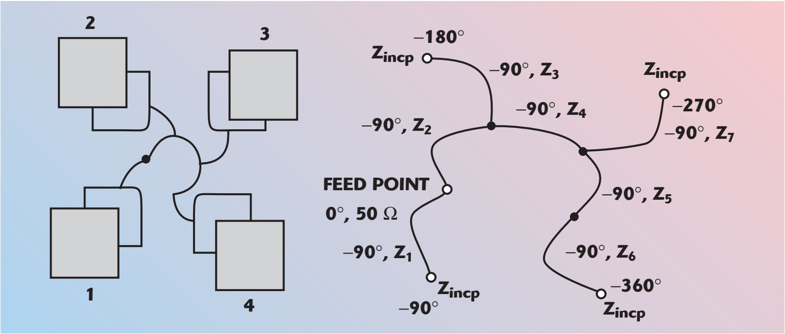
TECHNICAL FEATURE

DESIGN OF A CIRCULARLY POLARIZED 2 × 2 PATCH ARRAY OPERATING IN THE 2.45 GHZ ISM BAND

The design of a corporate feed network producing a sequential rotation for a 2 × 2 circular polarized patch array is presented in this article. The feed network has also been designed to produce equal power excitation for each patch and a match condition at the feed point. The design of the array is based on a new and simplified expression for the input impedance of a rectangular patch antenna. Compared with a single patch, the designed antenna produces an increased bandwidth for the return loss and axial ratio. There is good agreement between the simulated and experimental results for the return loss and axial ratio.

Microstrip antennas have a simple planar structure, low profile and can be easily fabricated using printed circuit technology.[1] Consequently, they are increasingly used in a variety of wireless communication systems. Circular polarized patch arrays normally consist of identical rectangular or square patches fed by a corporate feed network using couplers or power splitters.[2,3] This article describes the design of a serial corporate feed network producing sequential rotation for a 2 × 2 patch array. Sequential rotation improves polarization purity and radiation pattern symmetry over a wide range of frequencies.[4,5] The power splitters used in the feed network consist of seven quarter-wave transformers; consequently, it is not possible to obtain closed form solutions for the design. The design is therefore based on the required power split for each patch, the maximum realizable impedance values for the microstrip lines to reduce spurious radiation and coupling by the feed network, and to obtain a match at the feed point.

Fig. 1 Feed network for the 2 × 2 patch array.



DESIGN OF A SEQUENTIAL ROTATION CORPORATE FEED NETWORK

Figure 1 shows a 2 × 2 circularly polarized patch array consisting of four dual-feed circular polarized square patches, each with an input impedance Z_{incp} and a series feed network producing the sequential rotation. The feed

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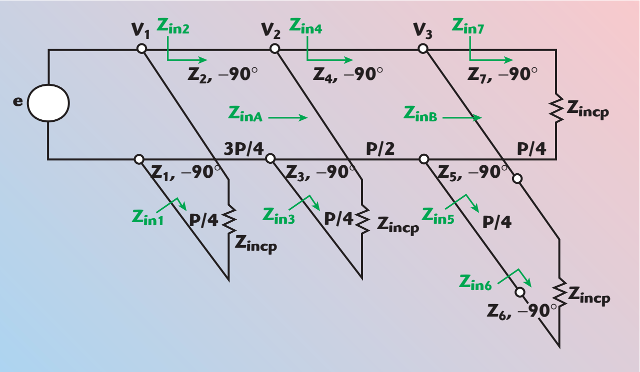
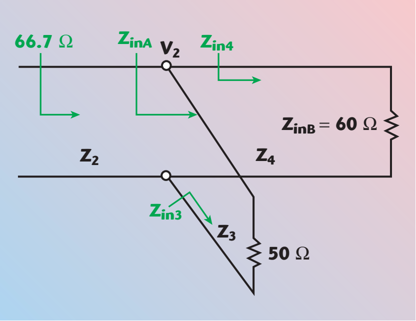


▲ *Fig. 2 Equivalent transmission line circuit of the array.*



▲ *Fig. 3 Feed network at V_2.*

network is designed to produce a match at the feed point, a 90° phase difference between adjacent patches and an equal power feed to each patch.

The transmission line equivalent circuit of the array is shown in ***Figure 2***. To reduce spurious radiation and coupling effects, it is important that the width of the microstrip feed lines be as narrow as possible and the characteristic impedances Z_1, Z_2,…Z_7 should be as high as can be practically realized.

In the design of the feed network, the following assumptions are made: The input impedance Z_{incp} of each individual two-feed circularly polarized patch antenna is 50 Ω; the highest characteristic impedance that can be practically realized is 140 Ω using a PCB (FR4) substrate ($\varepsilon_r = 4.3$, $\tan\delta = 0.017$, $h = 1.575$ mm and $t = 0.035$ mm).

The power P fed into junction V1 by the source is

$$\frac{V_1^2}{Z_0}$$

where

$Z_0 = 50\ \Omega$

For the required power split

$$\frac{P}{4} \text{ and } \frac{3P}{4}$$

$$\frac{|V_1|^2}{50}\frac{1}{4} = \frac{|V_1|^2}{Z_{in_1}} \tag{1}$$

$$\frac{|V_1|^2}{50}\frac{3}{4} = \frac{|V_1|^2}{Z_{in_2}} \tag{2}$$

hence,

$Z_{in1} = 200\ \Omega$
$Z_1 = 100\ \Omega$
$Z_{in2} = 66.7\ \Omega$

At junction V_3, to obtain narrow width feed lines, it is assumed that $Z_5 = 120\ \Omega$ and since equal power is required to be fed into patches 3 and 4, then $Z_7 = Z_6 = 77.5\ \Omega$, $Z_{inB} = 60\ \Omega$. The feed network at junction V_2 now reduces to the one shown in ***Figure 3***. At junction V_2, one third of the input power is fed into patch 2 and the remainder of the power is fed into patches 3 and 4 so that

$$Z_{in_4} = \frac{Z_{in_3}}{2} \tag{3}$$

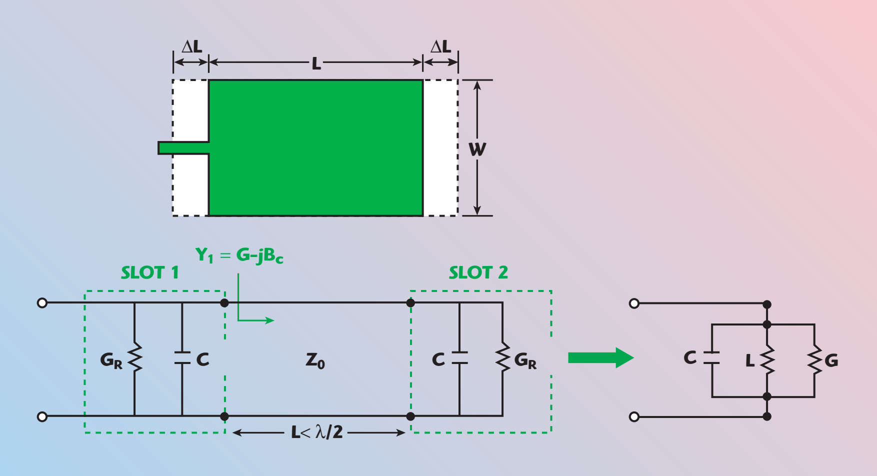
The feed network is now reduced to three variables Z_2, Z_3 and Z_4. It is necessary to make an assumption for one of these impedances. If $Z_3 = 120\ \Omega$, it can be shown that $Z_4 = 93\ \Omega$ and $Z_2 = 80\ \Omega$.

DESIGN OF A TWO-FEED CIRCULARLY POLARIZED PATCH ANTENNA

The design of a two-feed circular polarized patch antenna is discussed in the following section, where the patch is modeled as a parallel-tuned circuit taking into account copper, dielectric and radiation losses.

Modeling of the Patch Antenna by a Parallel-tuned Circuit

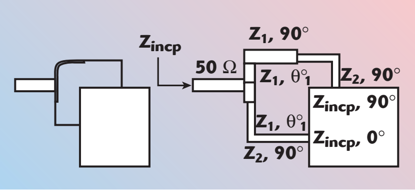
Figure 4 shows a rectangular patch antenna of length L and width W. The transmission line model of the antenna is also shown where G_R and C represent the radiation losses and fringing effects, respectively. A transmission line of length L, having a low characteristic impedance Z_0, connects the two parallel C-G_R circuits. The length L is designed to be slightly less than a half-wavelength at the design frequency, so that the input admittance is given by $Y_1 = G\text{-}jB_c$. The problem with the transmission line model is that it does not take into account the dielectric and copper losses. However, the antenna can now be modeled as a parallel G-L-C tuned circuit, where the



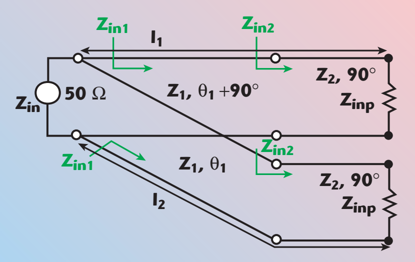
▲ *Fig. 4 Transmission line and parallel tuned circuit models of the patch antenna.*

TABLE I
INPUT IMPEDANCE

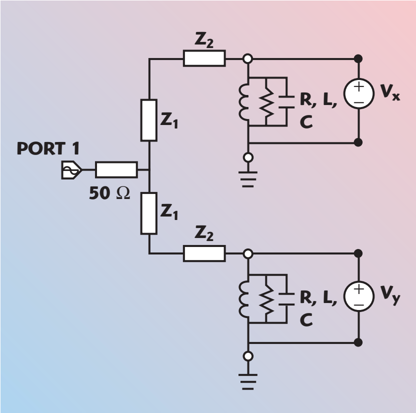
	R_{in} (Ω)	Q-Factor
Predicted	180	34.90
Practical	189	35.35
Simulation	194	34.01



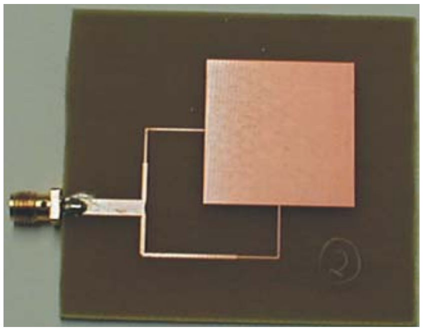
▲ *Fig. 5 Two-feed circularly polarized square patch antenna.*



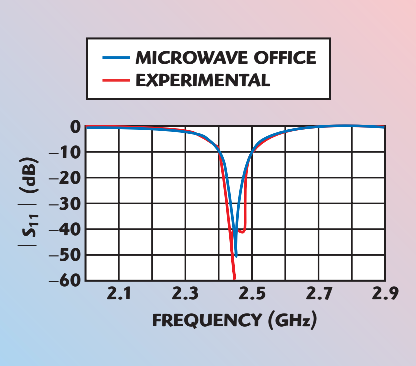
▲ *Fig. 6 Transmission line model of the circularly polarized patch antenna.*



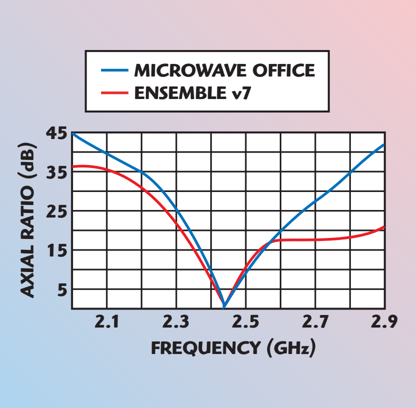
▲ *Fig. 7 Equivalent circuit of the circularly polarized patch antenna.*



▲ *Fig. 8 Two-feed circularly polarized patch antenna.*



▲ *Fig. 9 Return loss.*



▲ *Fig. 10 Axial ratio vs. frequency.*

conductance G represents the total losses.

Based on the parallel equivalent circuit C-L-G, it can be shown that a simplified expression for the input impedance of a rectangular patch, for the 10 and 01 modes, is given by[6]

$$Z_{in} = \frac{-j\omega\mu h}{kL}\cot(kW) \qquad (4)$$

where

k = a complex phase constant where the losses (copper, dielectric and radiation) of the patch are included by using the quality factor Q.

$$k = \left[\omega^2\mu\varepsilon_r\varepsilon_0\left(1-\frac{j}{Q}\right)\right]^{\frac{1}{2}} \qquad (5)$$

The dielectric under the patch can be considered to be lossy due to copper (Q_c), dielectric (Q_d) and radiation (Q_r) losses. The permittivity of the substrate ε_r can then be replaced by

$$\varepsilon_r\left(1-\frac{j}{Q}\right)$$

where

Q = total quality loss factor given by

$$\frac{1}{Q} = \frac{1}{Q_c} + \frac{1}{Q_r} + \frac{1}{Q_d} \qquad (6)$$

These losses can be determined using the following equations

$$Q_c = h\sqrt{\mu_0 \pi f_r \sigma_c} \qquad (7)$$

$$Q_d = \frac{1}{\tan\delta} \qquad (8)$$

$$Q_r = \frac{\pi}{4G\ Z_0} \qquad (9)$$

The characteristic impedance Z_0 of the patch is given by

$$Z_0 \approx \frac{120\pi}{\sqrt{\varepsilon_{reff}}} \bullet \frac{h}{W} \qquad (10)$$

where

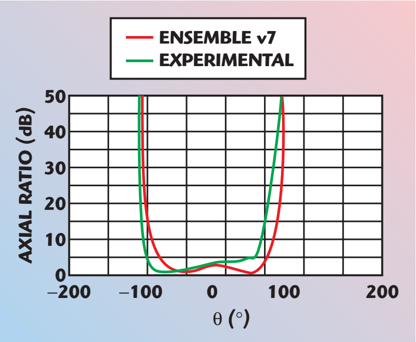
ε_{reff} = effective permittivity of the substrate
σ_C = metal conductivity

The total conductance G is given by

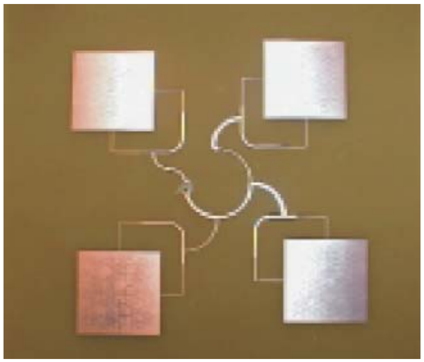
$$G = 2(G_R \pm G_{12}) \qquad (11)$$

G_R is the radiation conductance and G_{12} is the coupled conductance between the radiating slots of the antenna.

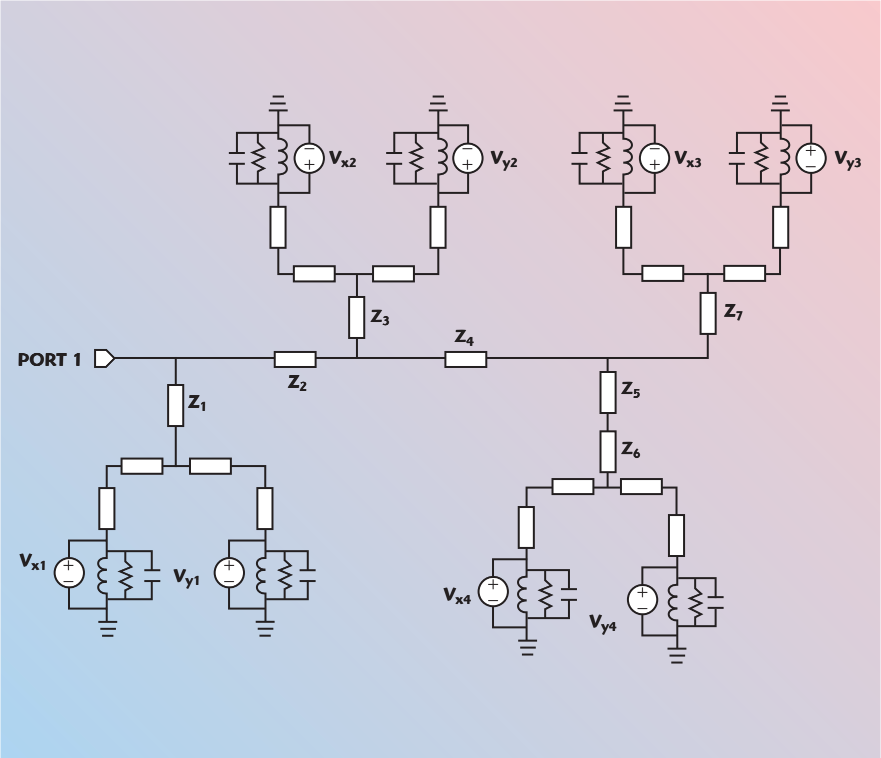
$$G_r = \frac{1}{120\pi^2}\int_0^{\pi}\left(\frac{\sin\left(\frac{k_0W}{2}\cos\theta\right)}{\cos\theta}\right)^2 \sin^3\theta\ d\theta \qquad (12)$$



▲ *Fig. 11 Axial ratio as a function of θ.*



▲ *Fig. 12 Printed circuit of the 2 × 2 array.*



▲ *Fig. 13 Equivalent circuit model of the 2 × 2 circularly polarized patch array.*

The mutual conductance G_{12} can be expressed as

$$G_{12} = \frac{1}{120\pi^2}\int_0^{\pi}\left(\frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right)^2 J_0\left(k_0 L\sin\theta\right)\sin^3\theta\ d\theta \qquad (13)$$

where

k_0 = phase constant in free space
θ = variable of the spherical coordinate system used to evaluate the radiated power from the patch antenna

A square patch antenna was designed to operate at 2.45 GHz. The predicted input impedance at resonance and the Q-factor of the antenna were determined using the above theory and compared with experimental measurements and full-wave analysis software (Ensemble v.7). The results are shown in ***Table 1***.

DESIGN OF DUAL-FEED SINGLE PATCH CIRCULARLY POLARIZED ANTENNA AND A 2 × 2 PATCH ARRAY

Figure 5 shows a two-feed power splitting arrangement for a square patch antenna to produce circular polarization and an input impedance Z_{incp} = 50 Ω. The transmission line equivalent circuit of the single two-feed patch is shown in ***Figure 6***.

The lengths l_1 and l_2 were designed to produce a 90° phase shift between the two feed points of the square patch. For Z_{inp} = 180 Ω and Z_{incp} = 50 Ω, then Z_1 = 100 Ω and Z_2 = 134 Ω. The equivalent circuit for the circular polarized patch antenna shown in ***Figure 7*** was modeled using Microwave Office 2001.[8]

It is possible using this software to determine the magnitude and phase of the voltages V_x and V_y across the two tuned parallel circuits. The axial ratio (AR) for the patch antenna is given by[9]

$$AR_{dB} = 10\log\left[\frac{E_x^2 + E_y^2 + \left(E_x^4 + E_y^4 + 2E_x^2E_y^2\cos(2\theta)\right)^{\frac{1}{2}}}{E_x^2 + E_y^2 - \left(E_x^4 + E_y^4 + 2E_x^2E_y^2\cos(2\theta)\right)^{\frac{1}{2}}}\right] \qquad (14)$$

where

E_x = magnitude of the electric field in the x-direction
E_y = magnitude of the electric field in the y-direction
θ = phase difference between the two electrical field components

The printed circuit board of the designed antenna is shown in ***Figure 8***. ***Figures 9*** and ***10*** show the measured and computer-predicted return loss and axial ratio as function of frequency, using Microwave Office 2001 and Ensemble v.7. ***Figure 11*** gives the axial ratio as a function of the angle θ simulated with Ensemble v.7 and measured experimentally. The corporate feed network was designed (as previously discussed) and a photograph of the circuit board of the array is shown in ***Figure 12***. The equivalent circuit of the 2 × 2 circularly polarized patch array shown in ***Figure 13*** was simulated using Microwave Office 2001 to predict the return loss and axial ratio. ***Figures 14*** to ***17*** show a comparison between the experimental and pre-

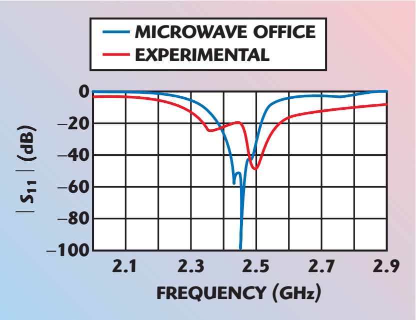


Fig. 14 *Return loss.*

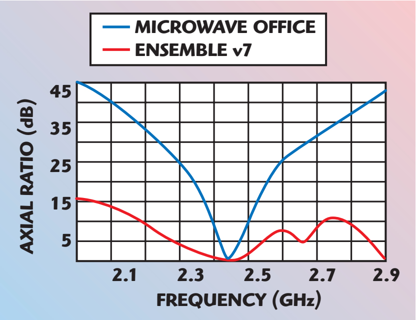


Fig. 15 *Axial ratio vs. frequency.*

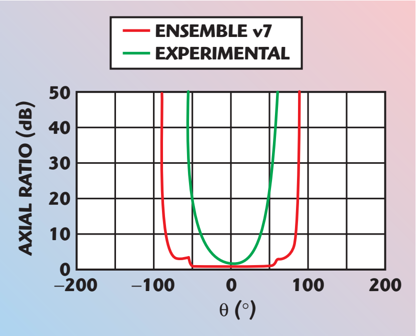


Fig. 16 *Axial ratio as a function of* θ.

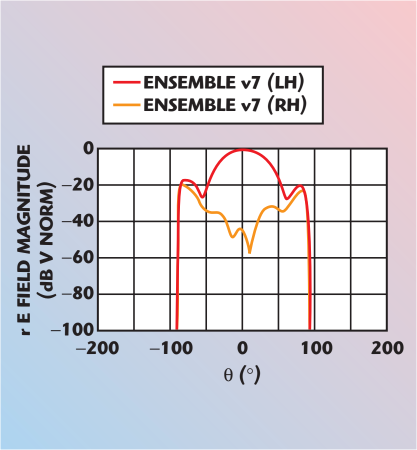


Fig. 17 *Polar pattern (RHCP, LHCP) at 2.45 GHz for* φ = 0.

dicted results for the return loss and axial ratio of the designed array.

CONCLUSION

The design of a sequential rotation corporate feed network for a 2 × 2 patch array has been presented. The fundamental element of the array is the circular polarized square patch. In this design the input impedance of the patch has been modeled as a parallel-tuned circuit where copper, dielectric and radiation losses have been taken into account. For the single patch and the array there is good agreement between theory, simulation and experimental results confirming the described design. The designed array shows a wide bandwidth for the return loss and axial ratio. ■

References

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