Circularly Polarized Planar Antenna Array Using Linear Polarized Microstrip Antenna with Beamforming for SAR Applications

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Abstract. Circular polarization is so important for satellite and SAR applications. Therefore, a relatively large planar array of 10 × 10 building blocks is proposed to get a high gain and to have the possibility of beamforming for such applications. The individual antenna element used in this array is a linear U-slotted microstrip patch. This allows for simplicity, lightweight and low cost. At first, a subarray of these microstrip antennas is constructed and analyzed to become a building block for the large array. This subarray is formed of four U-slotted microstrip antenna elements arranged in a cross form with 90° sequential rotation in orientation in space, and 90° sequential phase shift between adjacent microstrip elements. The distance between the centers of two opposite microstrip elements is selected to be 0.53λ₀. A linear array is formed of ten of these subarrays and analyzed to become one row or one column in the final planar array. The distance between subarray centers is kept to be 0.53λ₀, which implies a new arrangement technique using the superposition of elements of the adjacent subarrays. The phase and amplitude relations of this linear array are developed for beamforming using the particle swarm optimization algorithm. Finally, the planar array is formed and simulated. It also implies using the superposition theorem to get the final array form. This planar array has proved to produce a cosecant-squared radiation pattern in the ϕ = 0° plane normal to the array plane, and a flat-topped pattern in the other perpendicular plane of ϕ = 90°. This type of array is very suitable for SAR side looking applications.

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beamforming cannot be applied to them. The novelty of this work is to have a large array (of the order of $10 \times 10$ linear elements and could be more) with high gain and circular polarization radiation in the main direction. Linear elements apart from the dipoles are having cross-polarization. This cross-polarization usually spoils the circular polarization radiation especially in the case of large arrays. The effects of cross polarization of the linear elements (which are microstrip antennas in this work) used in the proposed arrangement for large arrays are not effective within a reasonable beam angle. However, in [1] a $2 \times 2$ microstrip linearly polarized antennas arranged in an array are sequentially rotated by an angle of $90^\circ$ for angular orientation and a sequential $90^\circ$ phase shift in the voltage feeds of the elements. The antenna elements are used in a loop arrangement. In [2] twelve CP corner truncated microstrip antenna elements were arranged in a CP-array of $2 \times 6$ and used in SAR application in the L-band. In this case no linear polarized elements are used. In [3], four linear rectangular microstrip elements are used to form a planar array of circularly polarized radiation. The patches are oriented with $90^\circ$ rotation, and fed by a sequential $90^\circ$ phase shift between each element and the next in sequential order. The crossed dipole antenna is discussed extensively in [4]. The configuration is formed of two dipoles crossing each other at their middle feeding points with a phase difference of $90^\circ$ between the feeds and a $90^\circ$ difference in spatial orientation of the two dipoles. This configuration is considered to be the basic configuration of the crossed linear antennas to generate CP-radiation. A wide band high gain right hand CP $2 \times 4$ arrays of patch antennas for L-band is reported in [5]. Sequential orientation rotation as well as sequential phase shift is also used in such array. In [6] 16 circular patch elements with a central cut in each element are arranged in a $4 \times 4$ array. A gain of more than 10 dB is realized with this arrangement with a bandwidth of 1.9 GHz at a center frequency of 6.3 GHz. An antenna array of $2 \times 2$ dipole elements are used to produce a switched beam in 9-directions is reported in [7]. This array is producing a wide 3-dB bandwidth of 48.6% as well as a wide axial ratio bandwidth of 46.2%. A high gain planar array of $2 \times 2$ dipole elements is given in [8]. This array is using stacked metal layers in addition to a metal reflector under the antenna to boost the gain. As seen from the above-reported work, the number of elements in the array is small. Thus the area of the array is small as well. So, the expected gain is moderate. Such a small number of elements in the array will not allow any beamforming to be applied.

In this paper a new design of circularly polarized planar array using linear polarized elements, that allows beamforming, is introduced. A U-slotted microstrip antenna element [9] is used as the building brick of the proposed large array. At first four of this microstrip antenna are arranged in a cross form to produce circularly polarized (CP) radiation. The four antennas are arranged in such a way to produce two perpendicular electric fields with a $90^\circ$ phase shift between them for the intended CP radiation. Then, this four-microstrip-antennas arrangement is used as the single element subarray for a large array (in this work $10 \times 10$ antenna array). Any two adjacent four elements subarrays are to be kept separated, center to center, by a distance of approximately $\lambda/2$. This has been achieved by superimposing two single microstrip elements, one from each of the two adjacent subarrays, on top of each other to link the two side by side four element subarrays. This concept has reduced the distance between the two centers of the adjacent subarrays, which eventually reduce the sidelobes levels. This has been extended to produce a $10 \times 10$ CP large array. Such array has been tailored to produce different beam shapes suitable for satellites and SAR applications by introducing beamforming techniques using an optimization algorithm. The particle swarm optimization algorithm (PSO) [10] is the one used in this case. A beam of a cosecant-squared shape in one plane and flat-topped in the other perpendicular plane for a $10 \times 10$ array is the radiation pattern to be realized.

After the first section, this paper is organized in the following way. In the second section the four-element subarray is to be introduced. In the third section, the design of a linear array of 10 subarrays is analyzed. In the fourth section a $10 \times 10$ array is detailed. The fifth section is devoted to the conclusions of this work.
2. Four Microstrip Antenna Elements For CP Subarray

A suitable linear element has to be used in an array for SAR applications. The one selected is a U-slotted microstrip designed at 5.3GHz, as given in [9]. The U-slotted microstrip antenna element is designed on an FR4 substrate with dielectric constant $\varepsilon_r = 4.4$, loss tangent $\delta = 0.015$ and a height $h=3.2$ mm. As shown in Figure 1, the patch has the dimensions $L = 12$ mm, $W = 12.5$ mm, and the U-slot has the dimensions $a = 8.35$ mm, $b = 10$ mm, $c = 1.35$ mm, and $W_r = 1.43$ mm. The patch is fed by a 50$\Omega$ SMA coaxial probe. The coaxial feed (probe) is positioned at $x = 0, y = F = 6.45$ mm. Four linear microstrip elements arranged in a cross form, with the successive rotation of 90$^\circ$ in space and progressive phase shift of 90$^\circ$ between each element and the next, are proposed for CP radiation. In this work, the U-slotted rectangular microstrip antenna is selected as a suitable practical element to be used to realize the mentioned cross-array. This planar antenna configuration is selected because it is wide bandwidth, easy to design and simple to fabricate. The four elements are placed with their centers on the circumference of a circle of radius $R = 15$ mm = 0.27$R$, which allows no touch between the adjacent elements. The four elements are assumed to be fabricated on one square substrate of side length 55mm. All the elements are fed with voltages of equal amplitudes but with a sequential advanced phase shift of 90$^\circ$ according to the left hand circulation as shown in Figure 1.

These dimensional parameters are set to the given values such that the operating frequency of the isolated single U-slotted microstrip antenna comes at a center frequency of 5.3GHz. The reflection coefficient $S_{11}$ for such an element using the CST package and compared with that using the HFSS package is shown in Fig.2. The two results are fairly close to each other. The bandwidth for $|S_{11}|< -10$ dB is from 5.15 to 5.45 GHz, which is about 5.4% of the center frequency (5.3 GHz). The reflection coefficient and the transfer coefficients for the elements of the four elements cross-array are shown in the same Figure. The reflection coefficient $S_{11}$ for the single element in the array has shifted slightly from that from the isolated single element. This indicates that the coupling between the elements is sufficiently low. The values of transfer parameters $S_{21}, S_{41}$ are of the same value and lower than $S_{31}$. This is because elements number 2 and 4 are orthogonal in space to element number 1. The 3-dB axial ratio band width is quite wide and extends from 4.57GHz to 6.4GHz. This satisfies an axial ratio bandwidth greater than the impedance bandwidth of the isolated single element. The maximum gain of the 4-elements array is 9dBi.

![Figure 1. Four element microstrip antenna array with 90$^\circ$ physical sequential rotation in space in addition to 90$^\circ$ sequential advanced phase shift.](image1)

![Figure 2. The reflection coefficient and axial ratio versus frequency of the linear polarized four U-slot microstrip patch elements array.](image2)
The 4-element array is arranged to produce right hand CP (RHCP) in the positive z-direction. Within the 3dB radiation pattern of the four element array, the cross polarization level (LHCP) is less than $-15dB$ as shown in Figure 3. Figure 4 indicates that the axial ratio 3 dB beamwidth extends from $-30^\circ$ to $+30^\circ$ at a frequency of 5.3GHz. Thus the 3dB CP E-field beamwidth coincides with the 3dB axial ratio beamwidth.

![Figure 3](image1.png)  
**Figure 3.** Simulated CP radiation patterns in the elevation planes $\phi = 0^\circ$ and $\phi = 90^\circ$ for RHCP and LHCP radiation for the linear polarized four U-slotted microstrip patch elements array at a frequency of 5.3GHz.

![Figure 4](image2.png)  
**Figure 4.** Variation of the axial ratio versus the elevation angle $\theta$ in the elevation planes $\phi = 0^\circ$ and $\phi = 90^\circ$ for the linear polarized four U-slotted microstrip patch elements array at a frequency of 5.3GHz.

### 3. The Linear Array of Ten Sub Array Elements

As a step towards considering the planar array, a linear array has to be considered at first. A uniform linear array is formed of 10 subarray elements of the cross arranged four microstrip elements. This array is assumed to be extending in the x-direction in the x-y plane. As the distance between the centers of the adjacent subarrays is kept at $0.53\lambda_0$, the dimensions of the ten elements array are kept at $325 \times 55mm^2$. Two microstrip elements of any two adjacent subarrays are coinciding; therefore, the currents in the two elements are to be superimposed. In the case of having the radiation in the z-direction normal to the plane of the array the currents are added and result in a current of twice the magnitude of any of them, with the orientation and phase of the two superimposed elements have been taken into consideration as shown in Figure 5. The linear array ends up with nine microstrip elements at the center with double the current magnitude of the current in one of them before superposition. Also, there are twenty two peripheral elements with current magnitude equal to the value which was for them before forming the linear array and with phase and direction as depicted in Figure 5.

![Figure 5](image3.png)  
**Figure 5.** The uniform linear CP-array of ten sub arrays with $0.53\lambda_0$ separation distance.
According to the given phase distribution, the main polarization is a right hand polarization in the positive z –direction, with the 3dB radiation beamwidth for this array is 9.4°, the first sidelobe level is 

-15dB as shown in Figure 6a. The cross polarization level (LHCP) has a value of −25dB in the main direction. In Figure 6b, it is shown that in the φ = 90° plane, the 3dB radiation beamwidth for this array is 61.5° in the positive z –direction with RHCP, which is quite close to the value of the single element subarray. For the uniform linear array of ten subarray elements, the 3dB axial ratio (AR) beamwidth in the φ = 0° plane is from −10° to +10° i.e. of width 20°. In addition, in the φ = 90° plane, as shown in Figure 7, the 3-dB axial ratio (AR) beamwidth is from −30° to +28° i.e. of width 58°. The maximum gain of thirty-one linear U-slotted microstrip elements array becomes 17.4dBic.

![Figure 6. RHCP and LHCP radiation for a uniform linear array of ten sub-arrays arranged in the x-direction at 5.3 GHz.](image1)

![Figure 7. Axial ratio variation with the angel θ in the elevation planes φ = 0° and φ = 90° for the uniform linear CP-array of ten sub-arrays at 5.3 GHz.](image2)

4. A Planar Circularly Polarized Array and Beamforming
The cross polarized four element array is used as a building block, i.e. a subarray element for a relatively large planar array. An array of 10 × 10 of these subarray elements is formed in a plane with a separation distance of 0.53λo between every two adjacent subarrays in the x –direction as well as adjacent subarrays in the y –direction. This can be achieved by using the superposition theorem to sum up each two coincident microstrip elements in one element with a resultant equivalent current equal to the sum of the currents in the two superimposed elements. When this is applied, one of the superimposed elements has to be reversed in direction and the current in the combined element will be in this case double the current of one of them. This is because the amplitudes of the currents in the crossed subarray are equal and the subarray is duplicated repeatedly to form the planar array.

For beamforming each subarray element is considered to be one unit with the four amplitudes of the four elements currents have to be multiplied by the same factor in magnitude and phase. The multiplication factor for the beamforming is determined by applying the Particle Swarm Optimization algorithm (PSO). The optimization process to obtain a specific beam shape for a planar array using the
PSO algorithm that runs to optimize linear arrays is detailed in [9]. The optimization is applied to one linear array of ten subarrays extending in the x −-z direction to form the needed radiation pattern in the x −z plane, with each subarray element is replaced by an isotropic source in the optimization algorithm. The weighting coefficients that are worked out using the PSO for one linear array of N isotropic sources (N = 10) in the x −-direction is applied to the other entire x −directed linear arrays (ten linear arrays in this case). To form the needed shape of the radiation pattern in the y −z plane, also isotropic sources are used to replace the subarrays to work out the weighting coefficients for the y −directed linear array. This means that applying the PSO to one linear array of N isotropic sources in the y −direction and the worked out multiplication coefficients are then applied to each y −directed linear array (ten linear arrays in this case also). The multiplication coefficient of one element of the y −directed array is applied to all subarray elements in its x −directed linear array of this element. This is repeated for each coefficient worked out for the y −directed linear array. This means that the coefficients of the elements of the y −directed array are repeated for the other nine y- directed arrays. In this case, the currents for the superimposed elements have to be added, and the sum is expected to be not equal to double the current in one of the superimposed microstrip elements as it was in the single linear array discussed in section 3. This will end up with the needed pattern shape in the x −z plane (φ = 0°) as well as the other needed pattern shape in the y −z plane (φ = 90°). This completes the beamforming of the three-dimensional radiation patterns.

This technique is applied to the 10 × 10 large arrays of cross-shaped subarray elements. A cosecant-squared pattern is formed in φ = 0° plane with the result is given in Figure.8a compared with the ideal cosec-squared beam within an angle range of −15° < θ < +15°. Also, a flat-topped pattern is formed in the φ = 90° plane. The result is compared with the ideal in Figure 8.b within an angle range of −20° < θ < +20°. The results are fairly close to the ideal in the range of interest. A three-dimensional radiation pattern is shown in Figure 9.

Figure 8. Radiation pattern and axial ratio obtained of a cosecant-squared planar array of 10×10 subarrays arranged in the x − y plane, with the angle θ is the off-nadir angle.

Figure 9. Three-dimensional (cosecant-squared/flat-topped) pattern synthesized by a planar array of 10 × 10 sub-arrays U-slotted microstrip patch elements.
5. Conclusion
A large size array of CP-radiation of a $10 \times 10$ subarray elements with a total of 220 linear slotted microstrip antenna elements is proposed to produce a relatively high gain, as well as its radiation pattern can be tailored to the required form. The gain of a radiation beam directed to the normal broadside direction has a maximum of $17.4 \text{ dBiC}$. To achieve this result, a CP-subarray building block of four U-slotted microstrip elements arranged in a cross-form is studied at first. A CP-linear array of ten subarrays is then simulated using a new technique for arranging the ten subarrays based on the superposition theorem to reduce the first sidelobe level. This proposed technique allows the separation distance between the individual subarrays to be close to $0.5\lambda_0$. Thus, the first sidelobe level of the order of $-15 \text{ dB}$ is obtained. A ten of this linear array are arranged side by side with keeping the separation distance between any two adjacent linear arrays to be of the order of $0.5\lambda_0$ as well. This ends up with the final planar array that has been tailored using the particle swarm optimization algorithm to get a cosecant-squared radiation pattern in the $\phi = 0^\circ$ plane and a flat-topped pattern in the $\phi = 90^\circ$ plane. This planar array is suitable for side-looking SAR applications.

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