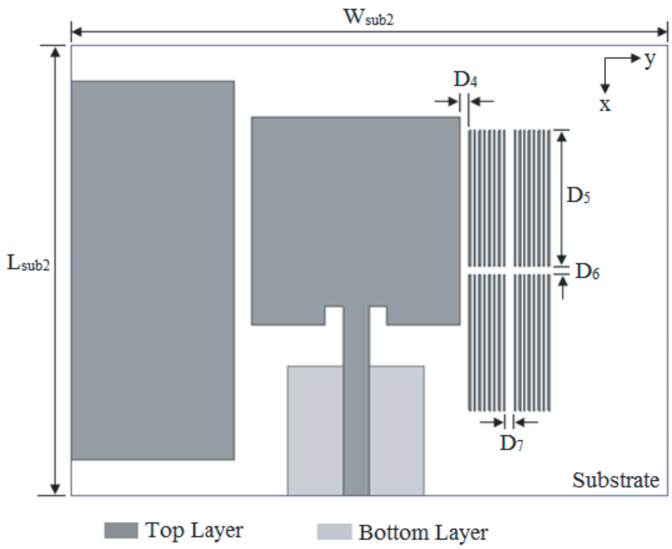
Table 3. Optimized design parameters of the MTM loaded qusi-Yagi antenna.

Parameters	L_{sub2}	W_{sub2}	D_4	D_5	D_6	D_7
(mm)	50	66	1	15	1	1

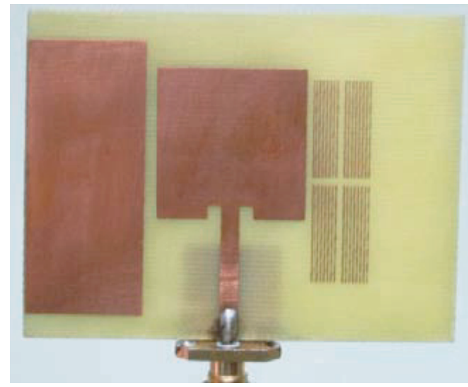
is shown in Fig. 4, with its fabricated prototype. The spacing between the metamaterial unit cells is optimized by simulating the design in High Frequency Structure Simulator (HFSS), which are given in Table 3. The total substrate area occupied by the loaded quasi-Yagi antenna is $50 \times 66\,\mathrm{mm}^2$.

4. RESULTS AND DISCUSSION

The simulated return losses of the metamaterial loaded quasi-Yagi and quasi-Yagi antenna with directors are shown in Fig. 5. By properly incorporating the metamaterial unit cells along the y-axis, the quasi-Yagi antenna results in impedance bandwidth of 22.86%, agreeing to an increase in bandwidth of around 60% in comparison with the quasi-Yagi antenna with conventional directors. Also, the directivity improvement of the metamaterial loaded quasi-Yagi antenna is noticed as the refractive index of the metamaterial is lower than that of the refractive index of the antenna substrate. A comparison of the overall dimension of the metamaterial loaded quasi-Yagi and the quasi-Yagi antenna with directors structures along with the directivity, bandwidth, radiation efficiency and gain are presented in the



(a)



(b)

Figure 4. Metamaterial loaded quasi-Yagi antenna, (a) schematic and (b) fabricated prototype.

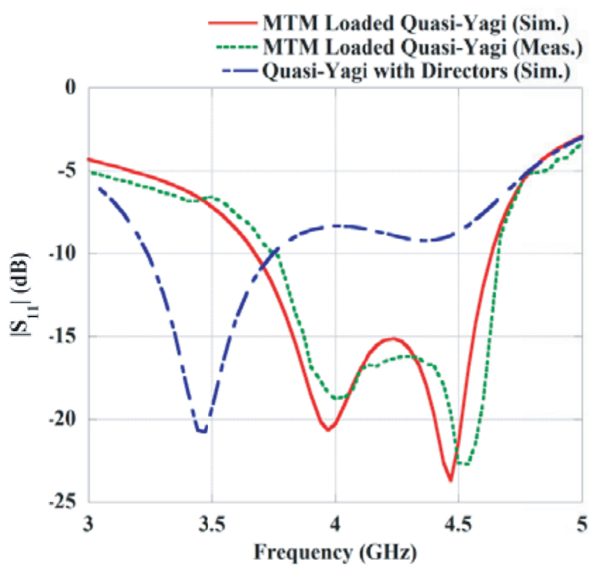
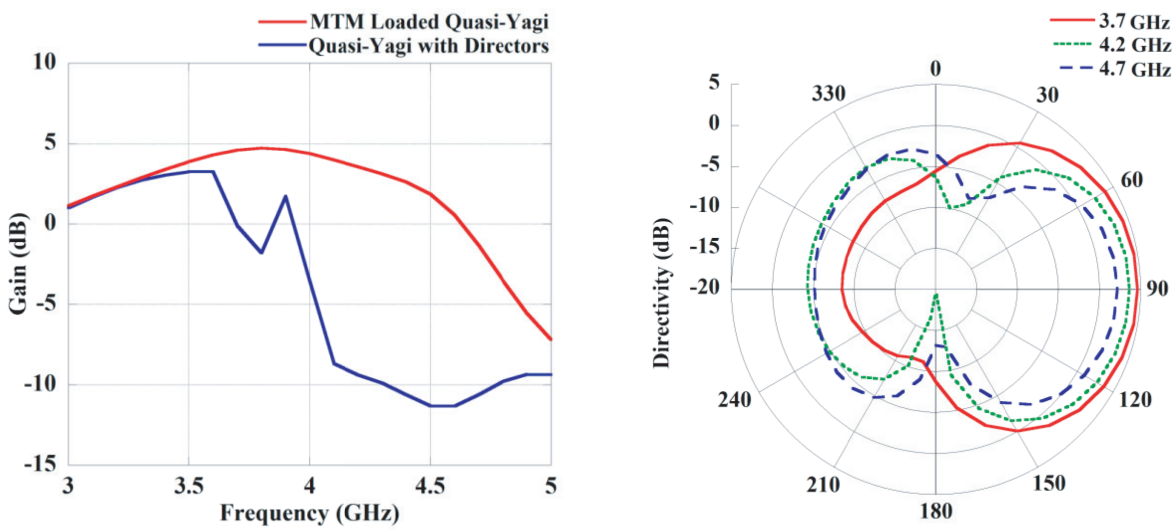


Figure 5. Simulated and measured return loss characteristics for designed antennas.

Table 4. Due to the low loss property of the metamaterial, there is a slight improvement in efficiency of the metamaterial loaded quasi-Yagi antenna compared with the quasi-Yagi antenna with directors. The enhancement in gain of the metamaterial loaded antenna has been observed in the operating frequency band of 3.68–4.63 GHz varying in the range of −0.38 to 4.71 dBi, which is shown in Fig. 6(a). The gain of the metamaterial loaded antenna reaches its maximum value of 4.71 dBi at frequency 3.8 GHz within the working band. In Fig. 6(b), the simulated radiation patterns of the metamaterial loaded quasi-Yagi antenna at three different frequencies at 3.7, 4.2 and 4.7 GHz within the frequency band are shown. It is demonstrated that the beamwidth decreases as the frequency increases, and the side lobe radiation increases with the increase in frequency.

Table 4. A comparison table between the metamaterial loaded quasi-Yagi antenna & Quasi-Yagi with directors.

Antenna Structures	Dimension (mm^2)	Directivity (dBi)	Bandwidth (%)	Radiation Efficiency (%)	Gain (dBi)
Quasi-Yagi with directors	50×90	3.37	14.32	97.28	3.25
Metamaterial loaded quasi-Yagi (by replacing directors)	50×66	4.77	22.86	98.64	4.71



(a) (b)

Figure 6. (a) Simulated gain against frequency of the metamaterial loaded quasi-Yagi antenna compared with the quasi-Yagi antenna with directors. (b) Simulated radiation patterns of the metamaterial loaded quasi-Yagi antenna in yz plane for different frequencies.

5. CONCLUSION

In this paper, we propose a novel technique to design a compact high gain quasi-Yagi antenna by incorporating the array of metamaterial cells in place of directors. A reduction in overall antenna configuration by 26.67% is achieved when directors are substituted by metamaterial structures. Moreover, improved radiation performance is achieved. The metamaterial loaded quasi-Yagi antenna shows an improved bandwidth of 22.86% and gain of 4.71 dBi. Owing to its high gain, improved bandwidth and compact size, the proposed structure will find broad applications in the design of end-fire antennas for wireless communication.

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