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WIDEBAND AND LOW SIDELOBE LINEAR SERIES FED YAGI-LIKE ANTENNA ARRAY

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Abstract—In this paper, a linear series fed Yagi-like antenna array is introduced leading to an end-fire fan beam with low sidelobe level, SLL, high front to back ratio, F/B, and wide impedance bandwidth. The array can provide −29 dB SLL at centre frequency of 16.26 GHz, −20 dB SLL bandwidth of 7.5%, 23 dB F/B and 10.6% impedance bandwidth. Further improvement in SLL can be achieved by extending narrow strips from the finite ground plane of the antenna structure leading to some −32 dB SLL at centre frequency and a −20 dB SLL bandwidth of 8.7%. To verify the accuracy of the simulation results, both of the arrays are fabricated and tested. Finally, to show the applicability of the proposed design, the linear end-fire array of the above are stacked on top of each other and simulation results for a 2-D phased array are provided.

1. INTRODUCTION

Printed antenna arrays have gained a great deal of attention and impetus for use in telecommunication systems such as point to point and point to multipoint and also in radar microwave and millimeter systems [1]. This is due to their numerous attractive features such as light weight, small size, low cost, high efficiency, ease of fabrication and installation and in array designs the microstrip feed network can be placed on the same substrate as the microstip patches [1, 2]. Furthermore, they are generally economical to produce since they are readily adaptable to hybrid and monolithic integrated circuits fabrication techniques at radio frequency (RF) and microwave frequencies [2].

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In radar systems parameters such as sidelobe level, SLL, front to back ratio, F/B, [1] and bandwidth, [3], are of high importance. Depending on the radar system SLL in between −20 to −50 dB is usually required [1]. With conventional printed antennas, realization of arrays with lower SLL than −25 dB becomes increasingly difficult mainly due to: mutual coupling between radiating elements; surface wave effect; parasitic radiation from a feeding network; and tolerances in fabrication [1].

There are usually two types of arrays in microstrip structures, the corporate fed and the series fed patch antenna array both of which are inherently narrow in bandwidth. The discontinuities, bends, power dividers, and other components in the corporate fed array cause spurious radiation that limits the minimum SLL achievable [1]. The structure of a series fed array is such that it uses shorter line length in comparison with corporate fed arrays and this leads to an antenna with less space on substrate, lower attenuation loss and spurious radiation from feed lines [4], but for large series fed arrays amplitude and phase tracking with frequency can be problematic [5].

In order to reduce the SLL in printed antenna arrays several approaches have been proposed. Among which are use of: coaxial probes along with phase shifters to reduce SLL to almost −35 dB [1]; feed network behind the ground and connected to the antenna via pins [6]; aperture coupled patch antennas [7, 8]; and a waveguide fed microstrip patch array at 76 GHz [9, 10].

Bandwidth enhancement in patch antenna array is mostly based on stacking patches on top of each other [11], or placing parasitic elements beside the patch antenna [12]. There is, however, no mention of the SLL performance of such array structures in these papers. Also, bandwidth enhancement in antenna array can be achieved by use of wideband antenna elements.

In low side lobe antenna array any extra components, phase shifters, etc., which are placed on the same substrate as the radiating elements cause spurious radiation that deteriorate the SLL dramatically. This problem becomes even more conspicuous in broad side arrays where the main radiation pattern and spurious radiation from other components are all at broadside direction. However, in an end-fire array, the broadside spurious radiations would have less effect on the end-fire SLL. Furthermore, end-fire printed arrays with high front-to-back ratio makes realization of a 2D array, by stacking many boards of such linear arrays, very practical. This allows space for RF front-end circuitry, such as low-noise amplifiers (LNA), mixers, etc., behind the antenna aperture [2]. Among the most widely used end-fire printed antennas are tapered slot antennas, TSA [13–18] and quasi-Yagi antennas [19–24].

Based on the literature review done by the present authors, it seems that most of the works published on printed end fire antennas are on increasing the bandwidth of the single element, and if placed in an array environment, no mention of SLL are provided.

Motivated by the aforementioned issues, in this paper a linear series fed yagi-like antenna array, SFY, is introduced leading to an end-fire fan beam with low SLL, high F/B and wide impedance bandwidth. Further improvement in SLL is achieved by extending narrow strips from the finite ground plane of the structure, between each Yagi-like antenna elements. This will be referred to as the modified series-fed Yagi-like antenna array, MSFY. These antenna arrays are optimized through the commercial package, Ansoft HFSS11. To verify the accuracy of the simulation results, both SFY and MSFY arrays are fabricated and tested. Finally, to show the applicability of the proposed design, the linear MSFY array of the above are stacked on top of each other and simulation results for a 2-D phased array are provided.

2. ANTENNA DESIGN

It is well known that printed Yagi antennas produce an end-fire radiation along with a large impedance bandwidth. Also it is known that a series fed printed antenna array can provide a lower SLL. The aim of this work is to implement these two ideas and to design a low SLL, wide bandwidth series fed Yagi-like printed antenna array.

The antenna array design consists of two main steps: design of a specific Yagi-like antenna array element according to some given specifications and the microstrip series-fed feeding network to provide a tapered amplitude distribution to achieve low SLL. Then, to further improve the SLL, a modification to the structure would be given. Finally, through simulation, optimization of the proposed antenna array for high F/B, low SLL and reasonable bandwidth takes place.

Figure 1(a) shows the geometry of the Yagi-like antenna which is based on double sided flat dipole implementation. As can be seen from the figure, the antenna consists of a driven element, two director elements and a finite ground plane acting as a reflector. The dipole is center-fed by a short pair of parallel strips, and as can be seen from Fig. 1(a) there is no complicated balun for matching the driven element to the antenna feedline. The width of the parallel strips is set too narrow to provide high input impedance, making it well suited for series-fed antenna array design. As a starting point in designing the antenna, the length of the driven element should be around $0.5\lambda_{\mathit{eff}}$ while the lengths of the directors should be in the order of $0.45\lambda_{eff}$ according to the Yagi design principles [25]. Here, λ_{eff} refers to the effective wavelength at the lowest frequency of operation, and is calculated as $(\varepsilon_r + 1)/2$, where ε_r is the dielectric constant of the substrate. The distance between the directors should be between $0.1\lambda_{eff}$ to $0.2\lambda_{eff}$. In order to develop a compact antenna we choose the value of $0.1\lambda_{eff}$. It should be noticed that the total impedance bandwidth of the antenna array is limited by the series-fed feeding network, thus to calculate the initial value of designing parameters, the design frequency for the proposed antenna is set to 15.9 GHz (while the desired center frequency is 16.26 GHz) which results in the following initial values of the antenna parameters assuming the substrate to be Rogers RT/duroid 5880 (0.508 mm, $\varepsilon_r = 2.2$): $L_d = 7.3$ mm; $W_d = 0.35$ mm; $L_{dir1} = 6.5$ mm; $W_{dir1} = 0.35$ mm; $L_{dir2} = 4.1$ mm; $W_{dir2} = 0.8$ mm; $S_{ref} = 2$ mm; $S_d = 1.46$ mm. The Ansoft's HFSS is used to optimize the antenna element design to achieve high F/B and high input impedance. This leads to following antenna dimensions: $L = 310$ mm; $W = 20$ mm; $W_f = 1.5$ mm; $L_d = 6.96$ mm;

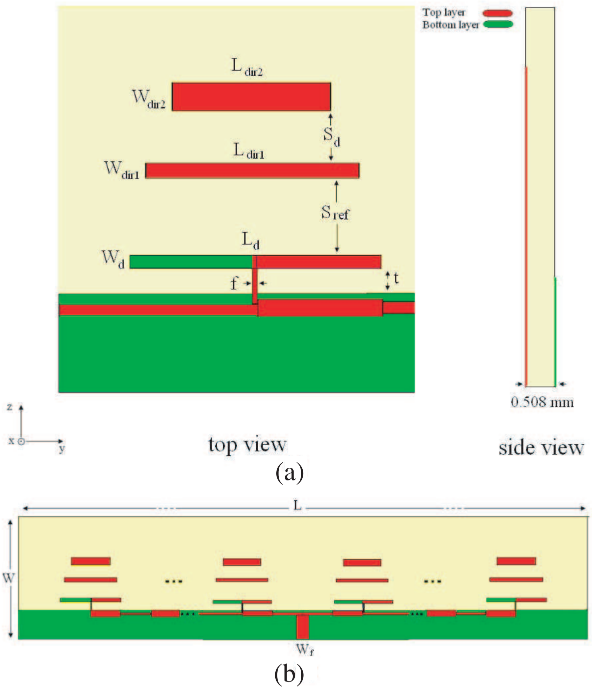

Figure 1. Series fed printed Yagi-like antenna array. (a) The single antenna element (b) The antenna array details.

$W_d = 0.35\,\text{mm}$; $L_{dir1} = 6\,\text{mm}$; $W_{dir1} = 0.35\,\text{mm}$; $L_{dir2} = 4.4\,\text{mm}$; $W_{dir2} = 0.8\,\text{mm}$; $S_{ref} = 2.2\,\text{mm}$; $S_d = 1.5\,\text{mm}$; $t = 1\,\text{mm}$; $f = 0.1\,\text{mm}$.

The microstrip series-fed Yagi-like antenna array is shown in Fig. 1(b). The array contains 22 similar Yagi-like antenna elements. The array is of resonant type and is designed for radiation in the end-fire direction. The design center frequency is 16.26 GHz. The antenna array is split in to two linear sub arrays and fed in the middle. This symmetric arrangement further improves the cross-polarization level of the array and prevents the beam-pointing direction from varying with frequency. As such, the cross polar component generated in one side of array is cancelled by the cross polar component generated in opposite side of array at boresight direction. In order to get a boresight pattern, the spacing between the feed points of the array elements must be set at one guided wavelength λ_g, to ensure an equal phase between the elements. The antenna array has been designed for a -35 dB SLL through appropriate Chebychev taper distribution. A tapered distribution is readily obtained using quarter-wavelength transformers along the line. After obtaining the amplitude coefficients, the ratio n, between amplitude of any two neighboring elements is calculated. According to [26, 27], square root of this ratio gives the relative characteristic impedance of the two connected quarter wave lines, $n^{1/2} = Z_1/Z_2$. For the first 7 elements, two $\lambda_g/4$ transformers along with a $\lambda_g/2$ transformer are used. The characteristic impedance of the $\lambda_g/4$ line closer to the $\lambda_g/2$ line can be set equal to each other and the value for the other $\lambda_g/4$ line can be calculated based on the mentioned ratio. This would result in less spurious radiation from such discontinuities. Unlike the first 7 elements, for elements 7 to 11, instead of $\lambda_g/2$ lines, two $\lambda_g/4$ transformers are used (in this way for

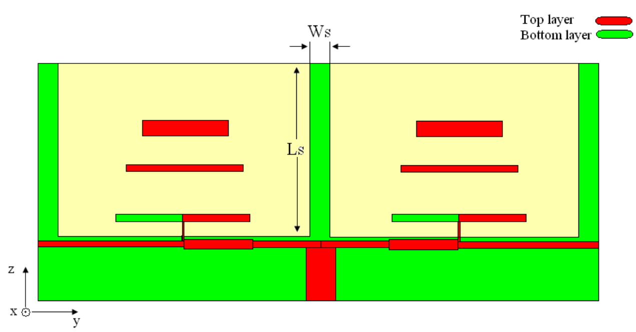

Figure 2. The center elements of the Modified series fed Yagi-like antenna array, MSFY.

the last array elements the size of the feed lines would be physically large enough to be constructed). The above ratio, $n^{1/2}$, between any two neighboring elements now should be considered for two pairs of $\lambda_g/4$. For each pair, one can consider a ratio $n^{1/4}$ between the two $\lambda_g/4$ lines and as before can assume a value for one of the $\lambda_g/4$ lines and calculate the characteristic impedance for the other line. Off course, the value chosen for the line should be such that the characteristic of the other line would be physically possible to fabricate. Overall, the characteristic impedance of the half wave lines is set at 115 Ohm while those of the quarter wave transformers are between 80–125 Ohms. The detailed design considerations for series-fed patch array are discussed in [26, 27]. Knowing the characteristic impedances of the lines, one can then calculate the lines widths and lengths between array elements.

Following the design of the single element and the array of such elements, to further improve the SLL of the array, narrow strips extended from the finite ground plane of the structure can be placed in between any of two Yagi-like elements, Fig. 2. In doing so, the effects of the surface wave coupling between the neighboring elements would be reduced. Through optimization for the lowest SLL, the size of the extended strips are $L_s = 11.64\,\mathrm{mm}$ and $W_s = 0.9\,\mathrm{mm}$.

3. RESULTS AND DISCUSSIONS

In this section, detailed simulation and experimental results of the proposed antennas are presented. Fig. 3 shows the simulated as well

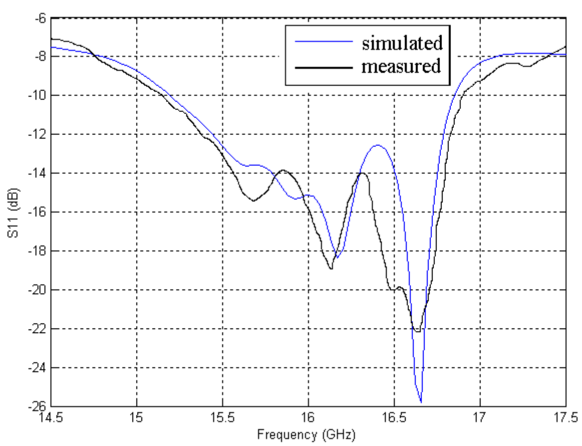

Figure 3. Simulated and Measured reflection coefficient of the SFY antenna array.

as the measured reflection coefficient of the microstrip series-fed Yagi-like antenna array, SFY, of Fig. 1(b). The results show that it has a wide impedance bandwidth of approximately 10.6%, ranging from 15.15 to 16.85 GHz for $S_{11} < -10\,\text{dB}$. In comparison to the patch antennas investigated in [1, 6, 28], the impedance bandwidth of the proposed antenna array is increased more than 4 times. The printed dipole antenna can provide wide impedance bandwidth individually. However, in the array design total achievable impedance bandwidth is limited by feeding network. The antenna is resonating around 16.2 and 16.6 GHz. These resonances may result from the lengths of the dipoles.

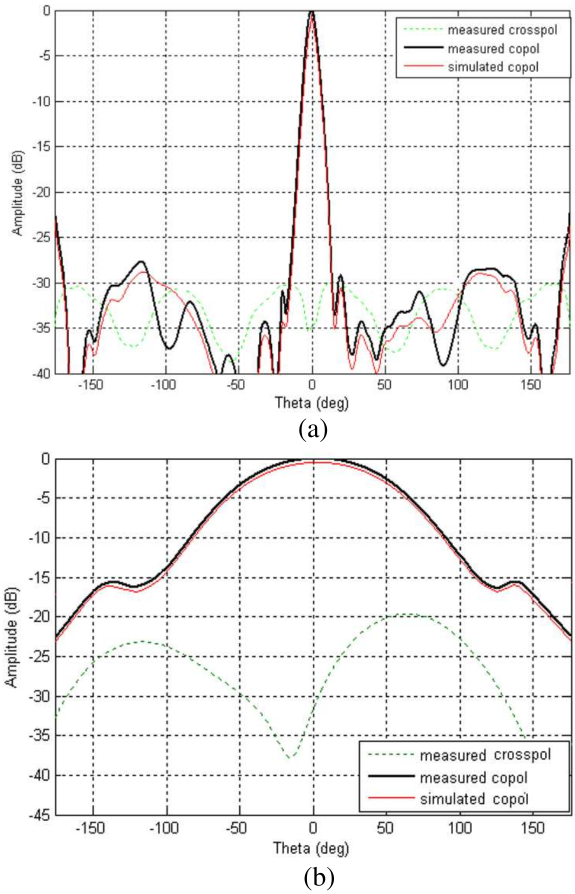

Figure 4. The simulated and measured radiation patterns of the SFY antenna array in the (a) (y-z) plane and (b) (x-z) plane.

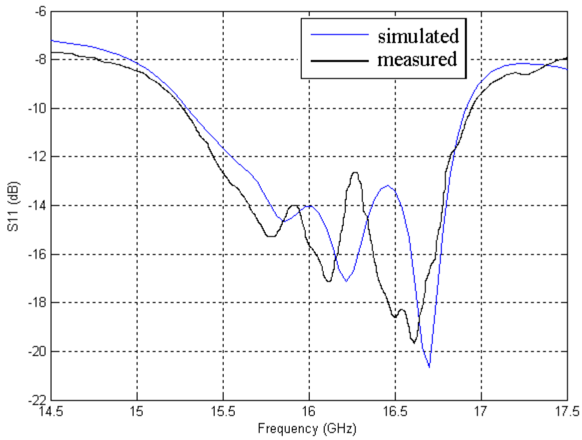

Figure 5. The simulated and measured reflection coefficient of the modified series fed Yagi-like antenna array, MSFY.

The simulated co-polar and the measured co-polar and cross-polar far-field radiation patterns in the (y-z) and (x-z) plane at the center frequency 16.26 GHz are shown in Figs. 4(a) and (b), respectively. From these figures it can be seen that the proposed antenna has a very good directional end-fire radiation pattern in the (y-z) plane and a fan beam in the (x-z) plane. The results indicate that SLL is -29 dB and the HPBW is 6° in (y-z) plane and 98° in (x-z) plane in the forward hemisphere ($-90° < \theta < +90°$). However, SLL increases to about -27 dB in the backward hemisphere. Compared to the patch antennas investigated in [6, 28], more than 8 dB improvement in SLL is observed. Also the proposed antenna has 23 dB of F/B level and a low cross polar component (i.e., < -30 dB in (y-z) plane and < -20 dB in (x-z) plane). At the beam peak, the proposed antenna has maximum co-polarization gain of 15.5 dBi at end-fire direction and the gain varies 0.6 dB within the operating bandwidth. The simulated (y-z) plane far-field pattern over the bandwidth 15.5–16.7 GHz indicate that the SLL is less than -20 dB.

To improve the SLL of the SFY antenna array, narrow strips extended from finite ground plane of the structure, between each Yagi-like antenna elements are introduced, MSFY, as shown in Fig. 2. These strips provide a path between the elements to conduct the fields more towards the forward direction (end-fire direction) and reduce the surface wave coupling between the array elements. Fig. 5 shows the simulated and measured reflection coefficient of MSFY antenna array. The results show that the presence of the grounded strips does not affect the impedance bandwidth of the array.

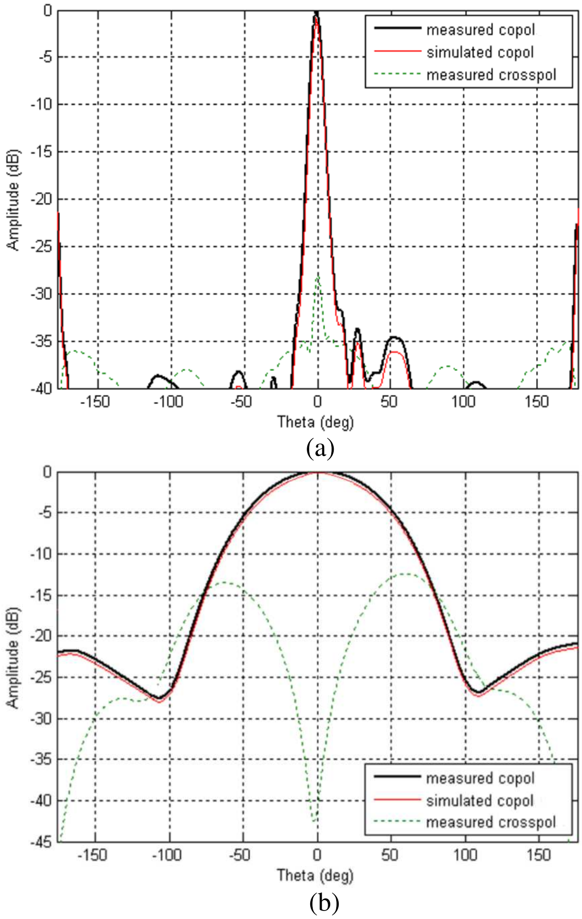

Figure 6. The simulated and measured far field radiation patterns of the MSFY antenna array at centre frequency. (a) (y-z) plane, (b) (x-z) plane.

The finite strips width, W_s, and length, L_s, have pronounced effect on the radiation pattern of the MSFY antenna array. The overall effect of changing W_s on antenna parameters is shown in Table 1. The results show that by increasing W_s the following changes can be observed: the maximum cross polarization is increased due to increase in amount of the current along the strips; the gain of the proposed antenna decreases because of adding the metallic strips reduces the efficiency of antenna.

The overall effect of changing L_s on antenna parameters is shown in Table 2. Similar to before, increasing L_s, increases the amount of

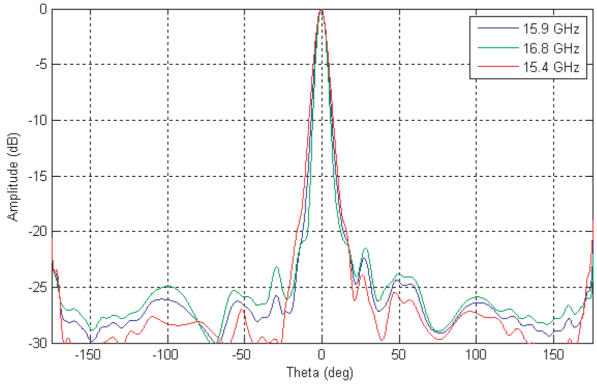

Figure 7. The simulated (y-z) plane radiation pattern of the MSFY antenna array at three different frequencies over the bandwidth.

the metallic surface on the ground plane leading to decrease in the total efficiency and gain of the antenna. Also due to the current follow along the strips which are orthogonal to the dipoles increase in cross polarization occurs. Table 3 summarizes the performance of the two antenna array structures, SFY and MSFY, described above. The MSFY array provides a lower SLL over a wider bandwidth.

Finally, to show further the applicability of the proposed design, the MSFY antenna array of the above are stacked on top of each other and simulation results for a 2-D phased array are provided. To do so, 8 linear antenna arrays with spacing of $\lambda_0/2$ are stacked on top of each other and fed through equal amplitude but with different phases are considered. the effect of beam scanning on the SLL of the proposed antenna is investigated. The simulated co-polar far-field (y-z) and (x-z) plane radiation patterns of the 2-D MSFY antenna array for $\pm 16^\circ$ at the center frequency are shown in Fig. 8. From simulation it can be observed that the SLL of the 2-D array changes over the various beam scan angles. The maximum angle which the SLL is kept below

Table 1. The effect of strip width, W_s, variation on array performance.

W_s (mm)	0.5	1	2	3
SLL (dB)	-29.2	-32	-27.6	-26
Cross polarization, Max (dB)	-18	-12.5	-10.5	-5.7
Gain (dBi)	15	14.8	13.5	11.2

Table 2. Effect of strip length, L_s, variation on array performance.

L_s (mm)	5	8	10	11.64
SLL (dB)	−26.2	−28.7	−29.8	−32
Cross polarization, Max (dB)	−19	−16.2	−13.8	−12.5
Gain (dBi)	15.3	15	14.9	14.8

Table 3. Comparison between SFY and MSFY antenna array performance.

Antenna Array type	Impedance BW (%)	Max. SLL obtainable (dB)	–20dB SLL bandwidth (%)	Gain (dBi)	F/B	cross-polar in (z-y) plane (dB)	cross-polar in (z-y) plane (dB)
SFY	10.6	29	7.5	15.5	23	–30	–20
MSFY	10.3	32	8.7	14.8	22	–27	–12.5

−20 dB is about ±16°. This means that out of this range up to ±27° the radiation pattern has a good beam shape. This scan range is higher than that reported in [28] for a series fed patch antenna arrays.

The simulated co-polar and measured co-polar and cross-polar far-field (y-z) plane and (x-z) plane radiation patterns of the MSFY antenna array at the center frequency 16.26 GHz are shown in Fig. 6. The radiation pattern of the modified antenna is similar to that of the SFY antenna array. The results show that the SLL is −32 dB and the HPBW is 6° in (y-z) plane and 76° in (x-z) plane. This means that, more than 5 dB improvement in SLL is obtained at the expense of higher cross polar component. The maximum cross polar components are < -27 dB in (y-z) plane and < -12.5 dB in (x-z) plane. Fig. 7 shows the simulated co-polar far field (y-z) plane radiation pattern of the MSFY antenna array at three different frequencies over the bandwidth. The results show that the −20 dB SLL bandwidth of the proposed antenna is 8.7% and the 3 dB SLL bandwidth with respect to the centre frequency is 1.85%.

The presence of the currents along the strips results in an increase in the cross polarization level, especially in the (x-z) plane. However, the cross polarization level at the end-fire direction is well below −38 dB which indicate that the currents on the strips does not affect the end-fire radiation much. Also the proposed antenna has 22 dB of F/B level. At the beam peak, the proposed antenna has maximum co-polarization gain of 14.8 dBi at end-fire direction and the gain varies 0.6 dB within the operating bandwidth.

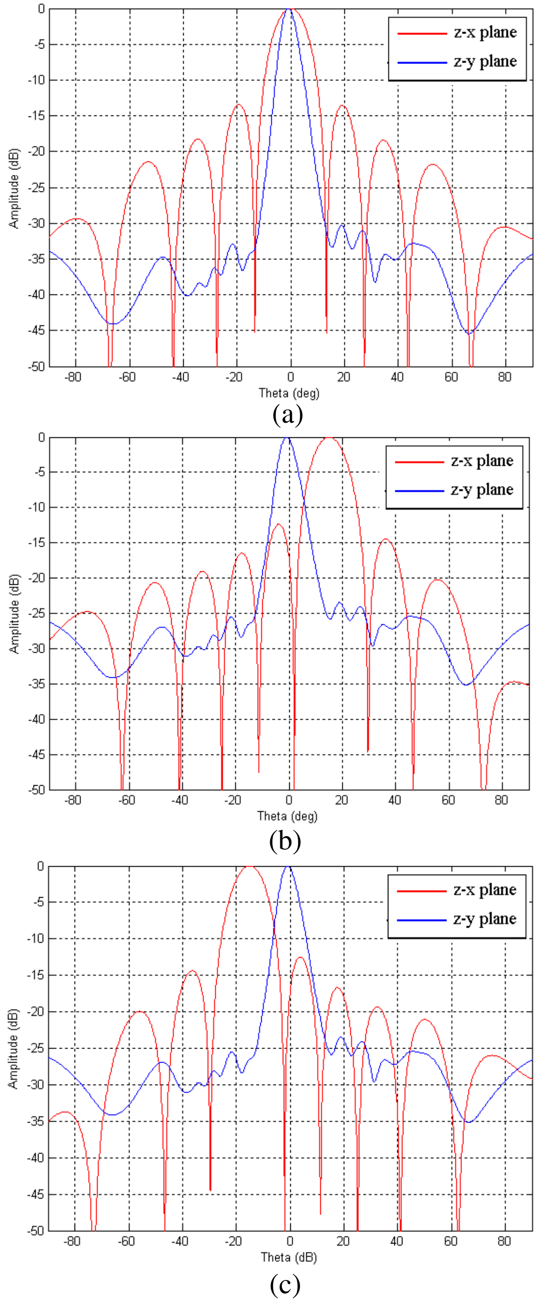

Figure 8. The simulated radiation pattern of the phased array of MSFY antenna array. Scanning angle of (a) 0°, (b) +16°, (c) −16°.

4. CONCLUSION

A low SLL, high F/B, and wide impedance bandwidth linear end fire series fed Yagi-like antenna array is proposed. By extending narrow strips from the finite ground plane of the antenna structure some 5 dB SLL improvement in the radiation pattern is obtained. Simulated and measured results on both of the arrays show a good agreement. The proposed array antenna is suitable for low SLL radar applications. A 2-D phased array of the series fed Yagi-like antenna array is shown to have a good SLL performance over a finite scan range.

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