Design and Analysis of Hybrid Feed Array for Metamaterial Loaded Microstrip Patch Antenna

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Abstract— In this paper, a novel design for metamaterial loaded rectangular microstrip antenna array has been proposed using hybrid feed combination. Metamaterial has been used as the substrate for single antenna to reduce its dimension and achieve dual band properties, while the hybrid combination of coaxial and microstrip feed has been used to accelerate the reduction of antenna array dimension. Moreover, with the help of metamaterial, dual-band operation with two different radiation pattern has also been achieved. To justify and analyze the performance of this novel design, different designs for 2 elements and 4 elements arrays have been proposed in this paper. In both arrays, the antennas and feeding network have been placed in two different layers. Unlike conventional array design, the feeding network has been designed using microstrip feed lines while coaxial feed cables have been used to connect the antennas to the feeding network. These designs successfully achieved almost 3 dB increase in the gain compared to the single element antenna. The arrays also provided smaller beamwidth and lower side lobe level.

Keywords—array, microstrip, metamaterial, ENG, feed network, coaxial feed

I. INTRODUCTION

Metamaterial is an artificial material, which has distinct electromagnetic properties those are not found in nature. In 1960, Vesleago formulated a material theoretically which had negative permeability (μ) and permittivity (ϵ) [1]. Then John Perdry proposed a structure by combining metallic wires and split-resonators (SRRs) in 2000 which opened a new research area in microwave region [2]. Metamaterial has been introduced as substrate in antenna research because of its amazing electromagnetic properties, which can reduce antenna size, increase gain or change radiation pattern [3-4]. Reduction of microstrip antenna dimension using metamaterial has been discussed in [5-7]. In [8-9], it has also been suggested that metamaterial based patch antenna can be used as dual band antenna with two different radiation patterns. On the other hand, antenna array is a combination of at least two or more antenna elements, which are connected together but act as a single antenna. The main purpose of using antenna array is to have a larger gain and narrower beamwidth [10]. Furthermore, properly designed antenna array can also be used to control the directivity of radiation pattern.

The aim of this paper is to incorporate the characteristics of miniaturization and dual-band operation in microstrip array designing. In order to achieve that, the design of rectangular microstrip patch antenna proposed in [9] has been chosen as the main antenna element. The first step of miniaturization of antenna array has been achieved by using this particular antenna. Then to reduce the size further, a novel feeding technique has been introduced. Normally in an antenna array, multiple antennas are connected through

microstrip lines known as the feeding network. For conventional patch antenna array system, both the antenna and the feed network are situated in the same plane [11-13]. But in this paper, the array has been designed keeping the antennas on a different layer above the microstrip feed network. The antennas and microstrip feed lines have been connected using coaxial feed cable. Moreover, a hollow box has been introduced to connect the grounds of both layers and to manipulate the electric field pattern. Details of the designs have been explained in section II using 2 elements and 4 elements antenna array. Then in section III, different properties of the two array designs have been analyzed. The proposed design has successfully fulfilled the target of miniaturization and dual-band operation. It also shows satisfactory performance in terms of return loss, radiation pattern and gain. It is expected that this design will enhance the use of metamaterial patch array in the field of modern communication.

II. HYBRID FEED ARRAY DESIGN

Microstrip patch antennas normally provide gain not more than 10dB. In order to have a larger gain, multiple numbers of antenna elements are connected together to form an antenna array. While designing an antenna array, designing the feeding process is very crucial. Microstrip planar antennas can mainly be fed in two methods: (a) Corporate feed (b) Series feed. As for series feed, it is difficult to implement and is also sensitive to frequency. It is also difficult to produce amplitude taper [14]. Corporate feeding method, on the other hand, provides better impedance matching and radiation pattern. So corporate feeding method has been chosen as the suitable feeding method for the proposed design. Before coming up with the proposed hybrid feed network design, different conventional corporate feeding networks have been applied to feed the antennas. But as the metamaterial loaded patch antennas had different physical structure, it was not possible for the feed network to provide current to the antennas. As a result, desired radiation pattern, gain or beamwidth were not achieved. In order to establish a proper connection between the antennas and feed network, a noble approach has been made. Instead of placing the antennas and the feed network on the same plane, the antennas have been placed on a second layer above the feed network and they have been connected to each other using coaxial cable lines. Designing process of the hybrid feed array has been discussed in details for 2 elements array and 4 elements array.

A. Feed Networks for 2 Elements & 4 Elements Array

The single element microstrip antenna that has been chosen as the antenna element provides some difficulties

Fig. 1. 2D diagram of (a) 2 elements array. (b) 4 elements array. (The dotted line represents the microstrip feed network layer and continuous line represents the antenna layer.)

while considering it for array design. First of all, calculating the input impedance of the element antenna theoretically was a great challenge. The available formulas to calculate input impedance did not provide satisfactory results for the metamaterial loaded antenna as presented in [9], which is quite different than the conventional microstrip patch antenna. The design has a patch dimension of 18mm $\times$ 25mm with a substrate height of 3mm. The substrate has normal double positive material ($\epsilon = 6.4$) and negative epsilon material ($\epsilon = -0.09$) juxtaposed side by side. Because of using metamaterial (ENG) along with normal material (DPS), the substrate is no longer homogenous. So instead of using theoretical formulas [12], which has been calculated considering a homogenous substrate, the input impedance has been calculated using the return loss magnitude achieved from the simulated results in CST. Using (1) the input impedance has been calculated as 55.16 ohms.

$$R_{in} = 50 \times \frac{1+S_{11}(\text{magnitude})}{1-S_{11}(\text{magnitude})} \quad (1)$$

2 elements and 4 elements feed network of microstrip line has been designed using T junction power dividing method [13]. All the impedance and width of different microstrip lines have been mentioned in Fig. 1. It is necessary to mention that as all the antenna elements have similar impedance and equal power is distributed between them, the feed network of the two elements on the left is similar to the feed network of the two elements on the right for Fig 1(b). As the length of the microstrip feed network does not affect the impedance, variable lengths have been used in order to keep the minimum $\lambda/4$ distance between the antenna elements. For the proposed array design, all the antenna elements are placed in parallel in a single row at one side of the ground. According to the single element antenna design in [9], there is no extended ground portion after the ENG slab. Therefore, in this array design, the elements have been placed in a way such that the ground does not have any extended portion at the edge of the antenna along the ENG side.

B. Connection Between Antennas & Feed Network

The most challenging part of the array design was to establish connection between the microstrip network and the antennas. For conventional microstrip patch antenna, the substrate is usually larger than the patch and microstrip line is used to feed the antenna. But for most of the metamaterial microstrip patch antennas in literature and also the single element metamaterial loaded antenna used in the proposed array design, the patch and the substrate occupies the same dimensions [9]. That only allows coaxial feeding method to be used for the single element antenna. As the coaxial feed line is situated perpendicularly below the antenna, it is difficult to keep the antenna and the feeding network in the same plane. So the only way to connect the antenna to the feeding network is to keep the antennas above the microstrip network and connect them using the coaxial cable. But it has to be ensured that the antenna ground does not touch the patch of the microstrip feed network. Because the width of the patch determines the impedance and as the material of both ground and patch used in this design is copper, the impedance of the microstrip lines would change if they have contact with the ground plane of antenna.

In order to establish a proper connection between both ground of the feed network and the array, a hollow box has been introduced. The thickness of the walls of the box is similar to the thickness of the ground of the antenna (0.5mm) and the material of the box is also copper. The microstrip network has been placed inside this hollow box. In order to keep the antenna ground separated from the microstrip network, the height of the walls of this hollow box is kept higher than the height of the microstrip network and the upper portion of the hollow box is covered by the ground of the antennas. There is a gap of 2 mm between the ground plane of the antennas and the patch of the microstrip feed network. The pin of the coaxial cable that is connected to the patch of the antenna has been extended below and has been added to the patch of the feed network as shown in Fig. 2. Similarly, the top and bottom wall of the hollow box is acting as the ground planes of the antennas and the microstrip feed. They are also connected to each other by the side walls. Finally, coaxial feed has been used as the main feeding technique. The use of this hollow box not only allowed to set up proper connection between the microstrip feed line and antennas but also manipulated the electric and magnetic field pattern which helped to achieve desired radiation pattern. The effects of the hollow box have been discussed in details in the next section.

Fig. 2. 3D cross section of array (2 elements) (a) Bottom view, (b) Side view

III. RESULT ANALYSIS

Both the proposed designs in the previous section have been simulated in CST Studio Suite and satisfactory results have been found. Different properties of the arrays have been discussed and analyzed in the following sub-sections.

A. Return Loss

Fig. 3. shows the S-parameter of both proposed designs. For 2-elements array, the first dominant resonant frequency (TM_{010}) has been found at 2.82 GHz with return-loss of -14.15 dB and return-loss for second dominant resonant frequency (5.28 GHz) is -20.93 dB. For 4 elements array, multiple resonance has been found for different frequencies but based on the gain value and the electric field pattern, the first and second dominant resonant frequencies have been identified at 2.83 GHz (TM_{010} mode) and 5.44 GHz (TM_{020} mode) with return-losses of -22.14 dB and -16.6 dB respectively. It is necessary to mention that increasing the number of antenna elements in an array may create multiple resonance within a short distance along the frequency domain but not all of them are effective. From a 16 elements design, not mentioned in this paper, it has been found that number of resonance is much higher than that of the 2 and 4 elements array. Based on the comparison of 2 elements and 4 elements antenna array it can be concluded that the return loss curve is in strong agreement with the return loss curve of the single element antenna in [19]

Fig. 3. Simulated S-parameter of 2 elements and 4 elements antenna array

Fig.4.Polar radiation pattern of 2 elements and 4 elements antenna array for (a) TM_{010} mode & (b) TM_{020} mode.

B. Gain & Radiation Pattern

The polar radiation patterns of TM_{010} mode of 2-elements and 4-elements array have been illustrated in Fig. 4. For 2-elements array, the radiation pattern at 2.82 GHz is broadside with maximum gain of 7.51 dB for the main lobe. For 4-elements array, a broadside radiation pattern is also found at 2.83 GHz with a maximum gain of 10.2dB. For TM_{020} mode, 2-elements array has the conventional bi-directional radiation

pattern where two main lobes are radiating opposite to each other. The lobe near to DPS has a gain of 6.94 dB whereas gain of the lobe near the ENG is 6.2 dB. For 4-elements array, the radiation pattern is also bidirectional with different gains of 9.23 dB for DPS side and 7.16 dB for ENG side. It can be concluded that both the arrays have successfully increased the gain compared to the single antenna. But the downside of the designs are that the TM_{020} mode has lost the characteristics of maximum gain in single direction that the element antenna had in [9] with the compensation of an increase of gain. The two main characteristics of any array are the increase of side lobes and decrease of beam-width. The proposed two designs show similar characteristics in these regards. In Fig. 5, it can be observed that for TM_{010} mode, 2 elements array does not have any notable side lobe whereas for 4 elements array there are side lobes along the y axis. For TM_{020} mode, though both the arrays have side lobes, the magnitude of the side lobes has increased in 4 elements array comparing to the 2 elements array. Moreover for both the resonance modes the beamwidth have decreased noticeably.

Fig.5. 3D radiation pattern of (a) TM_{010} for 2 elements (b) TM_{020} for 2 elements (c) TM_{010} for 4 elements (d) TM_{020} for 4 elements

Fig. 6. Electric field pattern of 2 elements array for (a) TM_{010} (b) TM_{020} mode

C. Electric Field Pattern

It has already been stated earlier that, one of the main targets of introducing this novel design is to establish connection between the antennas and microstrip feed network located at different planes. Electric field analysis for different resonance modes indicates that the proposed designs are successful in this regard. Fig. 6. shows the electric field pattern of TM_{010} & TM_{020} mode for 2 elements array. It is clearly visible that both the antennas are showing electric field patterns associated to them. More importantly the, direction and the phase shift of the electric field pattern is similar to that of conventional electric field pattern for TM_{010} & TM_{020} mode [11]. The hollow box played an important role in controlling the electric field pattern. From different simulations, it has been found that the distance of the sides of the hollow box from the microstrip lines causes change to the electric field pattern, which in the long run affects the return loss and radiation pattern. The probable reason behind this effect can be explained using cavity model. The walls of the hollow box works as a boundary of a large cavity and helps to keep the electric field concentrated in the microstrip lines. It has been found that when the distance between the walls and microstrip lines is increased, the electric field deforms and less current is delivered to the antennas. After lots of simulation, satisfactory results have been found for the proposed designs. Though not represented in figures here, all the other electric field patterns for the resonance modes for 4 element array also maintain conventional characteristics. This is a clear indication that the proposed hybrid microstrip feed network is capable to excite the antennas positioned at a different plane.

IV. CONCLUSION

In this work, designs of 2 elements and 4 elements antenna array with hybrid feeding method have been proposed. The proposed design has a smaller dimension than the conventional array and also have two radiation pattern for two different frequency bands. Both the designs are a successful representation of the proposed feeding technique that uses microstrip and co axial feed lines at the same time. It has also established a technique to feed metamaterial based antennas in different layers, which also consumes comparatively small space. This kind of feeding technique will be very useful for metamaterial based antennas as they often have a similar dimension for patch and substrate. The use of metamaterial has primarily reduced the size of antenna which helped to reduce antenna array size in the long run. Moreover, it allowed incorporating dual band operation in the array. In terms of performance, both the arrays show satisfactory results. With the increasing number of antenna elements in the array, it is possible to achieve higher gain and lower beamwidth. Though the side lobes may also increase but they are hardly affecting the overall radiation pattern. Antenna array of this kind can be used in satellite communication, object tracking and for communication in remote areas. The single element antenna used for designing the array operates in 2-6 GHz range. Because of the individual size of this type of antenna, it is very difficult to use more than four antennas in an array because of excessive power loss. So only 2 elements and 4 elements metamaterial loaded antenna array has been analyzed in this paper. But the

proposed novel hybrid feeding technique can also be used for mmWave and terahertz antennas which can be incorporated in designing arrays with huge number of antennas or in the field of massive MIMO system. The use of metamaterial in antenna designing has already enhanced the efficiency of single antenna by reducing its size [7] and modifying the higher modes for application [9]. Now with the proposed design, it will also be possible to build metamaterial based microstrip patch antenna arrays. It is expected that in near future, metamaterial based antenna array will introduce new applications for planner antenna arrays in the field of communication.

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