Single-Feed Circularly Polarized Microstrip Ring Antenna and Arrays

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***Abstract*—An analysis is presented for a microstrip-feed proximity-coupled ring antenna and a four-element array. Interactions between the embedded microstrip feed and the radiating element(s) are rigorously included. Results demonstrate that circular polarization of both senses can be achieved with a ring antenna with proper design of two inner stubs located at angles of $\pm 45°$ with respect to the feedline. Theory and experiment demonstrate an axial ratio 3-dB bandwidth of 1% and the voltage standing wave ratio (VSWR) <2 bandwidth of 6.1%. The axial ratio bandwidth is typical for a microstrip antenna with perturbations, while the VSWR bandwidth is larger than for the circular or rectangular patch with perturbations. A mutual coupling study between two elements shows that the axial ratio is less than 2 dB for interelement spacing greater than $0.55\lambda_{\text{eff}}$, while the VSWR <2 for all spacings considered. A comparison between theory and experiment is provided for a 2×2 element array. The benefits of sequentially rotating the antenna elements in an array environment are presented. The axial ratio and VSWR bandwidths are both increased to 6.1% and 18% for a four-element array. A single-element antenna with two orthogonal feeds to provide both senses of polarization is demonstrated. The ring antenna is small ($D/\lambda_0 = 0.325$), the substrate thickness is thin ($H/\lambda_0 \sim 0.035$), and the microstrip feed produces a completely planar antenna system, which is compatible with microwave and millimeter integrated circuits (MICs), and monolithic microwave integrated circuits (MMICs).**

***Index Terms*—Array, circularly polarized antenna elements, microstrip, single feed.**

I. Introduction

SINGLE-feed circularly polarized antennas are currently receiving much attention. Circular polarization is beneficial because current and future commercial and military applications (e.g., satellite, terrestial communications) require the additional design freedom of not requiring alignment of the electric field vector at the receiving and transmitting locations. A single feed allows a reduction in the complexity, weight, and RF loss of an array feed. Circularly polarized microstrip antennas have the additional advantage of small size and produce a completely planar antenna, which is compatible with microwave and millimeter integrated circuits (MICs), and monolithic microwave integrated circuits (MMICs). Previous works have demonstrated single-feed microstrip, aperture square, and circular patches with perturbations [4], [5]. Excitation is either a microstrip or a stripline feed.

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This paper introduces a novel design of a single-feed antenna system; namely a ring antenna with two inner stubs fed by proximity coupling from an embedded microstrip line. There are two particular advantages of the proposed design. First, the noncontact feeding mechanism reduces the complexity of probe feeding [4]. Second, the radiation efficiency is increased compared to proximity coupling by stripline [5]. We first present an analysis of a single element. Experimental data is included and compared to theory. Second, we study the mutual coupling between two elements to determine the effects on the axial ratio. From this information we design a 2×2 element array and present experimental data. We then demonstrate how the array performance can be improved with respect to boresight axial ratio and voltage standing wave ratio (VSWR) bandwidth by sequentially rotating the individual antenna elements. Finally, a single-element antenna with two independent orthogonal feeds to provide dual circular polarization is investigated. Dual circular polarization is defined as the ability of the antenna to receive/transmit both senses of polarization at the same time. One sense would be controlled by the first feed and the other sense by the second feed. It is shown that the axial ratio and self-impedance frequency characteristics for the individual ports are similar to the single-feed case at the expense of poor isolation between ports.

II. Single Stub Ring Antenna

The geometry is shown in Fig. 1(a). The antenna is fed by a 50-Ω feedline embedded in the middle of a 62 mil substrate with dielectric constant $\epsilon_r = \epsilon_1 = \epsilon_2 = 2.2$. The microstrip is defined as a perfect electric conductor and the substrates are defined as lossless. The effective wavelength is defined as $\lambda_{\text{eff}} = \lambda_0/\sqrt{\epsilon_{\text{eff}}}$, with the effective dielectric constant given by $\epsilon_{\text{eff}} = (1.0 + \epsilon_r)/2$. It is designed for a center frequency of 6.5 GHz for the TM_{11} mode [13]. The ring inner radius is 3.0 mm and the outer radius is 7.5 mm. The ring geometry allows for a smaller physical size, $2R_o/\lambda_0 = 0.325$ than the corresponding square and circular patch geometries. Feeding by proximity coupling from a microstrip line has the advantages of increasing the impedance bandwidth by the increased antenna/ground plane spacing and improved matching capabilities by simply moving the microstrip open end underneath the antenna [9]–[11] or by using different substrate–superstrate permittivities [12]. For high-frequency applications, proximity coupling has the further advantage of reducing radiation from the feeding network. Derivation and extensive discussion of the theory and numerical methodology for microstrip elements used in this communication is presented in [1]–[3]. In this work, an extension and a more efficient version of the ALFIOS

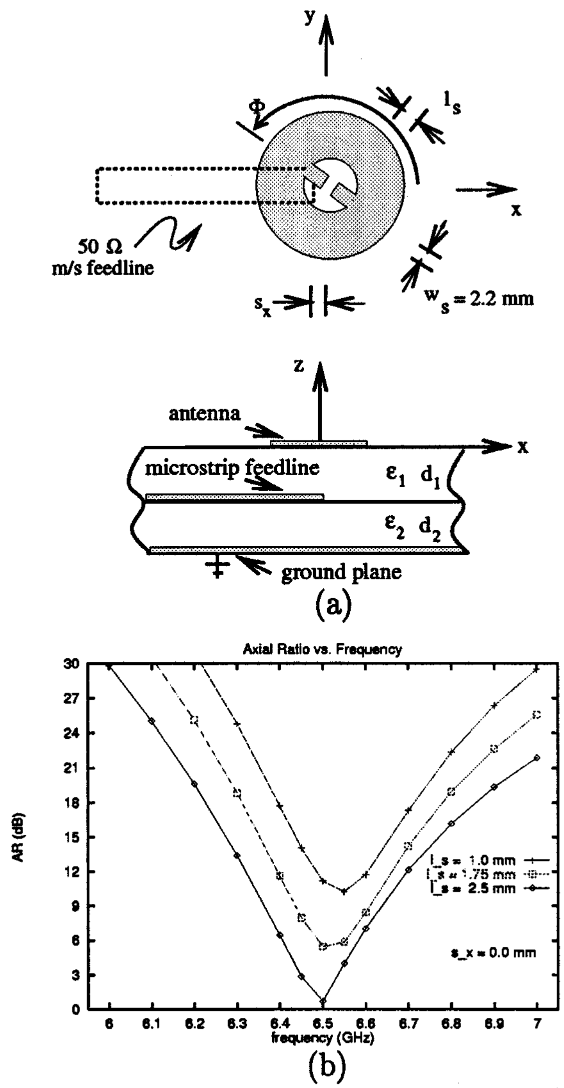

Fig. 1. (a) Single microstrip feed proximity-coupled stub ring antenna geometry. (b) Axial ratio for different inner stub lengths.

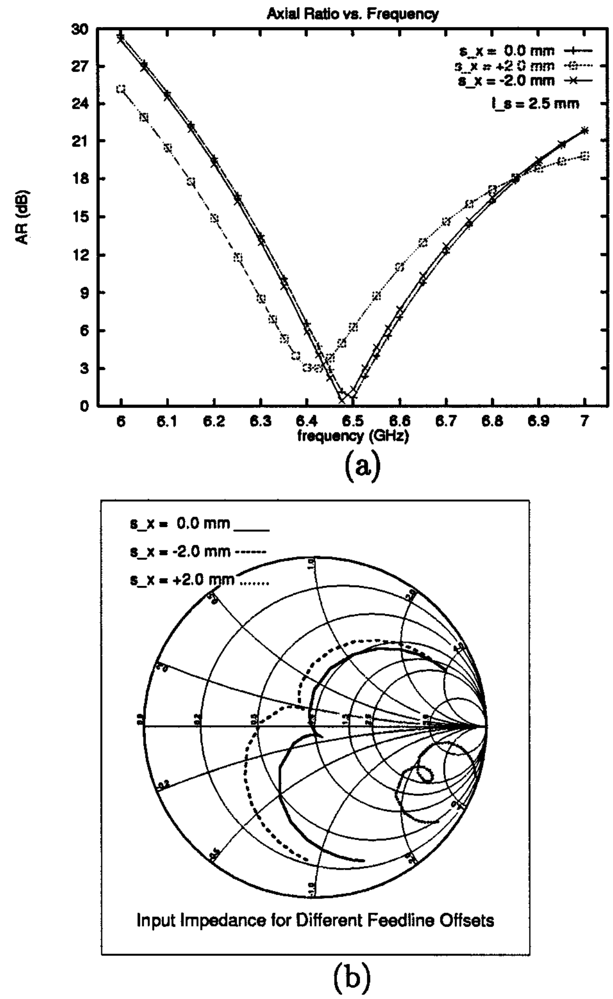

Fig. 2. (a) Axial ratio. (b) Input impedance for different feedline offsets.

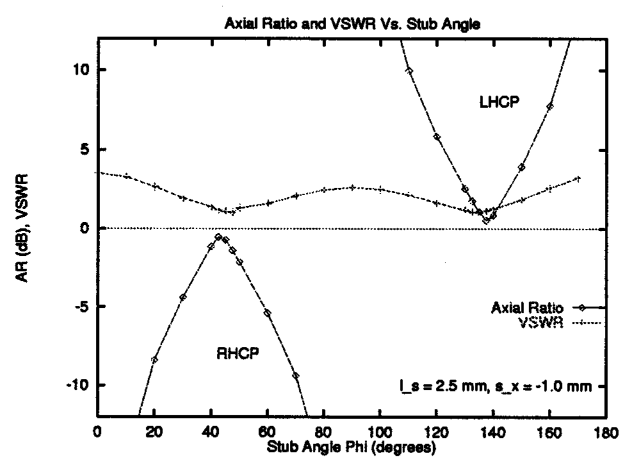

Fig. 3. Axial ratio and VSWR for different stub rotation angles of single stub ring antenna. Frequency is 6.5 GHz. Length of inner stubs is 2.5 mm and feedline offset is -1.0 mm.

moment-method-based computer code has been developed and used for the antenna designs under consideration.

A. Analysis of Antenna Geometry

Circular polarization is produced by perturbing the antenna geometry to excite two orthogonal modes and placing the feed such that these modes are excited in phase quadrature [4]. For this communication we use a ring as the antenna geometry and the perturbations are produced by adding two inner stubs. The feed is a microstrip feedline placed within the antenna substrate and excites the antenna by proximity coupling from the open end placed underneath the center of the antenna. Fig. 1(b) demonstrates the effect of the inner stub length on the axial ratio (AR) for a stub width of $w_s = 1.55$ mm and a feedline offset of $s_x = 0.0$ mm. The AR decreases with increasing stub length, with a value of 0.71 dB when the stub length is 2.5 mm. The AR bandwidth is typical of a resonant antenna—about 1.0%. Next, we investigate the effect of the feedline offset. We observe the AR increases along with a frequency shift for positive offsets while it is insensitive for negative offsets, as shown in Fig. 2(a). The input impedance as shown in Fig. 2(b) demonstrates that the optimum input match can be obtained with no feedline offset, resulting in a bandwidth of 5.4% for VSWR <2. The radiation efficiency ($P_{\text{rad}}/(P_{\text{rad}} + P_{sw})$) is 88% since the losses due to the conductors and substrate are defined as zero.

Fig. 3 shows the AR and VSWR as a function of rotation angle Φ of the ring antenna at the design frequency of 6.5 GHz.

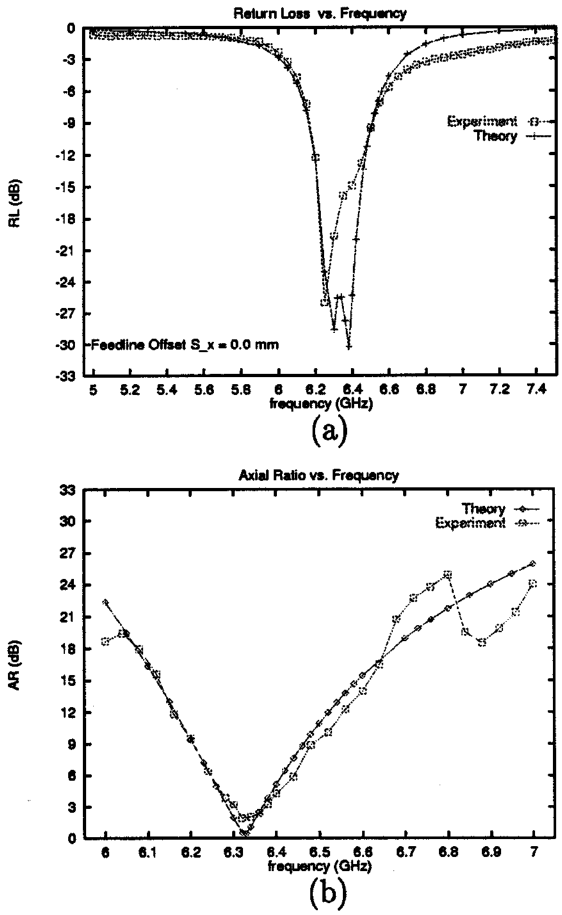

Fig. 4. Comparison of experiment and theory for single antenna. (a) Return loss. (b) Axial ratio. $d_1 = d_2 = 31$ mils, $\epsilon_1 = \epsilon_2 = 2.33\epsilon_0$, $s_x = 0.0$ mm.

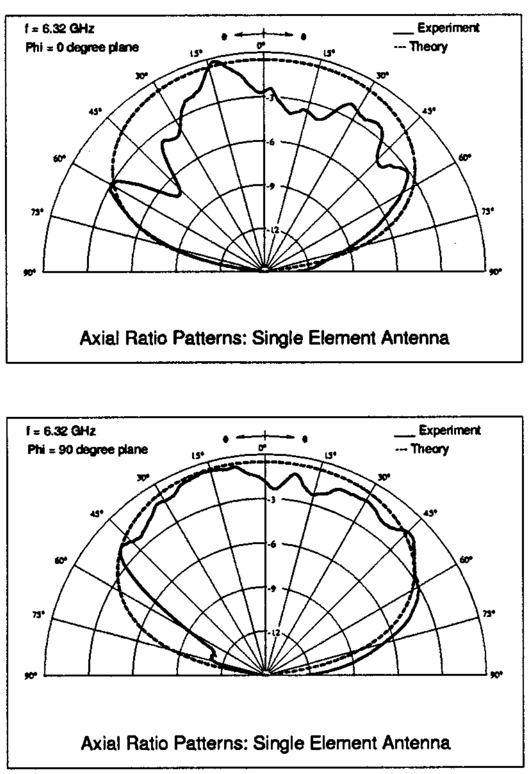

Fig. 5. Axial ratio patterns at 6.32 GHz for a single antenna.

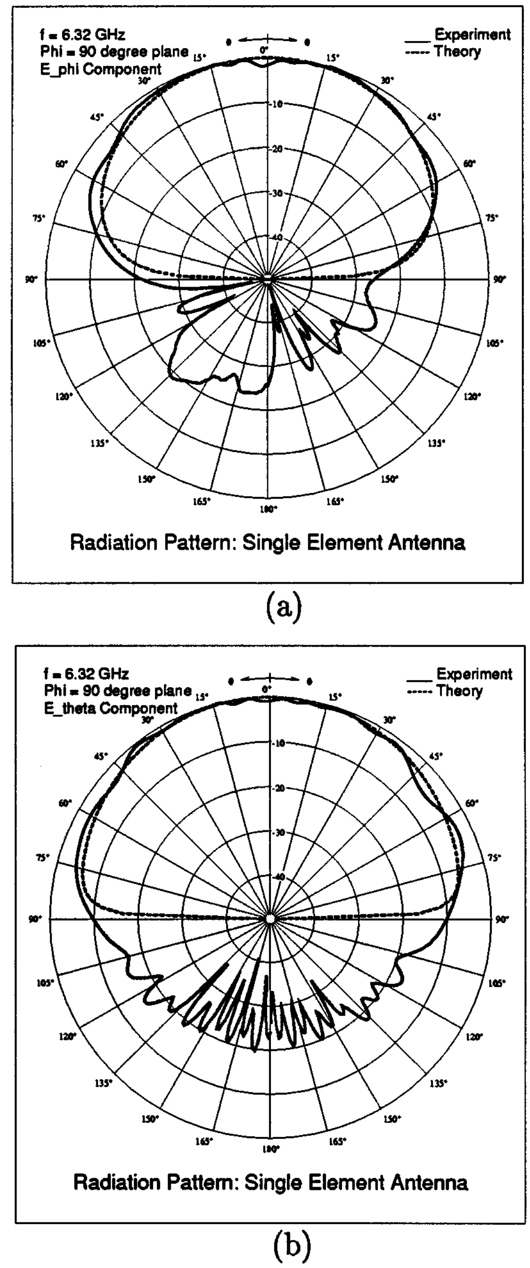

Fig. 6. Radiation patterns at 6.32 GHz in the $\phi = 90^\circ$ plane for a single element. (a) E_{phi}. (b) E_{theta}.

Both AR and VSWR are a minimum around a small range near $\Phi = 45^\circ, 135^\circ$. This aspect may be useful since this allows for a small tolerance error in manufacturing. We note that the two polarization senses corresponding to $\Phi = 45^\circ$ and $\Phi = 135^\circ$ are right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), respectively. The last section of this paper demonstrates that both polarization senses with a single element can be obtained by using two orthogonal feeds.

Broad patterns corresponding to about 80° 3-dB beamwidths are produced. In addition, broad and symmetric 3-dB axial ratio beamwidths of nearly 120 ° are obtained.

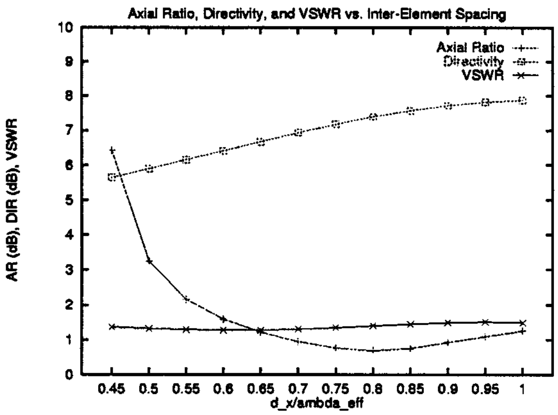

Fig. 7. Axial ratio, directivity, and VSWR for different interelement spacing d_x.

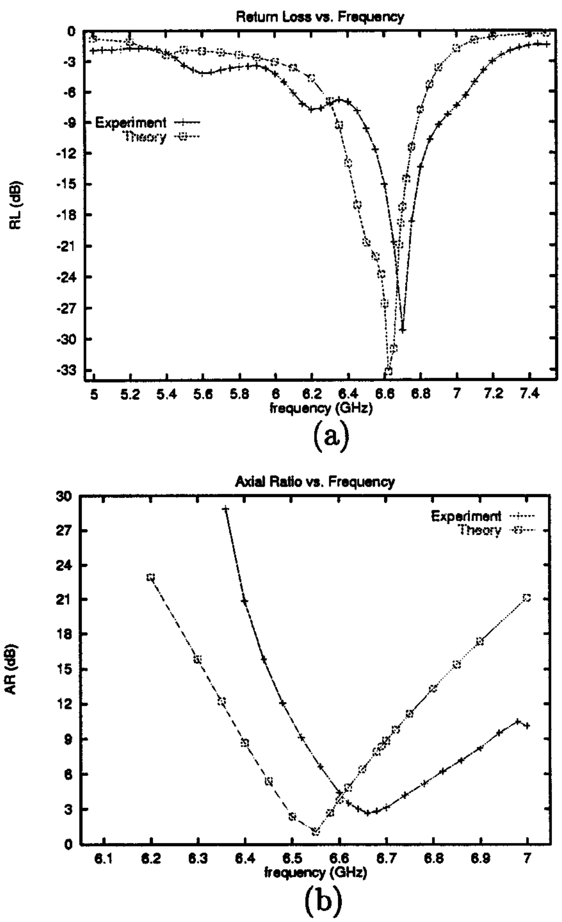

Fig. 8. Frequency characteristics. (a) Return loss. (b) Axial ratio. 2 × 2 element array. $d_x = 0.65\lambda_{\rm eff}$, $d_y = 0.70\lambda_{\rm eff}$.

B. Comparison of Theory and Experiment

An experimental validation of the novel antenna design was performed. Two RT/Duroid 5870 subtrates of thicknesses 31 mils and dielectric constant 2.33 were used. Fig. 4 compares the return loss and axial ratio frequency characteristics. Good agreement is obtained for both parameters. The downward shift in the resonant frequency to 6.3 GHz is caused by the higher dielectric constant substrate and can be predicted by the relation $\Delta f_r = \sqrt{2.20/2.33}$. The axial ratio patterns in the major planes at 6.32 GHz are shown in Fig. 5. The wide and symmetric 3-dB

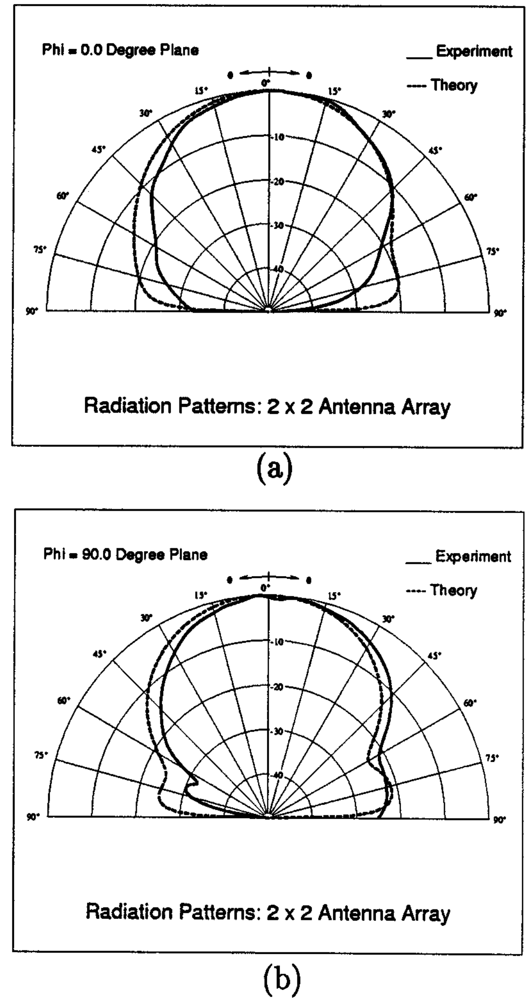

Fig. 9. Radiation patterns. (a) $\phi = 0.0°$. (b) $\phi = 90.0°$. Theory $f = 6.55$ GHz, experiment $f = 6.66$ GHz.

beamwidth is observed at $\phi = 90°$, while the $\phi = 0°$ plane does not clearly demonstrate the broad and symmetric pattern expected. The radiation patterns in the $\phi = 90°$ plane at 6.32 GHz are shown in Fig. 6. The separation into individual field components is chosen to compare to theory and also demonstrates the larger back radiation by the E_θ component. In all experiments the antennas under test were used in a receive mode with a linearly polarized standard gain horn as the transmitting antenna. Axial ratio was derived by recording the amplitude and phase of the received field for the transmitting antenna at two orthogonal planes.

III. Interelement Mutual Couping and a Four–Element Array

A large antenna array can be designed by first investigating the single antenna element to determine optimal antenna geometry, then by determining optimal interelement spacing, and finally by designing small arrays (subarray units) that can then be integrated into a larger array. This section will present an analysis of mutual coupling between two elements to determine the effects on axial ratio and VSWR. Then a four-element array will be designed and built. Comparison between theory and experiment will be presented.

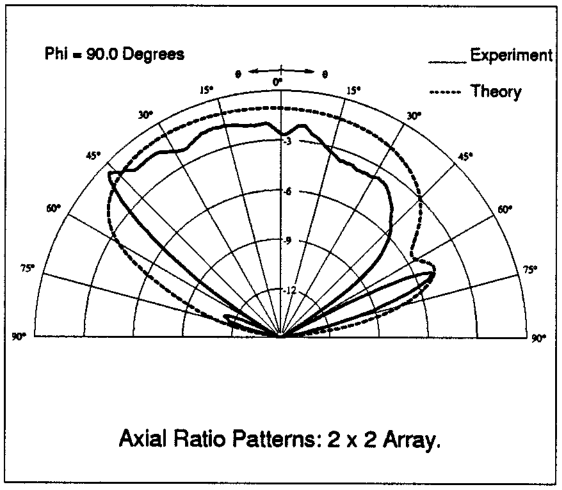

Fig. 10. Axial ratio patterns, in the $\phi = 90.0^{\circ}$ plane. Theory $f = 6.55$ GHz, experiment $f = 6.66$ GHz.

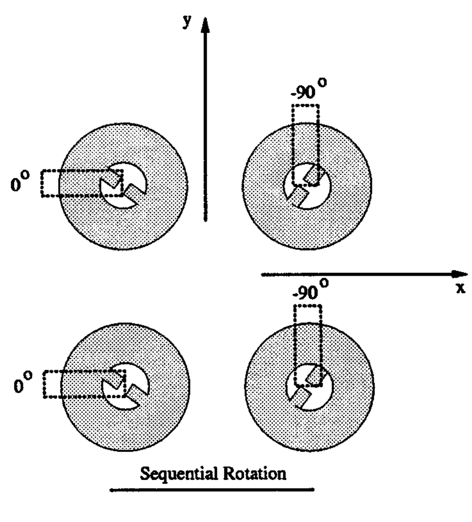

Fig. 11. Four-element array with sequential rotation feeding technique. Phase distribution and element rotation.

One 50-Ω feedline excites the array via a two way power divider. A quarter-wave impedance transformer (70.7 Ω) is used to convert the impedance at the power divider (100 Ω) to the required impedance at the antenna element feed point (50 Ω). The total subtrate thickness is 62 mils and the dielectric constant is 2.2. The antenna parameters of interest as a function of interelement spacing are shown in Fig. 7. We observe that the axial ratio is below 2 dB for spacings greater than $0.55\lambda_{\rm eff}$ while the VSWR is below two throughout the range shown.

Using the information above a 2 $\times$ 2 element array was designed, constructed, and tested. Two 31-mil-thick RT/Duroid 5880 substrates $\epsilon_r = 2.20$ were used. The element spacings are $d_x = 0.65\lambda_{\rm eff}$ and $d_y = 0.70\lambda_{\rm eff}$. The corporate feed is designed to produce excitation of equal amplitude and phase to each antenna element. The return loss and axial ratio frequency response is shown in Fig. 8. We observe a shift in frequency of 1.5% between theory and experiment. The radiation patterns

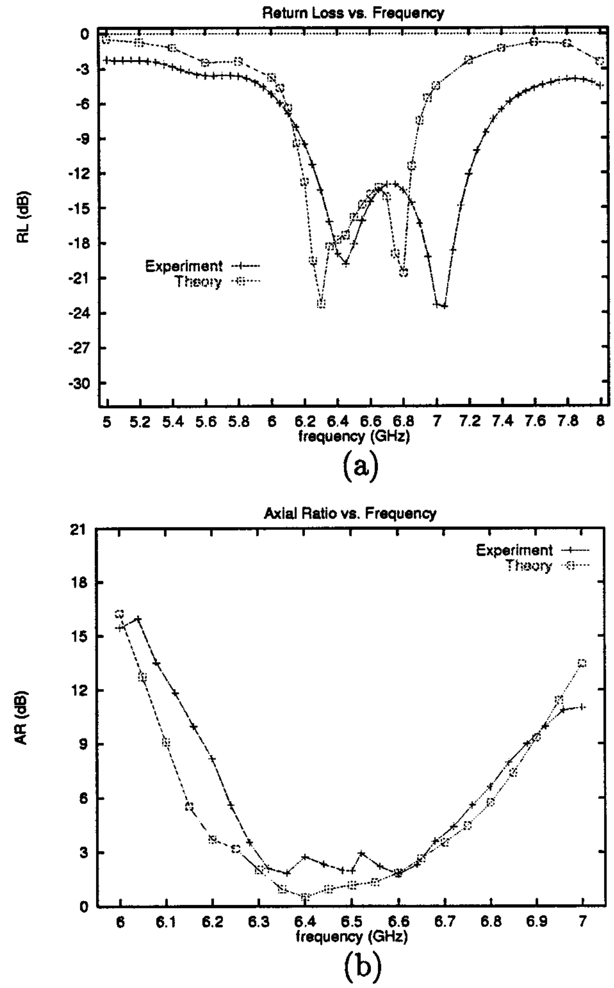

Fig. 12. Frequency characteristics for four-element array with sequential rotation. (a) Return loss. (b) Axial ratio.

are shown in Fig. 9. The comparison between theory and experiment is good with both patterns demonstrating symmetry and small sidelobes. The axial ratio pattern in the $\phi = 90^{\circ}$ is shown in Fig. 10. The measured pattern shows good agreement with theory.

IV. Four-Element Arrays with Sequential Rotation Feeding Technique

A method to increase the AR bandwidth of arrays is to use the sequential rotation feeding technique [4]–[8]. The antenna elements are physically rotated relative to each other and the feed phase is individually adjusted to each element to compensate for the rotation. The optimal sequentially rotated array is shown in Fig. 11. Two 31-mil-thick RT/Duroid 5880 substrates $\epsilon_r = 2.20$ were used. The interelement spacings are $d_x = 0.65\lambda_{\rm eff}$ and $d_y = 0.70\lambda_{\rm eff}$. The element phase shift is produced by adding the appropriate lengths of microstrip line within the feeding network. The frequency characteristics comparing theory and experiment are shown in Fig. 12. The measured return loss shows an upward shift in frequency by 1.5%, similar to the original array. The theoretical VSWR <2 bandwidth is 12% while the measured bandwidth is 18%. The theoretical and experimental AR bandwidths are 6.1%, four

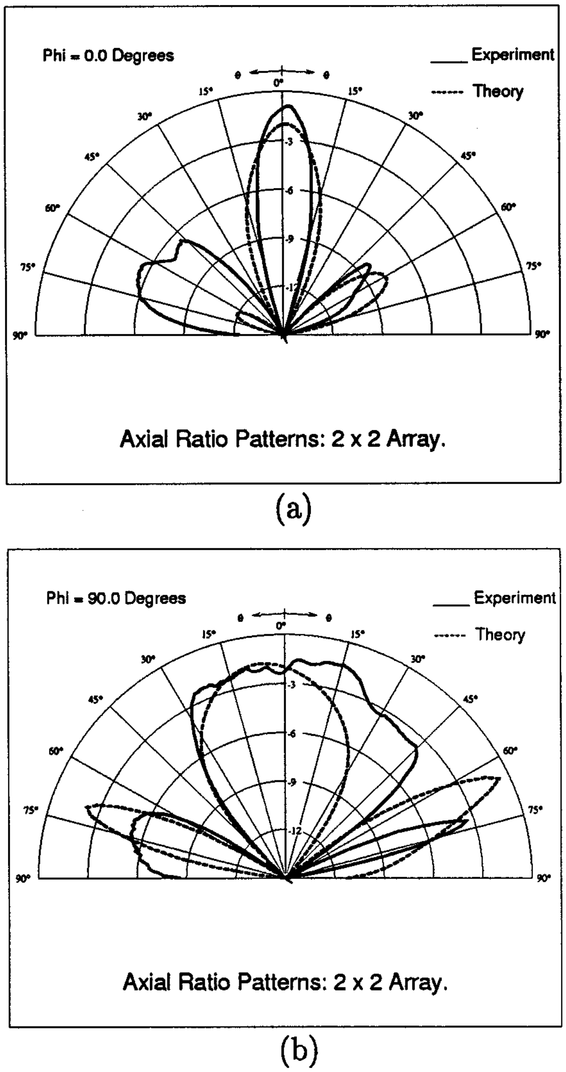

Fig. 13. Axial ratio patterns of 2 × 2 array with sequential rotation at 6.34 GHz. (a) $\phi = 0.0°$. (b) $\phi = 90.0°$.

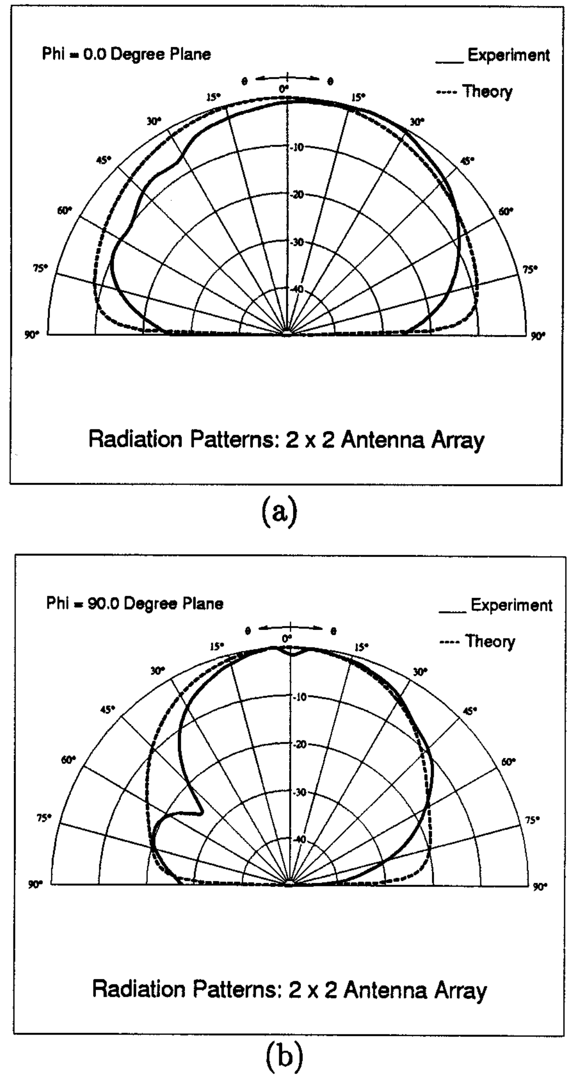

Fig. 14. Radiation patterns of 2 × 2 array with sequential rotation at 6.34 GHz. (a) $\phi = 0.0°$. (b) $\phi = 90.0°$.

times larger than the traditional array. The feedline offsets under the antenna elements are optimized to 0.0 mm. The AR is sensitive to the feedline offset, with similar responses as in the single-element case. The axial ratio patterns at the band edge 6.34 GHz are shown in Fig. 13. The corresponding radiation patterns are shown in Fig. 14. The different diagrams are used for clarity in comparing the experimental and theoretical results in the principal planes. The experimental results demonstrate the asymmetric patterns as predicted by theory. The asymmetries are caused by the rotated elements and the associated asymmetric feed network.

V. Dual Circular Polarization Capabilities using Two Feeds

The single-element analysis demonstrated that the stub ring antenna can radiate both senses of polarization. The sense of polarization is determined by the angle between the feedline and the inner stubs. We now wish to see if two feeds perpendicular to each other can be used for dual polarization. Fig. 15 presents the axial ratio and S-parameters for a single-antenna element excited by two 50-Ω feeds with offset of $S_{x,y} = -2.0$ mm. One quarter-wave transformer is used for each port. The inner stub lengths are 2.0 mm. The axial ratio for each excitation port is centered at 6.49 GHz. The reflection coefficients are slightly shifted from the axial ratio center frequency. The isolation coefficient magnitude reaches a maximum value of -9 dB at the center frequency. This coupling is much larger than the case for a dual linear polarized element (-20 dB). The very poor isolation between orthogonal ports will not allow its use in frequency reuse communications applications. Future work will investigate reducing mutual coupling in an array environment by using the sequential rotation technique.

VI. Conclusion

In conclusion, a ring antenna with inner stubs produces circular polarization utilizing just one microstrip feedline. The length of the inner stubs controls the quality of the circular polarization. Polarization of either sense is controlled by the angle between the inner stubs and the embedded feedline. The axial ratio bandwidth is 1.0% and the VSWR bandwidth is 6.1%. The 3-dB radiation patterns and axial ratio patterns are

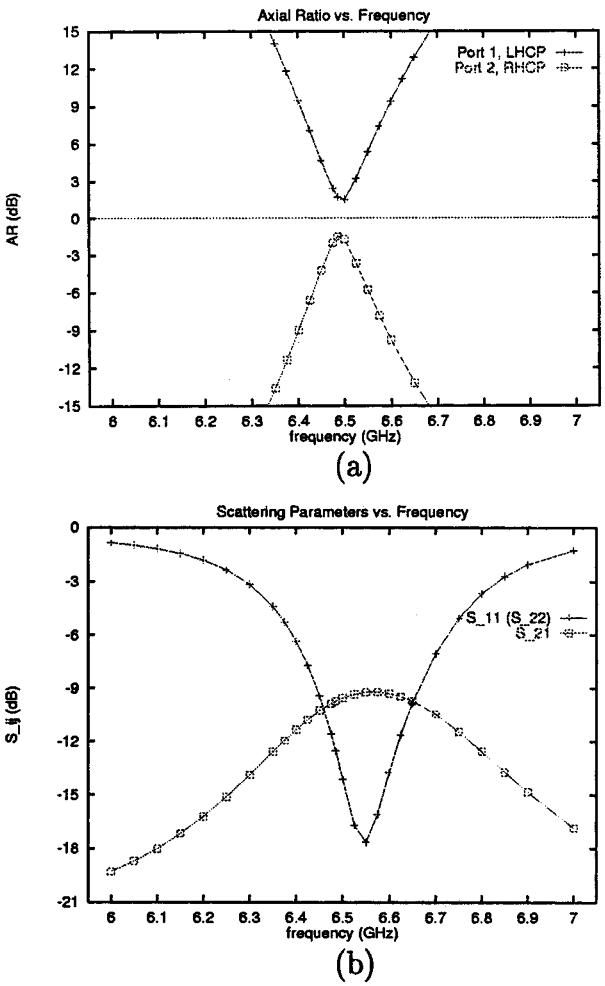

Fig. 15. Frequency characteristics for single element with two perpendicular feeds. (a) Axial ratio. (b) S parameters.

broad, 80° and 120°, respectively. The antenna system has the further advantage of small size $2R_o/\lambda_0 = 0.325$ and thin substrate thickness $D/\lambda_0 \sim 0.035$. The mutual coupling effects on AR and VSWR between elements in a two-element array were presented. The frequency response of a four element array was shown to be similar to the single element. It was shown that the sequential rotation feeding technique increased the AR and VSWR bandwidths to 6.1% and 18% for a four-element array. Dual polarization with one antenna element using two independent orthogonal feeds was also presented. The stub ring antenna element thus promises to be a viable candidate for circularly polarized array applications. The axial ratio and VSWR responses for the case of main beam scanning off broadside will be further investigated.

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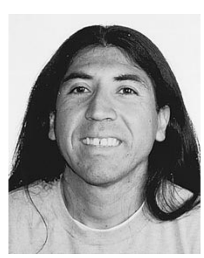

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Dr. Alexopoulos was corecipient of the IEEE S. E. Schelkunoff Prize Best Paper Award in 1985 and 1998.