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AN OUT-OF-LINE SERIES-FED MICROSTRIP ARRAY FED BY NOVEL CURLED-HORN-SHAPED STUB WITH LOW CROSS-POLARIZATION

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Abstract—A novel out-of-line series-fed patch array with low cross-polarization is presented in this paper. The element in the array is fed by a stub through one-port. The feeding stub is designed to be a novel curled-horn-shaped geometry, which can effectively suppress the cross-polarization due to its symmetry. The linear array consists of two identical subarrays which are located oppositely. By the antiphase feeding of two subarrays, the cross-polarization is further reduced. Furthermore, the theory analyses of the series-fed array indicate that it is competent for being applied to phased array systems. The simulated results show the cross-polarization levels of the linear array with 20 novel elements in E and H plane are lower than -30 dB and -60 dB, respectively. And, a prototype array is fabricated. Its low cross-polarization levels confirm the effective performance of the proposed design.

1. INTRODUCTION

Microstrip patch series-fed arrays have been widely applied to the radar and communication systems due to their low cost, light weight, good compactness, relatively higher antenna efficiency, and excellent conformal ability. Series-fed arrays can be sorted into two types by the difference feeding method of the in-line and the out-of-line [1]. This literature also indicates that the in-line feed array has the least polarization control and the narrowest bandwidth although its insertion loss is smallest. As compared with it, the out-of-line feed array has an agile polarization governing: only by altering

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the feeding port location of each patch element, the horizontal or vertical polarization can be obtained conveniently without altering the arrangement direction of the elements. Furthermore, a microstrip combline array [2] can be built up by combining the branch feed line with the primary feed line in out-of-line feed arrays, which means out-of-line feed arrays will become more flexible in array design.

Nevertheless, out-of-line series-fed patch arrays have a certain disadvantage: the polarization purity will be worsened significantly, as the patches are arrayed along the direction of polarization. Generally speaking, it is caused by the increase of the cross-polarization of the element. Accordingly, some measures that reduce the cross-polarization of the patch can overcome the drawback. Such as the balanced-feed technique [3, 4], the dual L-shaped printed antenna [5], the cross patch fed by two ports [6], the antenna fed by two printed L-probes [7], the differential-fed patch antenna with folded plate pair [8], and the aperture-coupled antenna using dual thin slots with a 180° phase shift [9]. These methods are alike essentially. They all have the two feeding ports with 180° out of phase or in-phase which are positioned symmetrically relative to the center of the patch. The limitation of these methods is mostly that the two feeding ports will result in the complication of the feed network. Another measure is that the adjacent rows or columns of elements in a planar array are oppositely excited in phase and in orientation [1, 10, 11]. However, the antiphase feeding technique with the opposite feed ports only makes the synthesis radiations of a planar array in the cross plane be suppressed. In fact, the cross radiations of each element and linear array themselves have not been reduced. Consequently, the phase offset between the adjacent rows or columns of elements must be a stable 180° to retain the low cross-polarization, and this kind of planar array is difficult to achieve phased scan with high polarization purity.

To improve the element polarization purity in the case referred to above, a method using a novel curled-horn-shaped feeding stub is investigated in this paper. With its help, the low cross-polarization of the patch element is realized. On this basis, by dividing the out-of-line series-fed linear array composed of the novel patch elements into two symmetrical subarrays which are fed with antiphase, the cross-polarization of the linear array is further decreased. To validate the proposed methods, a linear array with 20 novel patch elements is designed and fabricated. The measured results show the high polarization purity in E and H plane. The scan characteristic of the planar array constituted by this type of linear array is also analyzed in this paper.

2. LOW CROSS-POLARIZED RADIATION SOLUTION

In an out-of-line series-fed array, the feeding stub will be bended to a right angle as the direction of polarization is same with that of the elements arrangement. For example, some patch elements with horizontal polarization are rowed to consist of a series-fed array, just as shown in Fig. 1. Each element is uniform with the dimension of $L \times W$. The element spacing is d. The feeding network and patches are coplanar. The thickness of the substrate is h, and its permittivity is ε_r. In order to afford a strict comparison between the novel and conventional series-fed array in the matter of the cross-polarization, all illustrations in Sections 2 and 3 are simulated at the identical frequency with the same parameters as follows: $L = 10.8\,\text{mm}$, $W = 8.0\,\text{mm}$, $h = 1.27\,\text{mm}$, $\varepsilon_r = 2.2$.

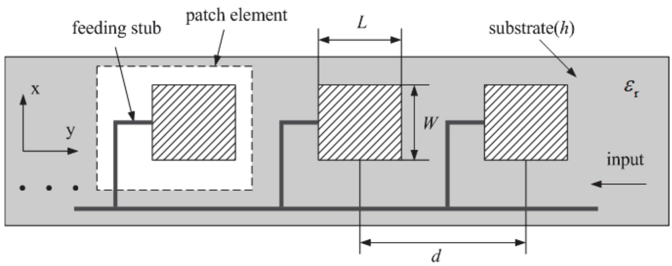


Figure 1. Geometry of the series-fed patch array with the conventional feeding stub.

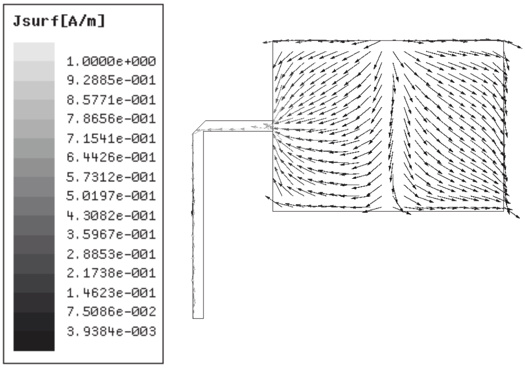


Figure 2. Surface currents on the patch element with the conventional feeding stub.

Due to the coupling of the vertical part of the stub and the non-radiation edge of the patch near that, the surface currents on the patch not always flow along one direction, and a portion of the surface currents on the patch will flow towards the vertical direction, as shown in Fig. 2. Moreover, the polarization direction of the spurious radiation from the stub and the co-polarization of the patch are cross. Consequently, the cross-polarization levels of the patch are raised. The simulated radiations of the patch element are revealed in Fig. 3.

The cross-polarization can be suppressed by feeding the opposite feed ports with antiphase. However, it only makes the cross-polarization of the plane about which the antenna configuration is symmetrical be depressed. Because there is the existence of symmetrical structure only about a certain direction for a linear array, the cross-polarization can be suppressed only in the H plane, and that in E plane is not reduced effectively for the array shown in Fig. 1 by the method. A linear array with four elements is simulated for proving the conclusion. The structure of the array is illustrated in Fig. 4. The two patches in the edge of the array are designed as the radiating match load. The patches are excited uniformly in phase and amplitude. The element spacing is λ_g (λ_g is the wavelength in the dielectric substrate). The simulated results are depicted in Fig. 5.

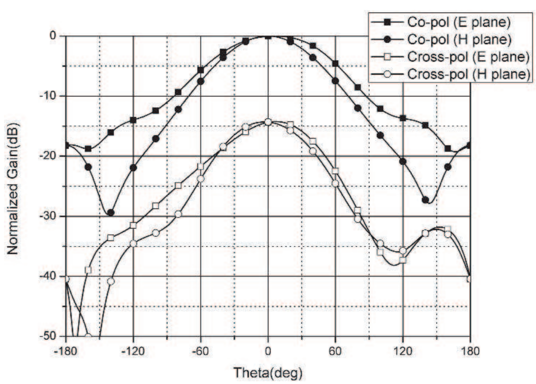


Figure 3. Simulated radiation patterns of the patch element with the conventional feeding stub.

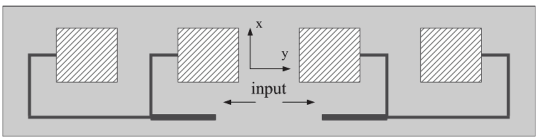


Figure 4. Structure of the linear array fed by two ports with four elements.

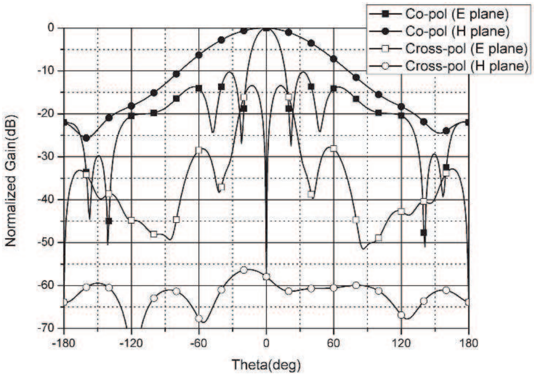


Figure 5. Simulated radiation patterns of the linear array with the conventional feeding stub.

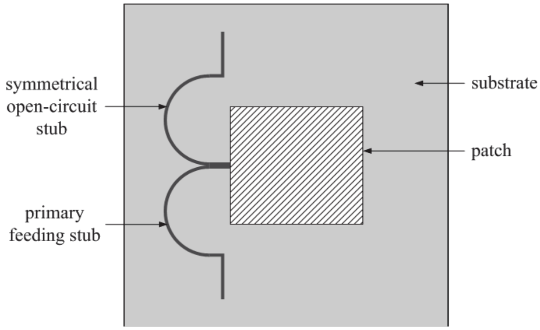


Figure 6. Structure of the patch with a novel curled-horn-shaped feeding stub.

The analyses referred above demonstrate the cross-polarization in E plane will be suppressed, if there is a symmetrical structure about y-axis in the antenna element. Hence, a microstrip patch antenna element fed by a novel cured-horn-shaped stub as shown in Fig. 6 is present in this paper.

The novel cured-horn-shaped feeding stub consists of the primary feeding and open-circuit stub. Each stub is designed as the same structure, and they are located oppositely with respect to the horizontal centerline of the patch. The length of the open-circuit stub is $1/2\lambda_g$. The energy at the termination of the stub can be reflected back to the patch. The phase of the currents on the two stubs surface is opposite, and the amplitude is reasonably identical, as revealed in Fig. 7. Therefore, the coupling effects of the stub and the two non-radiation edges of the patch can be canceled, and the currents on

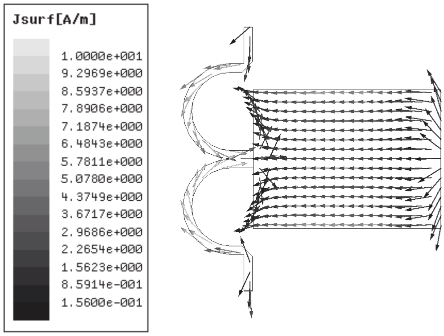


Figure 7. Surface current distribution of the patch with the curled-horn-shaped feeding stub.

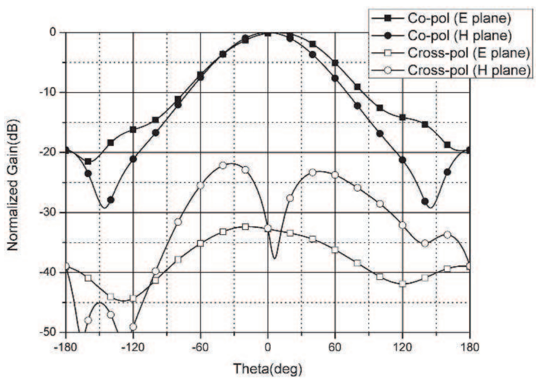


Figure 8. Simulated radiation patterns of the patch element with the novel feeding stub.

the patch mostly flow along the horizontal direction accordingly. In addition, the spurious radiation from the stub in the vertical plane can also be canceled. In respect that it is unable to attain the absolute cancelation of all radiations from the stub, the right angle stub shown in Fig. 1 is modified to be curled, which can further reduce the vertical component of the electric field. As a result, the antenna provides a relatively higher purity of horizontal linear polarization. Fig. 8 shows the simulated radiations of the novel patch.

The method also gives a flexibility of design: when the feeding stub is bended due to the limitation of the size or other matters, the relatively nice polarization purity can be supplied by using only one feeding port. On the side, the level of cross-polarization can be optimized by adjusting the shape of the stub and the space between the two stubs. A linear array composed of four novel patches is simulated,

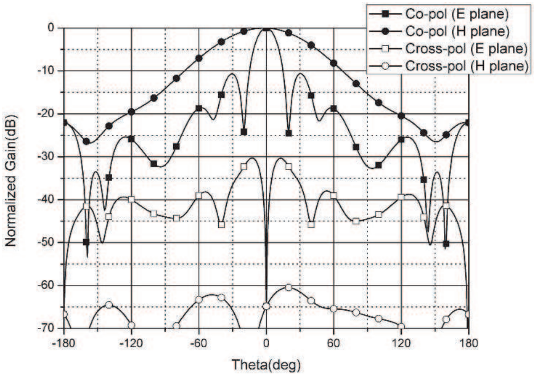


Figure 9. Simulated radiation patterns of the linear array with the novel feeding stub.

and the results are shown in Fig. 9. The construction of the array is same as the conventional series-fed array shown in Fig. 4. The elements spacing is also λ_g for broadside radiation. As compared with the results revealed in Fig. 5, the cross-polarization level of the novel linear array in E plane is greatly decreased.

3. SCAN CHARACTERISTIC OF THE NOVEL SERIES-FED ARRAY

When the conventional series-fed linear array shown in Fig. 1 is employed to construct a planar array, the phased scan with low cross-polarization is unable to be achieved. The reason is that the phase offset of the adjacent rows or columns of linear arrays cannot be change to pursue low cross-polarized radiations. In contrast to that, the maximal advantage of the novel linear array is that it can provide relatively higher linear polarization purity by itself, so that the phase offset excited to the adjacent linear arrays has not need to be a stable value. The characteristic indicates the phased scan can be obtained by controlling the phase of each linear array.

A planar array with 40 elements is simulated for discussing the change of the cross-polarization when it scans. The planar array consists of 10 uniform linear arrays with 4 novel patch elements. The linear array spacing is 0.6 free space wavelength in the vertical orientation. In respect that there is only the requirement of the qualitative analyses, the current amplitudes of the linear arrays are accorded with uniform distribution. In order to avoid the occurrence of the nearest grating lobe, the scan angle is restricted and must satisfy the follow formula [12]:

$$\frac{d_x}{\lambda_0} \leq \frac{1}{1+\sin\theta_0} \tag{1}$$

θ_0 is the scan angle, d_x is the spacing of the linear array, and λ_0 is wavelength in free space of the operating frequency. The formula indicates the scan angle has a largest value in theory for given d_x and λ_0. In this instance, the value is estimated at 40°. Hence, the analyses range of the scan characteristic is restricted in the value. The simulated results are shown in Fig. 10. The phase offset can be calculated by the follow equation [12]:

$$\phi = \frac{2\pi}{\lambda_0} d_x \sin\theta_0 \tag{2}$$

where ϕ is phase offset. Its value is 0°, 74°, 108° and 140° at scan angle of 0°, 20°, 30° and 40°, respectively.

As can be seen from the results, the cross-polarization is always a superduper performance within the scan range of ±20°. Although it in E plane runs up obviously at scan angle of 30°, it is still lower than −22 dB. But as the scan angle continues to be increased, the cross-polarization in E plane will deteriorate seriously. The cause of the phenomena can be explained as follows: As the scan angle increases, the feed phase offset between each linear array will be close to 180°, and result in the enhancement of x-direction component of the electric field under the mutual coupling influence of adjacent patches accordingly. Fig. 11 shows the current distribution in such a case. Thus, the cross-polarized radiation in E plane will be excited strongly.

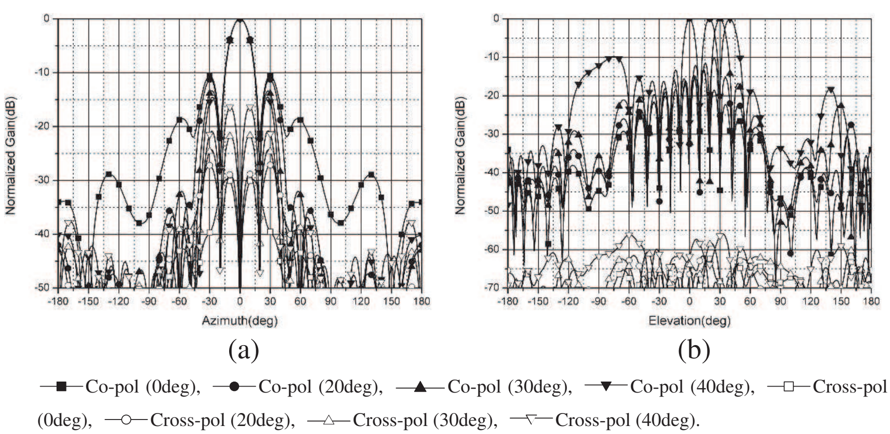


Figure 10. Simulated radiation of the planar array with different scan angle. (a) E plane, (b) H plane.

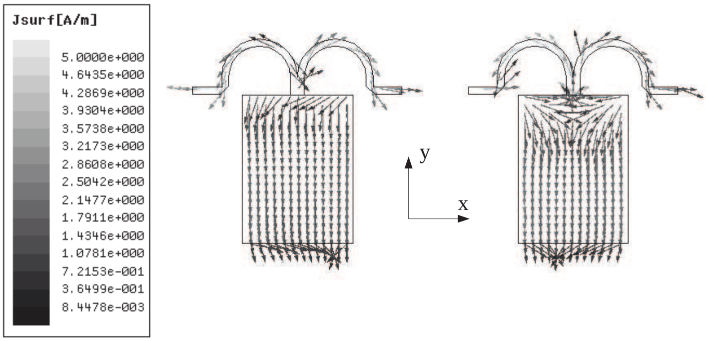


Figure 11. Surface current distribution of the patch and stub of the adjacent center embedded elements in the array. (scan angle is 40°, and phase offset is 140°).

In despite of that, because the x-direction component of the electric field is symmetrical about x-axis, it yields a null in the boresight. And thanks to the phase excited in the horizontal plane being always countering, the cross-polarized radiation in H plane is suppressed at all time.

4. SERIES-FED ARRAY DESIGN

Based on the analyses, a linear array with 20 novel elements is designed. The array consists of two series-fed identical subarrays with 10 patches which are located oppositely. The two terminations of each subarray are a matched load patch and a reflected stub, respectively. It is similar to the array structure in the literature [10]. In order to achieve the current distribution conveniently, avoid the larger insertion loss and the reflected power, the probe feed point of each subarray is located the center of the fourth and fifth element from the linear array center. The computational current distribution of the array is designed for -25 dB sidelobe in E plane. Each patch is designed with the same size, and the power division is achieved by the impedance transform of the transmission lines. The sketch map of the subarray in the left half and the physical photograph of the linear array are shown in Fig. 12 and Fig. 13, respectively. The array sizes are $520\,\text{mm} \times 22\,\text{mm}$. The thickness and the permittivity of the substrate are 1.27 mm and 2.2, separately. The patch element spacing is λ_g, and the dimensions of each patch are $10.4\,\text{mm} \times 8.5\,\text{mm}$.

Figure 14 depicts the comparison of simulated and measured VSWR. On account of the symmetrical structure of the array, only the

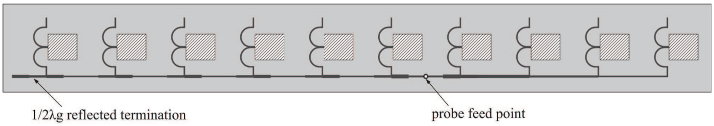


Figure 12. Subarray in the left half of the linear array.

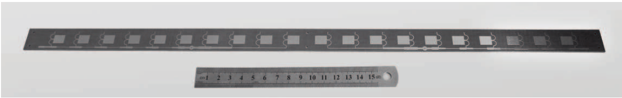


Figure 13. Top view of the linear array.

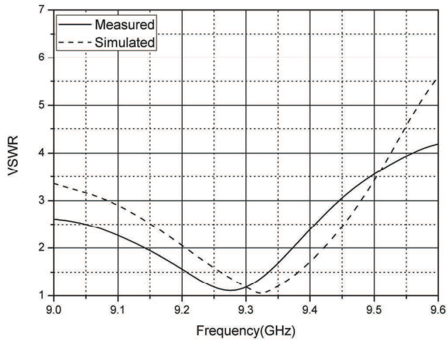
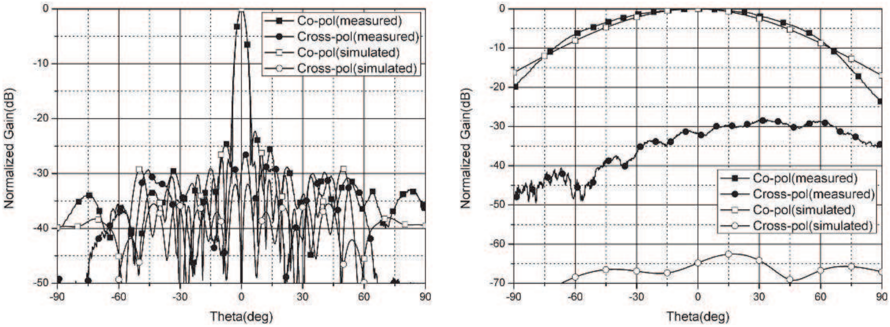


Figure 14. Measured and simulated VSWR of the linear array with 20 elements.

VSWR results of the left feeding port is displayed. As can be seen, the resonant frequency is 9.32 GHz calculated by HFSS, and the measured resonant frequency is 9.28 GHz. The measured resonance of the array is somewhat shifted downwards to the lower frequency band, but the relative offset whose value is 0.43% is small. The resonant frequency discrepancy is mostly due to the nonuniformity of the dielectric, the difference of simulation and fabrication. The radiation patterns of the linear array are measured with a 2-way power divider and a 180° phase shifter. The simulated and measured results are revealed in Fig. 15. The simulated side lobe level is below -26 dB in E plane, and the simulated cross-polarization levels are less than -30 dB and -60 dB in E and H plane, separately. The measured side lobe level is made asymmetric somewhat since the amplitude and phase errors between two feeding ports of the linear array. In addition to the amplitude and phase errors of each element due to the spurious radiations of the coplanar feed network and the fabrication errors, the measured maximum side lobe level is higher than the simulated results, and its



(a) (b)

Figure 15. Measured and simulated radiation patterns of the linear array with 20 elements at 9.28 GHz. (a) E plane, (b) H plane.

value is −22.4 dB. The deterioration of the measured cross-polarization is mostly caused by the installation errors. When the linear array is not ideally parallel with ground, the array radiation power will be divided into two components, and the electric field direction of one component is vertical with ground, which results in the increase of radiation at the vertical direction. According to our studies, for such low cross-polarization levels, the increase of the radiation at the vertical direction due to a small angle between the fixed plane of the array and the horizon can result in a sharp deterioration of the cross-polarization. Furthermore, the lower cross-polarization level, it is more sensitive to the errors. Nevertheless, the measure cross-polarization levels are below −26 dB and −28 dB in E and H plane, respectively. The performances still exceed them of the series-fed array fed by the conventional feed stub shown in Fig. 1, which confirms that the design approach to improve the polarization purity is effective.

5. CONCLUSION

A solution to low cross-polarization for the out-of-line series-fed patch linear array has been investigated in this paper. By the novel curled-horn-shaped feeding stub and opposite feed point with antiphase feeding, the cross-polarization of the linear array will be reduced, as the arrangement of the patch elements is along the direction of polarization. Moreover, a planar array constructed by the linear array can realize phased scan with low cross polarized radiations in a certain range. Accordingly, the application area of the out-of-line series-fed patch array is extended extremely. In the meantime, the theory analyses indicate that the cross-polarization of the patch with the novel stub can still be reduced in certain extent, even if the feed stub has need to be bended for special applications. It is means the further degrees of freedom in the feeding network design is also given.

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