Investigations of radiation properties of a circular disk microstrip antenna with a slot

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The radiation characteristics of a circular disc microstrip antenna (CDMAS) carrying a narrow slot on its surface are investigated experimentally and measured results are compared with computed results. The theoretical analysis of this antenna is carried out by applying cavity model-based modal expansion technique. A reasonably good agreement between computed and measured results is recorded which verifies the theoretical formulation applied in this work.

Keywords: Microstrip antenna, Cavity model, Radiation patterns, Return loss

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1 Introduction

Microstrip antennas acquired increasing popularity during past ten years due to their compact size, lightweight, conformal nature, ruggedness and low fabrication cost. These antennas are now applied in hand held mobile sets, DTH and DBS systems, radars and many more applications¹. Rectangular and circular microstrip antennas are the most common geometries and a lot of work on these geometries has been reported²³. However in every application, these geometries may not be applied, particularly when microstrip antennas are required for conformal mounting on pre-existing structures. In recent years annular ring⁴, annular sector antennas⁵, ring slot antennas⁶ and several such radiators are investigated, so that rectangular or circular geometries may be replaced by them as per requirement. Keeping this view in mind, a circular disk microstrip antenna (CDMAS) with a narrow slot is designed and tested in free space and measured results are compared with theoretically obtained results. The theoretical analysis of this antenna is carried out by applying cavity model-based modal expansion method. Applying IE3D simulation software, the simulation analysis for validation of theoretical results has been carried out. Both simulation and experimental work on these antennas are carried out at Communication Systems Group, ISRO, Bangalore, India.

2 Mathematical formulation and resonance frequency

A circular disk microstrip antenna with a slot (CDMAS) is shown in Fig. 1 having patch radius a, substrate thickness h (h < λ₀), substrate permittivity ε, and loss tangent tan δ. The slot angle (β) is considered narrow, so that β → 0. The theoretical analysis is carried out by applying cavity model-based modal expansion technique, because cavity model provides a good compromise between complexity of modes and accuracy of results. The region between the patch and...
the ground plane is treated as a cavity bounded by magnetic walls along the edges of the patch and electric walls above and below.

Let the patch is excited in such a way that the input filamentary current at feed location \((d, \phi')\) is

\[
J = J_z(\phi') \frac{\delta(\rho - d)}{d} \hat{z}
\]

with

\[
J_z(\phi') = \begin{cases} J, & \phi' - \phi < \phi' < \phi' + \phi \\ 0, & \text{elsewhere} \end{cases}
\]

\[J(\phi) = \begin{cases} J, & \phi' - \phi < \phi < \phi' + \phi \\ 0, & \text{elsewhere} \end{cases}
\] ... (1)

Here, \(2\phi\) is the width of current ribbon considered on the patch centered on the feed axis at a distance \(d\) from the centre of the patch.

The solution of wave equation

\[
(\nabla^2 + K^2) E_z = j \omega \mu_0 J
\]

is obtained after finding its eigen function. If \(K_{vn}\) is the eigen value of \(K\) then following the technique by Lo et al., the solution of wave equation will be

\[
E_z = E_0 J_v(K_{vn} \rho) \cos(v \phi')
\]

\[E_0 = j \omega \mu \sum \frac{2 J \sin(v \phi') \cos(v \phi') J_v(K_{vn} \rho)}{(K^2 - K_{vn}^2)^{1/4}} \left( J_v(K_{vn} \rho) \right)^2
\]

\[
\left[ a^2 \left( \frac{\rho}{K_{vn}} \right)^2 \right]^{1/2}
\]

\[
\left[ (2\pi - \beta) + \sin \left(\frac{2\pi(2\pi - \beta)}{2v} \right) \right]^{1/2}
\]

\[
... (5)
\]

and

\[
K = k_0 \sqrt{\varepsilon_r (1 - j \tan(\delta))}
\]

\[K_{vn}\] is equivalent wave number and \(v\) is the mode number given by

\[
v = n \quad \text{if} \quad \beta = 0
\]

\[
v = \frac{n}{2} \quad \text{otherwise}
\] ... (7)

For the theoretical analysis, \(J\) used in Eq. (5) is considered equal to unity. The resonance occurs when

\[
K = K_{vn} = (\chi_{vm} / a).
\]

Here \(\chi_{vm}\) is the \(m^{th}\) zero of the Bessel function \(J_v(K_{vn} a)\). The resonance frequency of antenna geometry is calculated with the relation

\[
f_r = \frac{(K_{vn} a) c}{2 \pi a_e \sqrt{\varepsilon_r}}
\]

To incorporate the fringe field effect, the patch radius is replaced by its effective patch radius \(a_e\). The effective patch radius is calculated by using radius extension expression of the circular patch antenna having the same surface area as that of CDMS geometry, i.e.

\[
a_e = r_e \left[ \frac{2 \pi}{2} \right]^{1/2}
\]

Here \(r_e\) represents the effective radius of the circular patch given by

\[
r_e = r \left[ 1 + \frac{2}{\pi} \right]^{1/2}
\]

\[
x \left[ \ln \left( \frac{r}{2h} \right) + (1.41 \varepsilon_r + 1.77) + \frac{h}{r} (0.268 \varepsilon_r + 1.65) \right]^{1/2}
\]

... (10)

and \(r\) the radius of circular patch of same surface area.

First the resonance frequency of a circular patch antenna of radius \(a\) is calculated using Eq. (8) by substituting \(\beta = 0\), in Eq. (9). This computed resonance frequency in TM\(_{11}\) mode of excitation is compared with the measured resonance frequency of identical circular disk microstrip antenna\(^3\) (CDMS) in Table 1 and an excellent match between the two results is recorded. After this validation process, the resonance frequency of proposed CDMS geometry of radius \(a\) and slot angle \(\beta = 5^\circ\) is computed by applying Eqs (8)-(10) and compared with the simulated resonance frequency of antenna. An excellent agreement between the two frequencies is again recorded. It is

| Table 1—Computed and measured resonance frequency of some antenna geometries |
|---|---|---|---|
| Geometry | Patch radius \(a\) (in mm) | Substrate permittivity \(\varepsilon_r\) | Resonance frequency \(f_r\) (GHz) |
| CDMA \(\beta=0^\circ\) | 10.7 | 2.65 | 4.722 | 4.723 |
| CDMS \(\beta=5^\circ\) | 20.00 | 2.55 | 2.647 | 2.635 |
found from the theoretical calculations that for a circular disk antenna \((\beta = 0)\), the simulated resonance frequency agrees well with computed frequency in TM\(_{11}\) mode of excitation, but for COMAS geometry \((\beta = 5^\circ)\). Also, fairly good agreement between computed and simulation results is obtained in TM\(_{21}\) of excitation. Therefore, all the theoretical formulations for COMAS geometries are carried out in TM\(_{21}\) mode.

By applying equivalence principle and image theory, components of equivalent magnetic current source \(M\) are developed, which are applied to find components of vector potential \((F)\). By applying suitable transformation, the field pattern factor \(R_{\theta, \phi}\) for COMAS geometry are calculated following

\[
R_{\theta, \phi} = \left[ |E_{\theta}|^2 + |E_{\phi}|^2 \right] \quad \ldots \quad (11)
\]

Here

\[
E_{\theta} = -j\omega \eta \left( F_{\theta} \sin(\phi' - \phi) + F_{\phi} \cos(\phi' - \phi) \right)
\]
\[
E_{\phi} = -j\omega \eta \left( F_{\theta} \cos(\theta) \cos(\phi' - \phi) - F_{\phi} \cos(\theta) \sin(\phi' - \phi) \right) \quad \ldots \quad (12)
\]

The frequency dependent return loss (RL) of probe fed COMAS geometry is determined by using following relation:

\[
RL(f) \, \text{(in dB)} = 20 \log \left( \frac{Z_c - Z_{in}(f)}{Z_c + Z_{in}(f)} \right) \quad \ldots \quad (13)
\]

where, \(Z_{in}\) is the input impedance of patch antenna and is given by

\[
Z_{in} = \left( \frac{-j \xi_v^2 h \omega}{2 \pi \varepsilon_0 \varepsilon_r A_w} \right) \sqrt{\frac{1 - j \delta_{ef}}{\omega^2 (1 - j \delta_{ef}) - \omega_m^2}} \left[ \frac{\sin(v w) \cos^2(v \phi') J_v(K_{vn} d)^2}{v w} \right] \quad \ldots \quad (14)
\]

Here, \(Z_c\) is 50 ohms, \(A_w = 0.33887\) and \(\xi_v\) is taken equal to unity. \(\delta_{ef}\) is the effective value of loss tangent. After comparing computed and simulated input impedance results of antenna at different points on edge OA, a proper feed location \((d, \phi'')\) on antenna is obtained, so that it may match with input impedance (50 \(\Omega\)) of feed line. Based upon this theoretical analysis, COMAS geometry is prepared for experimentation.

### 3 Experimental details

A COMAS geometry with slot angle \(\beta = 5^\circ\) is fabricated on TFG substrate for experimentation and is shown in Fig. 2. The thickness of substrate in this antenna is 1.6 mm, while substrate permittivity is 2.55. The substrate carries copper layers on both the sides, covered with a protective layer of (Sn-Pb). The total thickness of this metal layer on the two sides is 35 \(\mu\)m. On one side of this substrate, copper layer is retained as it is, while on the other side, COMAS patch with patch radius 20 mm is prepared. The dimensions of ground plane in the designed structure are 7.5 cm \times 6.5 cm and the patch is coaxially fed with a SMA connector. Since a nice agreement of computed and simulated input impedance of antenna with the feed line impedance (50 ohm) is recorded at feed location \((\phi', d) = (0, 4.95 \text{ mm})\), this point on the patch geometry is used for feeding this antenna.

The radiation patterns are measured by placing designed test antenna inside an anechoic chamber. The separation between this test antenna and receiving horn antenna is kept around two metres. With the help of a sweep generator, 2.635 GHz signal is applied and radiation patterns are measured in \(\phi = 0\) and \(\phi = 90^\circ\) planes. The return loss and input impedance of antenna are measured by applying HP vector network analyzer and its associated computer programmes. During impedance measurement, due consideration was given to accuracy enhancement techniques to

![Fig. 2—Designed antenna for experimentation](image-url)
correct effective directivity, effective source match and frequency tracking errors.

4 Results and discussion

The radiation patterns of designed CDMA structure with slot angle $\beta = 5^\circ$ are recorded by placing it in an anechoic chamber at frequency 2.635 GHz. The $\phi = 0$ and $\phi = \pi/2$ plane measured radiation patterns are compared with computed radiation patterns in Figs 3 and 4. The measured radiation patterns are showing little radiations in the backward direction of the antenna, which are around 20 dB down in comparison to the radiations in the forward direction and hence they may be neglected. An excellent agreement between measured and computed patterns is obtained. This antenna is predominantly radiating in the broadside direction with 3 dB beam width 105° and 82° in $\phi = 0$ and $\phi = \pi/2$ planes, respectively.

Some of the measured results of this antenna are compared with computed results in Table 2. The measured return loss of designed structure is compared with computed values in Fig. 5. The computed and measured return losses are -23.51 and -16 dB, respectively. The return loss results indicate a fair matching between the patch antenna and the feed line. The measured input impedances of CDMA geometry is plotted as a function of frequency on Smith chart and is shown in Fig. 6. The computed and measured input impedances of this antenna at resonance frequency are also shown in Table 1. Though a fairly good agreement between real parts of input impedance $\text{Re}(Z_m)$ is obtained, but a little difference in measured and computed reactive part of input impedance $\text{Im}(Z_m)$ is recorded. The possible reason for this discrepancy may be the ignorance of mutual coupling.

<table>
<thead>
<tr>
<th>Antenna geometry</th>
<th>Resonance frequency (GHz)</th>
<th>3 dB beam width</th>
<th>Input impedance (at resonance)</th>
<th>Return loss (at resonance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot $\beta=5^\circ$</td>
<td>2.647</td>
<td>2.635</td>
<td>E-plane 105°</td>
<td>$61.68 + j8.274$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E-plane 83°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H-plane 81°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H-plane 82°</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6—Measured and computed input impedance of antenna under test between closely spaced straight edges OA and OB shown in Fig. 1, during mathematical formulation.

The overall radiation performance of designed CDMAS geometry is comparable or, to some extent, better than that of identical circular disk microstrip antenna. The performance of CDMAS geometry may be improved further by adding more slots on the patch and by incorporating the effect of mutual coupling between radiating edges. In the light of presented results, proposed geometry may replace a circular disk microstrip antenna as per requirement.

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