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A Simple Feed Network for Designing Antennas with Polarization Agility

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Abstract

A simple feed network is described which is general enough to be integrated with various antennas to produce polarization agility. The network contains three digital phase shifters which can be set such that the antenna radiates any one of clockwise circular, counter-clockwise circular, or linear polarization at any orientation. As an example, this paper presents a circuit configuration for a wideband microstrip patch antenna operating at L-Band. The patch can radiate any one of four polarization states, with at least a 10% bandwidth. This configuration is of particular interest to mobile wireless applications which would benefit from polarization diversity.

1.0 Introduction

One of the challenges facing mobile communications in urban environments is how to overcome the problem of signal fading due to depolarization from multi-path scattering. One method for combatting this fading is to use a mobile terminal that incorporates antennas with polarization diversity. Having more than one antenna for the mobile terminal, however, is not the ideal solution due to the added real-estate, complexity, and costs required. Having a single antenna which could radiate different polarizations would be an attractive solution.

In the past few years, there has been some research carried out on antennas with polarization diversity. One method involved microstrip antennas fabricated on ferrite substrates [1, 2]. The antenna polarization was switched from linear to circular by applying a dc magnetic bias field. Similar results have also been obtained using ferrite resonator antennas [3]. Both these antennas suffer from certain disadvantages such as: narrow bandwidth performance (about 1%); the requirement for an electromagnet which significantly increases the cost and size; and only one orientation of linear polarization can be achieved.

A second approach involved the integration of four varactor diodes with a single probe fed microstrip antenna [4]. By proper biasing of the diodes, the antenna generated vertical linear (VL), horizontal linear (HL), clockwise (CW) circular and counter-clockwise (CCW) circular polarization. This approach is more amenable to practical applications; however, the impedance bandwidth reported was still quite narrow ($< 1\%$). Also, in this configuration, the diodes were inserted into the substrate, adding to the complexity of the antenna, and increasing labour costs in volume production.

A third configuration consisted of a stacked disk antenna with four probes, where the probes were connected using a network of three hybrid circuits [5]. The polarization of this antenna could be altered between CW and CCW circular polarization by appropriate selection of one of two input points of the feed configuration. A similar approach with only two hybrid circuits was also proposed which could provide either VL or HL polarization. Although only two polarization states were achieved, this configuration offered a wide impedance bandwidth of over an octave.

In this paper, a simple four-point feed network is proposed which, in principle, can be used for generating any polarization state. In Section 2, a general circuit configuration is described, based on the concept of the superposition of two circularly polarized fields. In Section 3, a circuit is designed for feeding a microstrip antenna, allowing for any one of four polarization states. Measured results for a prototype antenna are presented in Section 4. Finally, in Section 5, advantages and limitations of this feed network are discussed.

2.0 Polarization Agility using the Concept of Superposition

Linear polarized fields are sometimes described using the concept of the superposition of two circular polarized (CP) electromagnetic fields with equal magnitudes but opposite sense of rotation [6] as shown in Figure 1. For the more general case, where both the sense of rotation of the two CP fields and the phase difference ($\phi_o = \psi_1 - \psi_2$) between them can be controlled, then the resultant field could be synthesised with either linear polarization of any orientation (ψ_r) or a circular polarization with either sense. This can be seen from the following derivation. If the time-domain E-field components of the two CP fields are represented by:

$$\vec{e}_1(t) = E_o \cos(\omega t) \hat{x} \pm E_o \sin(\omega t) \hat{y} \quad (1)$$

and

$$\vec{e}_2(t) = E_o \cos(\omega t + \phi_o) \hat{x} \pm E_o \sin(\omega t + \phi_o) \hat{y} \quad (2)$$

then the total E-field is:

$$\vec{e}_r(t) = E_o [\cos(\omega t) + \cos(\omega t + \phi_o)] \hat{x} + E_o [\pm \sin(\omega t) \pm \sin(\omega t + \phi_o)] \hat{y} \quad (3)$$

For the case when ϕ_o is zero, (3) reduces to:

$$\vec{e}_r(t) = 2E_o [\cos(\omega t)] \hat{x} \pm 2E_o [\sin(\omega t)] \hat{y} \quad (4)$$

which represents a CP field with either CW or CCW sense. If, on the other hand, ϕ_o is not zero, and $\vec{e}_1(t)$ and $\vec{e}_2(t)$ are chosen with opposite senses of polarization, then the total field becomes:

$$\vec{e}_T(t) = E_o [\cos(\omega t) + \cos(\omega t + \phi_o)] \hat{x} + E_o [-\sin(\omega t) + \sin(\omega t + \phi_o)] \hat{y} \quad (5)$$

By introducing a shift in the time variable, $\omega t = \omega t' - \phi_o/2$, (5) becomes:

$$e_T(t) = E_o \left[\cos(\omega t' - \frac{\phi_o}{2}) + \cos(\omega t' + \frac{\phi_o}{2}) \right] \hat{x} + E_o \left[-\sin(\omega t' - \frac{\phi_o}{2}) + \sin(\omega t' + \frac{\phi_o}{2}) \right] \hat{y} \quad (6)$$

which when expanded becomes:

$$\vec{e}_T(t) = 2E_o \cos(\omega t') \cos(\frac{\phi_o}{2}) \hat{x} + 2E_o \cos(\omega t') \sin(\frac{\phi_o}{2}) \hat{y} \quad (7)$$

From (7), the magnitude of the total E-field will be :

$$|\vec{e}_T(t)| = 2E_o \cos(\omega t') \quad (8)$$

and the orientation with respect to the x-axis will be:

$$\begin{aligned} \psi(t) &= \tan^{-1} \left(\frac{2E_o \cos(\omega t') \sin(\phi_o/2)}{2E_o \cos(\omega t') \cos(\phi_o/2)} \right) \\ &= \phi_o/2 \end{aligned} \quad (9)$$

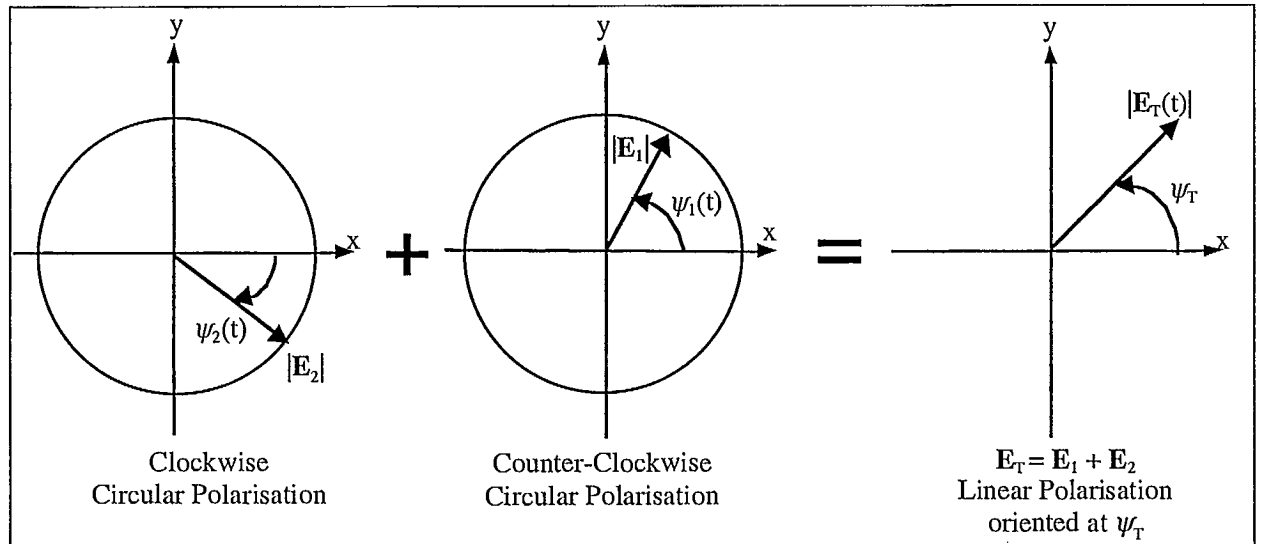


Figure 1. Superposition of two CP fields.

Equations (8) and (9) represent a linear polarized field, oriented at an angle of $\phi_0/2$ from the x-axis. Thus, by proper selection of the sense and the phase difference of the two CP fields, the resultant field can have either circular polarization (CW or CCW) or a linear polarization with any orientation ψ , with respect to the x-axis.

A simple circuit used to implement this concept is shown in Figure 2. The circuit consists of two one-bit digital phase shifters (PS2, PS4), a variable or N-bit phase shifter (PS0), and two 3 dB quadrature hybrid (QH) couplers. The four ports (1, 2, 3, 4) of the circuit are connected to the four ports of an antenna having a rotational symmetry of at least $\pi/2$ (such as a square or circular microstrip patch, a square pyramidal or conical horn, a crossed dipole, etc.). Ports 1 and 2 are used to generate one CP field (E_1), while ports 3 and 4 are used to generate the other (E_2). By appropriate selection of the phase shifter bits, the senses of each CP wave as well as the phase difference between them can be controlled. Table 1 summarises the various achievable polarization states and the required phase shifter settings. The relative phases at the four ports ($\phi_1, \phi_2, \phi_3, \phi_4$) are indicated in the table to help visualise the superposition concept. The columns labelled E_1 -Pol and E_2 -Pol indicate the polarization states of the two CP fields, while the final column (E_T -Pol), shows the polarization state of the total field. Other combinations of phase shifter settings are also possible to achieve the various polarization states. The circuit of Figure 2 can, in principle, be used to design an antenna with the capability of full polarization agility.

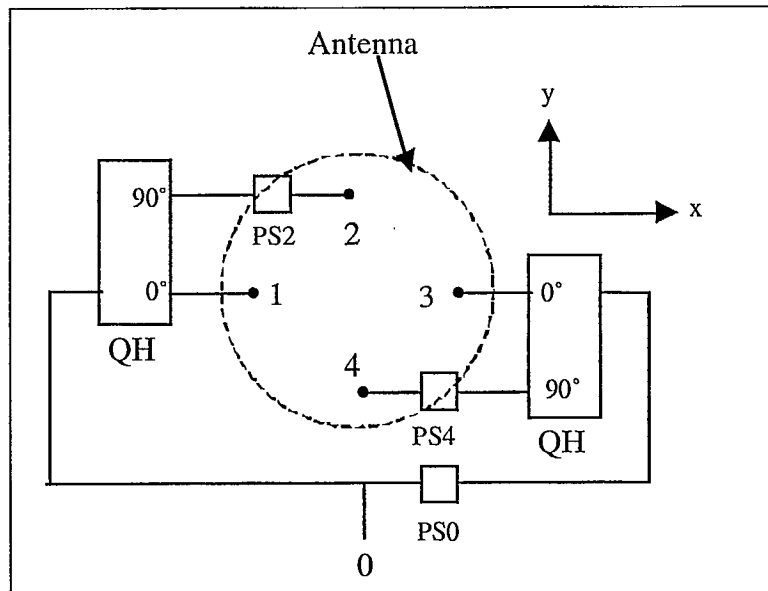


Figure 2. Feed network implementation for the superposition of two CP fields.

PS0	PS2	PS4	ϕ_1	ϕ_2	ϕ_3	ϕ_4	E_1 -Pol	E_2 -Pol	E_T -Pol
0°	0°	0°	0°	90°	0°	90°	CCW	CCW	CCW-CP
0°	0°	180°	0°	90°	0°	-90°	CCW	CW	HL
0°	180°	180°	0°	-90°	0°	-90°	CW	CW	CW-CP
180°	0°	0°	0°	90°	180°	90°	CCW	CW	VL
ϕ_0°	0°	180°	0°	90°	ϕ_0°	$\phi_0^\circ - 90^\circ$	CCW	CW	$0.5\phi_0^\circ$ -LP

Table 1. Phase shifter settings for various polarizations for the circuit of Figure 2.
 $0.5\phi_0^\circ$ -LP linear polarization oriented at an angle of $0.5\phi_0^\circ$ from the x-axis

3.0 Feed Network for a Probe-Fed Microstrip Antenna

The above development was based on two assumptions: that the four antenna ports were identical; and that there is no interaction or mutual coupling between the ports. The first assumption is valid for most antennas, as long as the feed points are positioned in locations giving the same antenna input impedance. The second assumption is valid only in certain cases, such as for conical horns, where the four ports can be positioned along the circular waveguide feed so that there is minimum interaction between them. For other antennas, such as the microstrip patch, there will be strong mutual coupling between certain ports, and this must be taken into account in the feed circuit. For example, if the antenna in Figure 2 represents a circular microstrip patch, then there will be strong interaction between the co-linear ports (i.e. between 2 and 4; 1 and 3) since the co-linear probes couple into the same mode of the microstrip patch. Care must also be taken in the location of the feed points in order to ensure minimum interaction between orthogonal ports (1 and 2; 3 and 4). The strong interaction between the co-linear ports will limit the combination of polarization states which can be achieved using the feed circuit of Figure 2, since the three phase shifters can no longer be set independently. To excite the dominant mode (TM_{01} or TM_{10} for a square or circular patch), the excitation of the two co-linear probes must have equal amplitude and opposite phase (when they are located with the same offset from the radiating edges of the patch). Conversely, to suppress the dominant mode, the two probes are excited with equal magnitude and phase. To make use of this dependence, the circuit has been re-arranged as shown in Figure 3. In this case, all three phase shifters are one-bit digital phase shifters. Table 2 shows the phase shifter settings, phases at the ports, and polarization state of the antenna. For this configuration, the number of polarization states is limited to four.

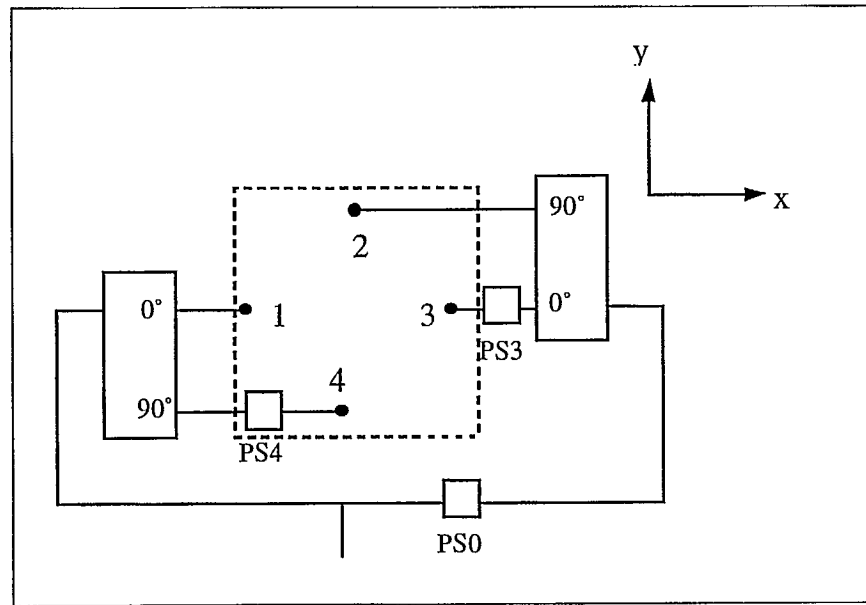


Figure 3. Feed network configuration integrated with a square microstrip patch.

PS0	PS4	PS3	ϕ_1	ϕ_2	ϕ_3	ϕ_4	Polarization
180°	0°	0°	0°	270°	180°	90°	CCW-CP
0°	180°	180°	0°	90°	180°	270°	CW-CP
0°	180°	0°	0°	0°	0°	180°	VL
0°	0°	180°	0°	0°	180°	0°	HP

Table 2. Phase shifter setting for various polarizations for the circuit of Figure 3.

4.0 Results and Discussion

The above feed concept was realised using a microstrip network and was integrated with a square microstrip patch designed at L-Band. The patch, which was printed on a 0.76 mm thick sheet of fibreglass, was suspended 7 mm above the ground plane with air as the substrate. This height was chosen in order to obtain an impedance bandwidth of approximately 10%, required for various mobile communication applications. The probes were located in positions where there was low mutual coupling between orthogonal probes (i.e. between 1 and 4; 2 and 3). Microstrip stubs were used to tune out the reactive component of the probes and to provide an adequate impedance match. For this prototype, the one-bit phase shifters were implemented by inserting transmission line lengths corresponding to 0° and 180° of phase delay at the design

frequency of 1.5 GHz. In practical applications, one-bit digital phase shifters could be used to electronically control the polarization states. Also, to minimise real-estate, Wilkinson power dividers were used instead of 3 dB QH couplers.

Figure 4 shows the measured return loss of the antenna for the four different polarization states. The impedance bandwidth for the circular polarization states is 24% with a 15 dB return loss. The linear polarization impedance bandwidths are somewhat degraded but the return loss is still adequate for operation over a 10% frequency range. The impedance bandwidth of the four-port patch is significantly wider than that of the single probe-fed patch due to the Wilkinson power dividers, which absorb out-of-band reflections.

The radiation patterns at 1.5 GHz in the two principal planes for the four polarization states are shown in Figures 5 to 8. A rotating linear source was used to measure the axial ratio of the circular polarized states. A boresight axial ratio of approximately 1.5 dB was measured for both the CW-CP and CCW-CP states. The gain of the antenna when radiating circular polarization was approximately 7 dBic (determined using the conversion from a rotating linear measurement as outlined in [7]). The axial ratio and gain is plotted versus frequency for the CW-CP state in Figure 9. For the linear polarizations, cross-polarized levels were better than 20 dB below co-polarized peak gains. Linear polarized gains are approximately 5 dBi. The skew in the E-plane pattern of vertical polarized antenna is probably caused by probe radiation.

For the four-port microstrip patch, the feed circuit shown in Figure 3 uses a technique involving the cancellation of fields to obtain linear polarization. For vertical polarization, the horizontal component is suppressed (by setting $\phi_1 = \phi_3 = 0^\circ$); for horizontal polarization, the vertical component is suppressed (by setting $\phi_2 = \phi_4 = 0^\circ$). Half the power is thus lost due to this cancellation, resulting in a 3 dB drop in gain between the circular and linear polarizations. Only 2 dB gain drop is measured, since the circular polarization is not perfect: with 0 dB axial ratio, the CP gain would have been 8 dBic. The return loss for the linear polarization states remains acceptable since the reflected power from the suppressed field component is absorbed in the Wilkinson resistors. In certain applications, this gain drop in the linear polarization state will be more than offset by the increased gain obtained through polarization diversity of this polarization agile antenna. Furthermore, this problem should not arise in other antennas, such as conical horns which could be useful in radar or polarimetry applications.

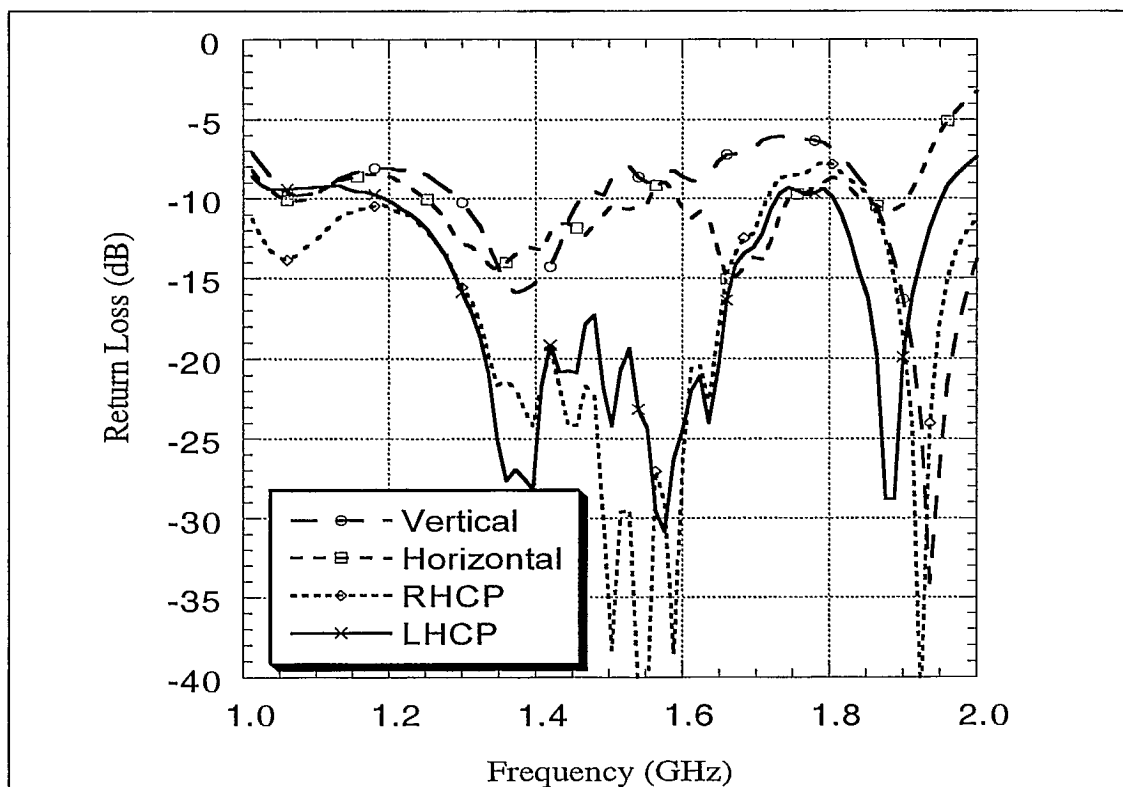


Figure 4. Return Loss for the four polarization states.

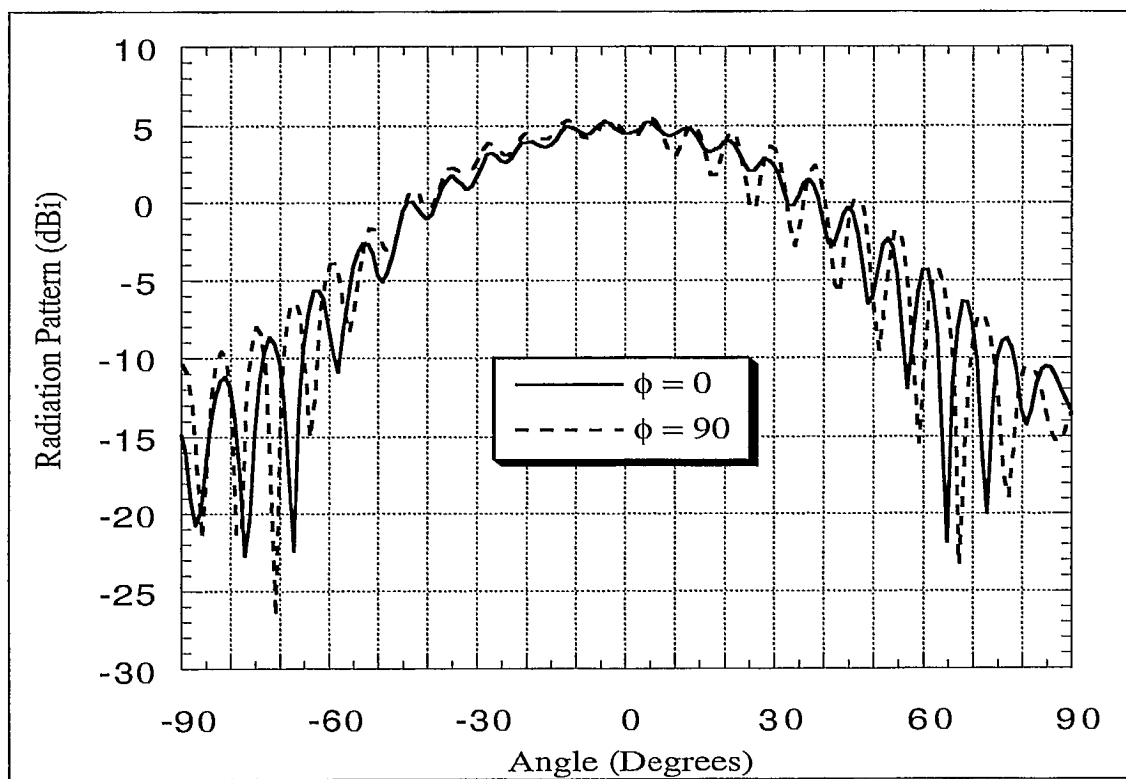


Figure 5. Clockwise circular polarization.

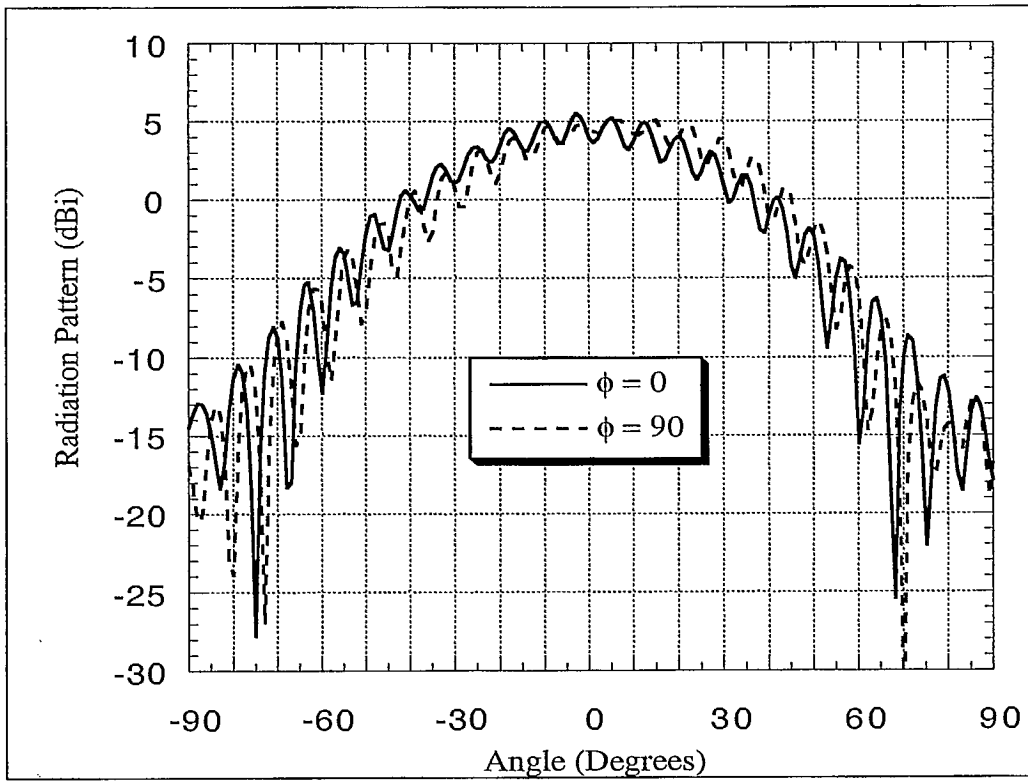


Figure 6. Counter-clockwise circular polarization.

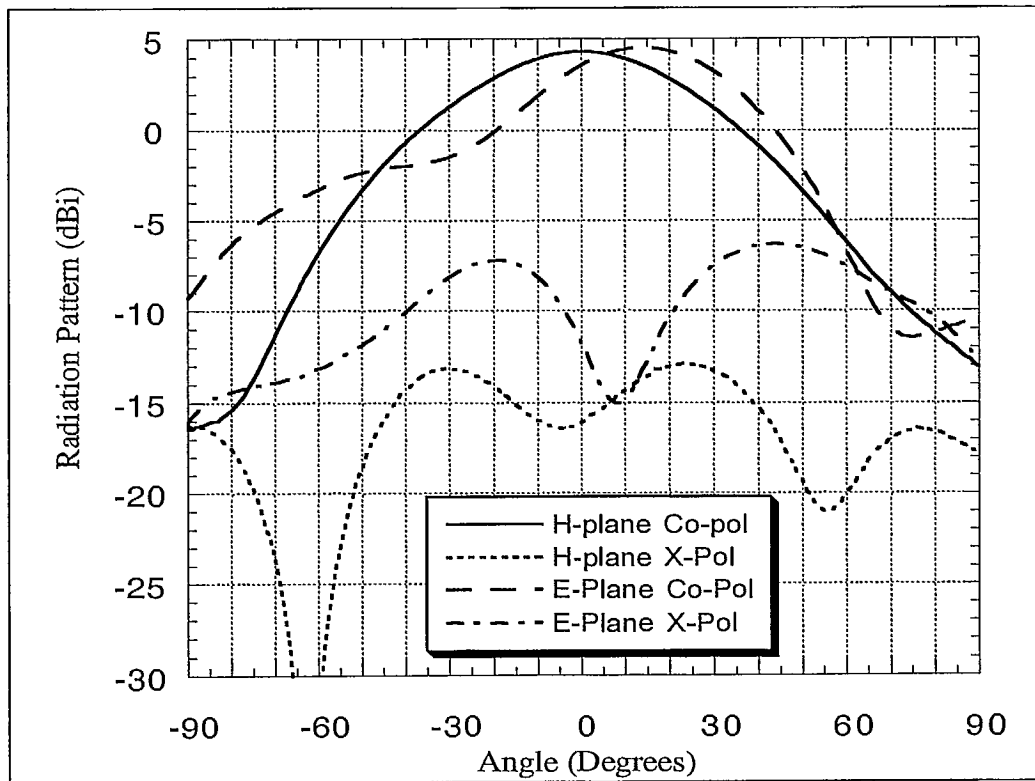


Figure 7. Vertical polarization.

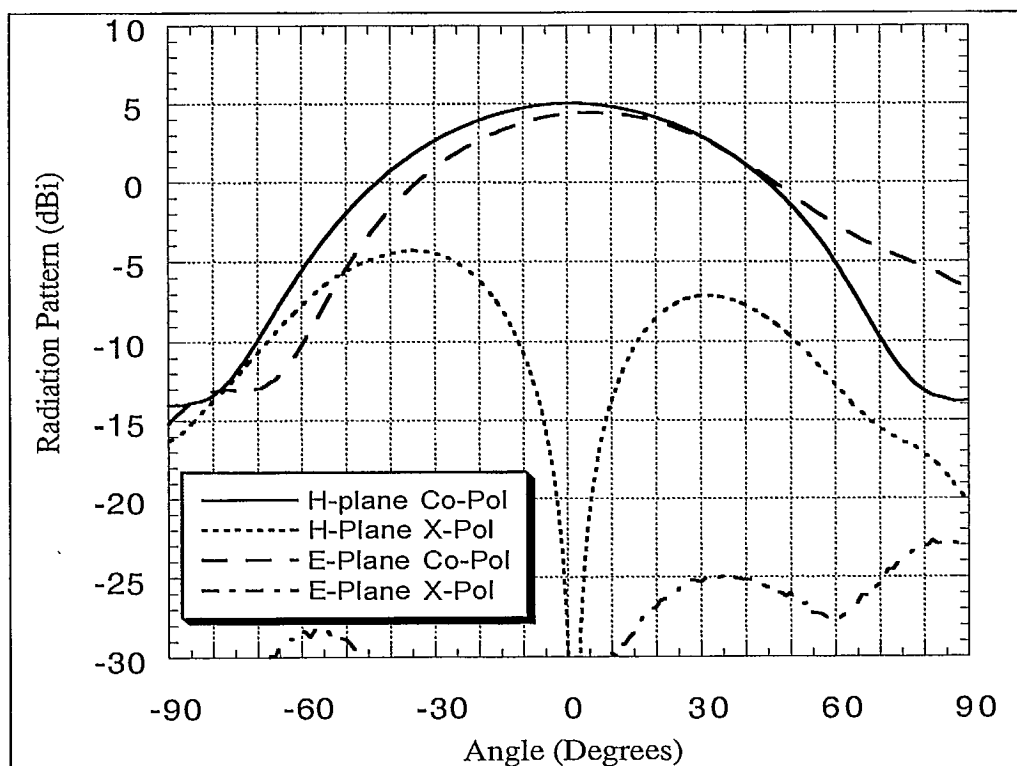


Figure 8. Horizontal polarization.

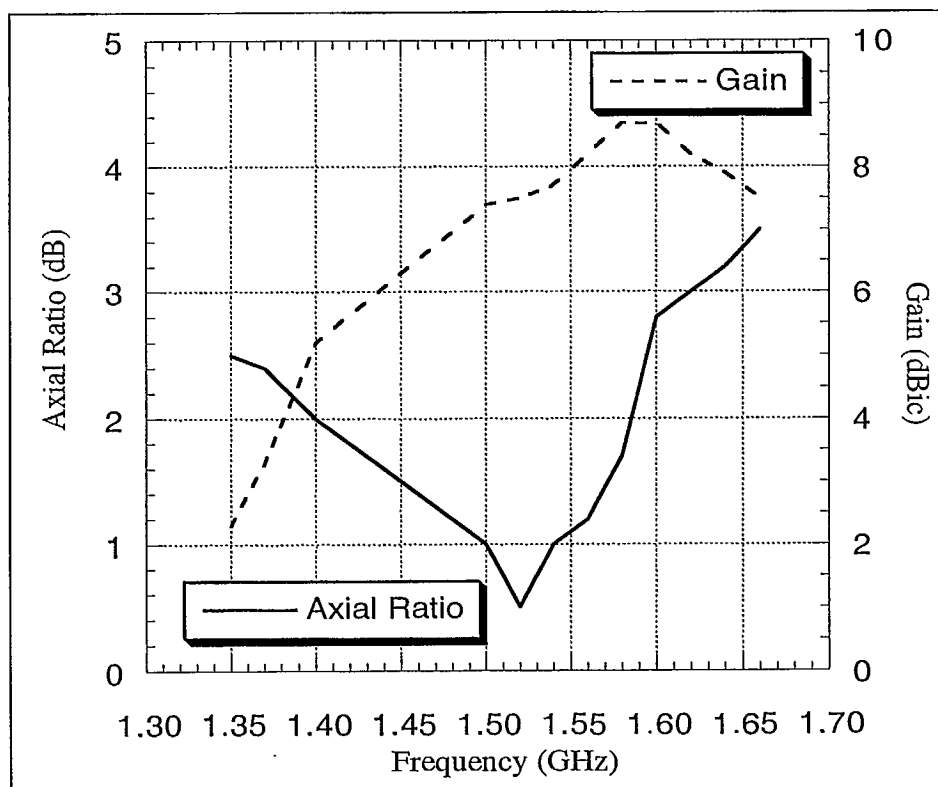


Figure 9. Gain and axial ratio vs. frequency for the CW-CP state.

5.0 Summary

Drawing upon the concept of the superposition of two CP fields, a generic feed network has been proposed for converting an antenna with fixed polarization into one with polarization agility. This configuration can be implemented using a simple feed network containing three digital phase shifters. Although this concept was demonstrated using a microstrip patch configuration, it is equally applicable to any antenna having a rotational symmetry of at least $\pi/2$.

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