Abstract—Analysis and optimized designs are presented of three types of single feed circularly polarized microstrip antennas, namely, a diagonal feed nearly square, a truncated-corners square, and a square with a diagonal slot. The Green's function approach and the desegmentation methods are used. The resonant frequencies are calculated for two orthogonal modes which together yield circular polarization. Optimum feed locations are determined for the best impedance match to a 50 Ω coaxial feed line. Axial-ratio bandwidths, voltage standing-wave ratio (VSWR) bandwidths and radiation patterns are evaluated and verified experimentally.

I. INTRODUCTION

Several circularly polarized microstrip antenna configurations have been reported during the last decade [1]-[10]. In this paper, three types of single feed circularly polarized microstrip patch antennas (diagonal-fed nearly square, truncated-corners square, and square with a diagonal slot) have been studied analytically as well as experimentally. For a diagonal-fed nearly square patch antenna ($\varepsilon_r = 2.62$, substrate thickness is 1.588 mm), an experimental value of axial ratio of 1.4 dB has been reported earlier by Carver and Coffey [11] for a ratio of length of sides of the rectangle equal to 1.029. A successful attempt has been made in the present work to improve the axial ratio to 0.17 dB. The truncated-corners square patch antenna and the square patch antenna with a diagonal slot had been studied experimentally by Kerr [7], but no theoretical analysis and design procedure for these structures have been available so far. In the present investigation, the optimum dimensions and the feed locations for these antennas have been determined. Axial ratio and input voltage standing-wave ratio (VSWR) are evaluated as functions of frequency. Radiation patterns are also evaluated. The analysis is based on Green’s functions for rectangular and triangular segments [12]-[14] and recently reported segmentation and desegmentation methods [14]-[16].

II. METHOD OF ANALYSIS

In this method, the antenna is modeled as multiport network. The procedure is illustrated in Fig. 1. The physical periphery of the antenna is extended outward to obtain a planar model with a magnetic wall boundary. This planar model is treated as a lossless resonator during the initial steps of the analysis. The periphery of the planar model, with effective dimensions, is divided into several sections of small widths so that the field variation over the width of each of these sections is negligibly small. Each one of these sections is considered as a port (Fig. 1(c)). The radiated power is taken into account by terminating the ports of the multiport network by resistors corresponding to the radiation resistances [17]. The values of radiation resistances are calculated as follows: 1) the radiation conductance [17] for each of the straight edges of the radiating patch is evaluated; and 2) the conductance so calculated is distributed amongst all the ports on the corresponding edge in proportion to the port widths. The entire radiation resistance network is treated as one multiport network $\beta$ as shown in Fig. 1(d). The entries in the $Z$-matrix of the $\beta$-network are all zeros except the diagonal elements $Z_{ii}$ which are equal to resistances connected to various ports. The multiport network that represents the lossless planar model is treated as another network $\alpha$.

The input impedance and voltage around the periphery of the antenna are evaluated using the segmentation method [15] and/or desegmentation method [17] as discussed in the following subsections.

B. Application of Segmentation Method [15]

When a two-dimensional configuration $\gamma$ can be considered as combination of several segments, the $Z$-matrix for the combination $\gamma$ can be expressed in terms of the $Z$-matrices of the constituent segments. The $Z$-matrices of the various segments are grouped together as [16],

\[
\begin{align*}
\mathbf{V}_p &= \begin{bmatrix} Z_{pp} & Z_{pc} & Z_{pd} \end{bmatrix} \mathbf{I}_p \\
\mathbf{V}_c &= \begin{bmatrix} Z_{cp} & Z_{cc} & Z_{cd} \end{bmatrix} \mathbf{I}_c \\
\mathbf{V}_d &= \begin{bmatrix} Z_{dp} & Z_{dc} & Z_{dd} \end{bmatrix} \mathbf{I}_d
\end{align*}
\]

(1)
where \( p \) refers to the unconnected ports of the various segments of \( \gamma \) (i.e., the external ports of the circuit \( \gamma \)). Subscripts \( c \) and \( d \) represent the interconnected ports which are numbered in such a way that the port \( c_i \) is connected to the port \( d_i \) as illustrated in Fig. 1(d). The submatrices in (1) are obtained from the \( Z \)-matrices of the individual segments as [15],

\[
\bar{Z}_\gamma = \bar{Z}_{cp} + [\bar{Z}_{pc} - \bar{Z}_{pd}] \bar{Z}_{cp}
\]

where

\[
\bar{Z}_{cp} = [\bar{Z}_{cc} - \bar{Z}_{cd} - \bar{Z}_{dc} + \bar{Z}_{dd}]^{-1}[\bar{Z}_{dp} - \bar{Z}_{cp}].
\]

For a electric current \( I_p \) fed into the \( p \)th port, the voltages at the interconnected \( c \) and \( d \) ports are given by

\[
\mathbf{V}_c = \mathbf{V}_d = [\bar{Z}_{cp} + [\bar{Z}_{cc} - \bar{Z}_{cd}] \bar{Z}_{cp}] I_p.
\] (3)

C. Application of Desegmentation Method [16]

Consider the configuration (a) of a truncated-corners square patch antenna shown in Fig. 2(a). This configuration can be considered as obtained by removal of two isosceles triangular segments \( \beta_1 \) and \( \beta_2 \) from the two opposite corners of a square patch (\( \gamma \)-segment) as illustrated in Fig. 2(b). The interfaces between \( \alpha \) and \( \beta \)-segments are divided into discrete number of ports. These interconnected ports are named as \( c \)-ports on \( \alpha \)-segment and \( d \)-ports on \( \beta \)-segments (Fig. 2(b)). The unconnected ports on the \( \alpha \)-segment are named as \( p \)-ports and those on the \( \beta \)-segments are named as \( q \)-ports. It has been shown [16] that when the number of \( q \)-ports equals that of \( d \)-ports (equals that of \( c \)-ports), the \( Z \)-matrix of the \( \alpha \)-segment is given in terms of the \( Z \)-matrices of \( \beta \) and \( \gamma \)-segments as

\[
\bar{Z}_\alpha = \begin{bmatrix}
\bar{Z}_{pp} & \bar{Z}_{pc} \\
\bar{Z}_{cp} & \bar{Z}_{cc}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
\bar{Z}_{pp'} & \bar{Z}_{pq'} \\
\bar{Z}_{q}\bar{q}' & \bar{Z}_{dd'}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
\bar{Z}_{qq'} & \bar{Z}_{q}\bar{q}' \\
\bar{Z}_{q}\bar{q}' & \bar{Z}_{dd'}
\end{bmatrix}
\] (4)

where

\[
\bar{Z}_{qp} = [\bar{Z}_{qq'} - \bar{Z}_{q}\bar{q}']^{-1} \bar{Z}_{qp}
\]

\[
\bar{Z}_{qd} = [\bar{Z}_{qq'} - \bar{Z}_{q}\bar{q}']^{-1} \bar{Z}_{qd}.
\] (5)

\( \bar{Z}_{dq}, \bar{Z}_{qd}, \bar{Z}_{qq} \) are submatrices of \( \bar{Z}_\beta \) for \( \beta \)-segments, and \( \bar{Z}_{pp}, \bar{Z}_{pq}, \bar{Z}_{qp}, \bar{Z}_{qq} \) are submatrices of \( \bar{Z}_\gamma \) for \( \gamma \)-segment. \( \bar{Z}_\beta \) and \( \bar{Z}_\gamma \) are evaluated by using the Green's functions for an isosceles triangle [13] and for a rectangle [12].

For the square patch antenna with a diagonal slot (Fig. 2(c)), the \( \gamma \)-segment of Fig. 2(d) is obtained when a rectangular patch (\( \beta \)-segment) is added to the \( \alpha \)-segment of Fig. 2(c). In this case both \( \bar{Z}_\beta \) and \( \bar{Z}_\gamma \) are evaluated from the Green's function for an isosceles triangle, and \( \bar{Z}_\alpha \) is obtained from (4) and (5).

As shown in Fig. 1(d), the ports of the \( \alpha \)-segment are terminated into radiation resistances. The input impedance and the voltage along the radiating edges are evaluated employing (2) and (3).

D. Radiation Characteristics

The radiation characteristics are evaluated in terms of the equivalent magnetic current distribution along the periphery of the antenna. The far field at a distance \( r \) is given by [11]

\[
\mathbf{E}_\theta = \eta \mathbf{H}_\theta = jk_0 \mathbf{F}_\theta = jk_0 (\mathbf{F}_x \sin \phi + \mathbf{F}_y \cos \phi)
\]
The reactive component of the input impedance is $Z_{i1}$. It may be recalled from the scaling principle of two dimensional components [18] that, for the same effective dimensions of a planar component, the impedance level (reactive power, is reduced from $62.42\, \Omega$ to $53.2\, \Omega$. The optimum feed location on the diagonal of the substrate is reduced to half. Therefore, another antenna (thickness $= \frac{1}{8}\, \text{in}$, $\varepsilon_r = 2.52$) in the $0.17$ dB, is found to be $1.026$ which is different than the effective width equals the effective width of the $\frac{1}{8}$ in thick polystyrene substrate ($\varepsilon_r = 2.52$), the best value of axial ratio (equal to $0.12$ dB) is $3.1750$ GHz. As the dielectric constant for the available substrate with thickness equal to $1/16$ in was different ($2.49$), the antenna designed was optimized again and these results are summarized in Table I.

The input VSWR can be reduced further if a $1/32$ in thick substrate is used. Extrapolating the results, the input impedance is expected to be around $(45.3 + 7)\, \Omega$ and the input VSWR is likely to be about $1.19$. Although the input VSWR improves with reduction in the thickness of the substrate, it has been observed that the axial ratio limited bandwidth also decreases. Thus a design trade-off is involved in the selection of the substrate thickness.

C. Bandwidth and Radiation Patterns

Theoretical and measured values of input VSWR and axial ratio as functions of frequency for one of the antennas is shown in Fig. 4. The measured values of bandwidth (for axial ratio less than $6$ dB) is $34.8$ MHz (1.12 percent), the corresponding theoretical value being $33.7$ MHz (1.086 percent). The VSWR variation over this band of frequencies is small (Fig. 4). The bandwidth of the antenna is therefore limited by the axial ratio and not by the input impedance. Similar results have also been observed for the antenna on $1/16$ in thick substrate, but the axial ratio bandwidth is lower by nearly 40 percent (Table I).

The experimental and theoretical radiation patterns for the antenna (thickness $= 1/8 \, \text{in}$, $\varepsilon_r = 2.52$) in the $\theta = 90^\circ$ plane are shown in Fig. 5. The beamwidth is calculated from the radiation pattern. Table I gives the summary of the result for the diagonal-fed nearly square patch antennas investigated.

IV. TRUNCATED-CORNERS SQUARE PATCH ANTENNA

In this case (Fig. 2(a)), the two orthogonal modes of resonance are diagonal modes which would individually yield linear polarization along the directions of the two diagonals. Chopping of the two corners makes the resonant frequency of the mode along this diagonal to be higher than that for the mode along the unchopped diagonal. The frequency of operation and the feed point are chosen such that the two modes are excited in phase quadrature.

A. Optimum Configuration

The periphery of the truncated-corners antenna (Fig. 2(a)) is divided into 32 ports which include four e-ports at each of the truncated corners. An additional port is considered to represent the feed point. Thus, there are $25$ p-ports and four d-ports for each of the $\beta$-segments. The desegmentation method is used to evaluate the $Z$-matrix of the multiport planar model. The antenna characteristics are evaluated as discussed in Section II. It has been found that for the chosen dimensions ($2.73\, \text{cm} \times 2.73\, \text{cm}$) of the square patch, and $1/8$ in thick polystyrene substrate ($\varepsilon_r = 2.52$), the best value of axial ratio ($= 0.12$ dB) is obtained at $3.175$ GHz when $b/a = 0.04578$ where $b$ is the amount of truncation in cm and $a$ is the length of sides of the square patch. The theoretical values of the resonant frequencies of the two orthogonal modes, which can be excited independently by locating the feed point at the corners, are $3.1340$ GHz and $3.212$ GHz, respectively. The frequency for the best circular polarization (axial ratio equal to $0.12$ dB) is $3.1750$ GHz.
TABLE I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Antenna I</th>
<th>Antenna II</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. Thickness, $e_r$</td>
<td>1/8&quot;, 2.52</td>
<td>1/16&quot;, 2.49</td>
</tr>
<tr>
<td>ii. Width 'a' (cm)</td>
<td>2.66</td>
<td>2.80</td>
</tr>
<tr>
<td>iii. Length to width ratio (b/a)</td>
<td>1.0526</td>
<td>1.0296</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th>Theoretical</th>
<th>Experimental</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Best axial ratio (dB)</td>
<td>0.45</td>
<td>0.5</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>2. Center frequency $f_c$ (GHz)</td>
<td>3.1030</td>
<td>3.101</td>
<td>3.1658</td>
<td>3.1664</td>
</tr>
<tr>
<td>3. Resonant frequencies of orthogonal modes (GHz)</td>
<td>3.035</td>
<td>3.032</td>
<td>3.122</td>
<td>3.116</td>
</tr>
<tr>
<td>4. Input VSWR at $f_c$</td>
<td>1.73</td>
<td>1.77</td>
<td>1.33</td>
<td>1.55</td>
</tr>
<tr>
<td>5. Bandwidth (MHz) for axial ratio &lt; 6 dB</td>
<td>33.70</td>
<td>34.80</td>
<td>20.00</td>
<td>21.20</td>
</tr>
<tr>
<td>6. Beamwidth for 3 dB difference between $</td>
<td>E_x</td>
<td>$ and $</td>
<td>E_y</td>
<td>$</td>
</tr>
</tbody>
</table>

Fig. 4. Theoretical and experimental results for axial ratio and input VSWR for a diagonal fed antenna on 1/8 in thick substrate ($e_r = 2.52$).

Fig. 5. Radiation pattern for diagonal fed antenna; thickness = 1/8 in, $e_r = 2.52$, frequency = 3.103 GHz.

**B. Feed Point Location**

Variations of the axial ratio and the input VSWR with the feed location, on the line joining the midpoints of two opposite sides, are illustrated in Fig. 6. The input VSWR improves from 5.8 for feed location at $(x/a, y/a) = (0.5, 0.0)$ to 2.26 for feed at $(x/a, y/a) = (0.5, 0.326)$ and increases again for feed $y/a > 0.326$ on the line $x/a = 0.5$. At the location of the feed where the input VSWR is minimum the axial ratio is 0.36 dB at 3.175 GHz.

The axial ratio improves to 0.02 dB when the operating frequency is changed to 3.1758 GHz for feed at the location of minimum input VSWR. For another antenna designed on 1/16 in thick substrate ($e_r = 2.51$), the minimum input VSWR is found to be 1.6 and occurs at feed location $(x/a, y/a) = (0.5, 0.3204)$. The input VSWR thus improves when the thickness is reduced. Details of these two antennas are summarized in Table II.

**C. Bandwidth and Radiation Pattern**

The calculated and measured values of axial ratio and input VSWR for one of the truncated-corners square antennas ($e_r = 2.52$) are shown in Fig. 7. The theoretical and experimental values of bandwidth defined for an axial ratio less than 6 dB are 26.4 MHz (0.831 percent) and 29.4 MHz (0.925 percent). The corresponding values for the antenna on the 1/16 in thick substrate ($e_r = 2.51$) are found to be 14.0 MHz (0.44 percent) and 14.4 MHz (0.4535 percent). The reduction in the substrate thickness to half reduces the theoretical axial ratio bandwidth by 47 percent and the measured value by nearly 51 percent. The radiation patterns, at center frequencies, have been evaluated and verified experimentally. These are shown in Fig. 8.
TABLE II

PERFORMANCE OF CORNERS CHOPPED SQUARE PATCH ANTENNAS

<table>
<thead>
<tr>
<th>I. Parameters</th>
<th>ANTENNA I</th>
<th>ANTENNA II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thickness, ( \varepsilon )</td>
<td>( \frac{1}{8} ), 2.52</td>
<td>( \frac{1}{16} ), 2.51</td>
</tr>
<tr>
<td>2. Dimensions ( a \times a ) cm²</td>
<td>2.73 ( \times ) 2.73</td>
<td>2.86 ( \times ) 2.86</td>
</tr>
<tr>
<td>3. Truncation ( b/a )</td>
<td>0.04578</td>
<td>0.0573</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Performance</th>
<th>Theoretical</th>
<th>Experimental</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Center frequency ( f_c ) (GHz)</td>
<td>3.1758</td>
<td>3.1750</td>
<td>3.1756</td>
<td>3.1753</td>
</tr>
<tr>
<td>2. Resonant frequencies of orthogonal modes (GHz)</td>
<td>3.1340</td>
<td>3.1325</td>
<td>3.1370</td>
<td>3.1343</td>
</tr>
<tr>
<td>3. Axial ratio at center frequency (dB)</td>
<td>0.02</td>
<td>0.0</td>
<td>0.12</td>
<td>0.15</td>
</tr>
<tr>
<td>4. Bandwidth (MHz) for axial ratio &lt; 6 dB</td>
<td>26.4</td>
<td>29.4</td>
<td>(0.83%)</td>
<td>(0.925%)</td>
</tr>
<tr>
<td>5. Input VSWR at center frequency</td>
<td>2.26</td>
<td>2.26</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>6. Beamwidth for 3 dB difference between</td>
<td>(</td>
<td>E_0</td>
<td>) and (</td>
<td>E_4</td>
</tr>
</tbody>
</table>

V. SQUARE PATCH ANTENNA WITH A DIAGONAL SLOT

For a square patch antenna with a diagonal slot (Fig. 2(c)) also, the two orthogonal modes are diagonal modes. The difference in the resonant frequencies is caused by the rectangular slot which disturbs one mode more than the other. The de-segmentation method is used to evaluate the \( Z \)-matrix of the multiport planar model as explained in Section II-C. The outer periphery has been divided into 24 ports which constitute \( p \)-ports. The number of \( q \)-ports needed (and hence that of \( c \)-ports and \( d \)-ports also) is 27. Equation (4) is used to evaluate the \( Z \)-matrix of the multiport model.

A. Optimum Configuration

The thickness and dielectric constant of the substrate are \( 1/8 \) in and 2.52, respectively. The outer dimensions of the square are 2.602 cm \( \times \) 2.602 cm. The optimum dimensions of the slot are 2.89 cm \( \times \) 0.47 cm. These yield an axial ratio of 0.198 dB at 3.130 GHz. The two orthogonally spaced modes of the antenna structure can be excited independently by feeding at points 1 and 2 (Fig. 2(c)) respectively. The measured values of resonant frequencies of the two orthogonal modes are 3.060 GHz and 3.210 GHz. The respective theoretical values are 3.063 GHz and 3.212 GHz. As before the operating frequency for circular polarization lies between the two values.

The variation of axial ratio and input VSWR with feed location on the line joining the midpoints of two opposite sides (\( x/a = 0.5 \)) is shown in Fig. 9. The optimum feed location is found to be at (\( x/a, y/a \) = (0.5, 0.1636)) where input VSWR is 2.3 and axial ratio equals 0.2 dB. For \( y/a > 0.1636 \) on the line \( x/a = 0.5 \), the input VSWR improves further but axial ratio starts degrading.

B. Bandwidth and Radiation Pattern

The axial ratio and input VSWR as functions of frequency are plotted in Fig. 10. Input VSWR and axial ratio have been calculated for two feed locations. The theoretical values of axial ratio bandwidths are same for the two feed locations. VSWR variations in the two cases are shown in Fig. 10. Experiments have been conducted for feed location at (\( x/a, y/a \) = (0.5, 0.064)). The theoretical and experimental values of bandwidths (for axial ratio to be less than 6 dB) are 38.0 MHz (1.214 percent) and 35.5 MHz (1.134 percent), respectively. The variation in input VSWR over this frequency range is small as compared to the variations in axial ratio values. The theoretical and experimental radiation patterns are illustrated in Fig. 11. Table III summarizes the performance of this antenna.
Fig. 9. Variations of input VSWR and axial ratio with feed locations for square antenna with a diagonal slot (thickness = 1/8 in, $\varepsilon_r = 2.52$, frequency = 3.130 GHz).

Fig. 10. Theoretical and experimental results for square antenna with a diagonal slot (thickness = 1/8 in, $\varepsilon_r = 2.52$, frequency = 3.130 GHz).

Fig. 11. Radiation pattern for a square antenna with a diagonal slot (thickness = 1/8 in, $\varepsilon_r = 2.52$, frequency = 3.130 GHz).

### TABLE III

**Performance of Square Patch Antenna with a Diagonal Slot**

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Center frequency $f_c$ (GHz)</td>
<td>3.130</td>
<td>3.130</td>
</tr>
<tr>
<td>2. Resonance frequency of orthogonal modes (GHz)</td>
<td>3.063</td>
<td>3.060</td>
</tr>
<tr>
<td>3. Axial ratio at $f_c$</td>
<td>0.198</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Bandwidth for axial ratio less than 6 dB</td>
<td>35.5 MHz (1.12%)</td>
<td>38.0 MHz (1.21%)</td>
</tr>
<tr>
<td>5. Input VSWR at chosen feed location</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>6. Beamwidth for 3 dB difference between $</td>
<td>E_0</td>
<td>$ and $</td>
</tr>
</tbody>
</table>

Substrate thickness = 1/8 in, $\varepsilon_r = 2.52$. Dimensions of square patch = 2.602 x 2.602 cm.
Dimensions of the slot = 2.89 x 0.47 cm.
VI. CONCLUDING REMARKS

A technique employing impedance Green's functions for segments with magnetic wall boundary is used for analysis and design of three types of single feed circularly polarized microstrip patch antennas. The dimensions of the three types of antennas are optimized for obtaining the best axial ratios. The input VSWR and axial ratio variations with feed locations are investigated in an attempt to achieve a better input VSWR without using an external impedance matching network. It has been observed that for the three types of antennas investigated, perfect matching with a 50 Ω feed line is not practical unless an impedance matching network is used. Better input VSWR can be realized by using a thinner substrate, but the axial-ratio bandwidth is reduced by nearly 40 to 50 percent when the thickness of the substrate is halved. Among the three types of antennas reported, the square patch antenna with a diagonal slot has the largest axial ratio bandwidth, whereas the minimum VSWR is obtained with diagonal-fed nearly square patch antenna. The truncated-corners antenna exhibits the best axial ratio (0.02 dB) but has the least axial-ratio bandwidth. The input VSWR values of the same order as the square antenna with a diagonal slot. The theoretical and experimental results are found to be in a reasonable agreement.

REFERENCES


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Dr. Gupta is a fellow of the Institution of Electronics and Telecommunication Engineers, India.