Analysis of Circular Disk Patch Antenna Loaded with U- and V-shape slot for Broadband Operation

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Abstract—A broadband antenna is achieved by introducing two different shapes of slot in circular disk patch. In U- slot loaded disk antenna, typically 24.21 % bandwidth is obtained however in V- slot loaded patch antenna bandwidth improves up to 34.58 %. Variation of slot length ($L_s$), slot width ($T$), base length ($L_b$) as well as V-arm angle ($\alpha$) are also studied to obtain the desired bandwidth and good matching. The theoretical results are also compared with IE3D simulation and experimental results.

Index Terms- Circular disk patch, broadband antenna, parasitic disk patch and microstrip patch antenna.

I. INTRODUCTION

Due to the advancements in communication technology and significant growth in the wireless communication market there is a need for smaller, broadband and reliable antennas. Therefore, bandwidth enhancement and size reduction are becoming the major design considerations of patch antenna for practical applications. Several useful techniques applied to improve the bandwidth and size reduction have been reported so far [1-3]. A number of theoretical and experimental researches have been done to improve the bandwidth of the antenna [4-6]. Loading of shorting pins and stacking of patches are some techniques to increase the bandwidth of microstrip antennas [7-8]. Different shapes of slot loading in fed patch also enhance the antenna bandwidth [9-10].

In the present paper the multiresonator techniques is utilized by introducing the slots in the patch which improves the antenna bandwidth. Two antenna geometries are presented theoretically, first one is U- slot loaded disk and another is V-slot loaded disk patch antenna. Both the geometries are analyzed using cavity model which has not been done so far. Different antenna parameters are studied as a function of slot dimensions such as slot length ($L_s$), base length ($L_b$), slot width ($T$) and V-arm angle ($\alpha$).

Results obtained from the analysis are compared with IE3D simulation [11] and reported experimental results [12].

II. ANALYSIS OF U-SLOT LOADED DISK PATCH ANTENNA

Fig.1 shows the geometry of the antenna in single layer configuration along with its current distribution, in which U- shape slot is incorporated in fed disk patch.
Disk patch antenna is considered as the parallel combination of capacitance ($C_i$) inductance ($L_i$) and resistance ($R_i$), the values of which can be calculated as [13]

$$C_i = \frac{Q_i}{2\pi R_i f_r}$$

(1)

$$L_i = \frac{R_i}{2\pi f_r Q_i}$$

(2)

and

$$R_i = \frac{h^2 E_0^2 J_n^2(k x_0)}{2 P_r}$$

(3)

where

$J_n(k x_0) = \text{Bessel functions of order ‘n’}$

$x_0 = \text{feed location from the center of the disk patch}$

$h = \text{thickness between ground plane and fed patch}$

$Q_r = \text{total quality factor of the resonator}$

$P_r = \text{total power loss in the cavity}$

$f_r = \text{resonant frequency of the disk antenna}$

for TM$_{11}$ mode

$$= \frac{k_{nm} c}{2\pi R_e \sqrt{\varepsilon_r}}$$

in which

$k_{nm} = \text{mth zero of the derivative of Bessel function of order ‘n’}$

$c = \text{velocity of light}$

$R_e = \text{effective radius of the circular disk [14]}$

$\varepsilon_r = \text{dielectric constant of the substrate}$

Fig.1 (b). Current distribution of U- slot loaded disk patch antenna at 4.52 GHz

Slot in microstrip patch can be analyzed by using duality relationship between the dipole and the slot. In this paper the patch is fed by a coaxial feed (50Ω). The U-shape slot is considered as three slots i.e. two parallel to y-axis and the third one perpendicular to the y-axis. The impedance of a single slot parallel to the y-axis is given as [15].

$$Z_s = R_s(k L_s) - j \left[ 120 \left( \log \frac{L_s}{T} - 1 \right) \cot \frac{k L_s}{2} - X_A(k L_s) \right]$$

(4)

where

$k = \frac{2\pi}{\lambda} \text{ (wave vector)}$

$L_s = \text{length of the slot}$

and $X_A(k L_s)$ is given as

$$X_A(k L_s) = 30 \left[ 2 C_i(k L_s) - C_i(2 k L_s) - C_i \left( \frac{2 k T^2}{L_s} \right) \right]$$

where $T$ is the width of the slot and $R_s$ is the radiation resistance and is given by

$$R_s = \frac{2 W_T}{I_m^2} = -\frac{\eta_0}{2\pi} \int_0^{2\pi} \frac{\cos^2 \theta - \cos \frac{k L_s}{2} d\theta}{\sin \theta}$$

(5)

here $\eta_0 = 120\pi$ (characteristic impedance of free space)

$W_T = \text{total radiated power}$

$I_m = \text{maximum current in the slot}$

Radiation resistance $R_s$ is calculated as

$$R_s = 60 \left[ C_i(k L_s) - C_i(2 k L_s) + \frac{1}{2} \sin(k L_s) \right]$$

$$[ C + \ln \left( \frac{k L_s}{2} \right) + C_i(2 k L_s) - 2 C_i(k L_s) ]$$

(6)

where $C$ (Euler's constant)=0.5772

and $S_i(k L_s)$ and $C_i(k L_s)$ are the sine and cosine integral and given as

$$S_i(x) = \int_0^x \frac{\sin(x)}{x} dx$$

and $C_i(x) = -\int_0^x \frac{\cos(x)}{x} dx$

Now the impedance of slot perpendicular to the y-axis is given as
The input impedance of the microstrip disk patch antenna can be calculated from Fig. 2 as

\[ Z_{sp} = -j \left[ 120 \left( \frac{L_b}{T} - 1 \right) \cot \left( \frac{kL_b}{2} \right) \right] \]

\( L_b \) = length of the slot along x-axis

The equivalent circuit of the microstrip disk patch antenna can be calculated from Fig. 2 as

![Equivalent Circuit of the disk patch](image)

The theoretical analysis of the proposed antenna is derived by considering the two slots along the y-axis as an inclined slot of the length \( L_s \) at an angle \( \alpha \) and a base slot at an angle \( 90^\circ + \alpha \) which is along x-axis of the patch. Considering the coordinate of the slot \((x_1,y_1)\) the longitudinal component of current into the inclined slot is given as [16].

![Fig. 2 Equivalent Circuit of the disk patch antenna](image)

\[ Z_p = \frac{1}{\frac{1}{R_1} + j\omega C_1 + \frac{1}{j\omega L_1}} \]  
(7)

where the value of \( R_1, L_1, \) and \( C_1 \) are calculated by [13]. The equivalent circuit of the proposed U-slot embedded patch can be given as shown in Fig. 3, in which \( Z_{u1} \) is the impedance due to two U-slot length and \( Z_{u2} \) is the impedance due to base length of the U-slot.

![Fig. 3 Equivalent circuit of U-slot loaded disk patch antenna](image)

Now the total input impedance of U-slot loaded disk patch antenna can be calculated from Fig. 3 as

\[ Z_T = \frac{Z_p Z_{u1} Z_{u2}}{Z_{u1} Z_{u2} + 2Z_p Z_{u2} + Z_p Z_{u1}} \]  
(8)

**III. ANALYSIS OF V-SLOT LOADED DISK PATCH ANTENNA**

The geometry of V- shape slot loaded disk patch and corresponding current distribution is shown in Figs.4(a-b) respectively.

![Fig. 4a. Geometry of V-slot loaded disk patch antenna](image)

\[ I(y_1) = \text{Im} \cos(\alpha) \sin \left[ k \left( \frac{L_s}{2} - y_1 \right) \right] \quad y_1 > 0 \]

\[ = \text{Im} \cos(\alpha) \sin \left[ k \left( \frac{L_s}{2} + y_1 \right) \right] \quad y_1 < 0 \]

(9)

where

![Fig. 4 b. Current distribution of V-slot loaded disk patch antenna at 4.5 GHz](image)
Im = maximum current in the inclined slot
and \( \alpha \) = inclination angle.

The impedance due to the inclined slot can be calculated as [16].

\[
Z_r = \frac{jk \cos^2 \alpha}{4\pi \omega e_0} \int \left[ \frac{e^{-j\beta_1}}{r_2} + \frac{e^{-j\beta_2}}{r_2} - 2\cos(\beta_2) e^{-j\beta_2 \cdot \sin \theta} \right] dy_1
\]  
(10)

where, \( r_1 = \left[ x_1^2 + (L_y - y_1)^2 \right]^{\frac{1}{2}} \)

\( r_2 = \left[ y_1^2 + (L_x - y_1)^2 \right]^{\frac{1}{2}} \)

and \( r_0 = \left[ x_1^2 + y_1^2 \right]^{\frac{1}{2}} \)

The real and imaginary parts of equation (10) can be given as

\[ Z_r = R_r + jX_r \]

where \( R_r \) is the real part and equivalent to the radiation resistance of the inclined dipole (slot) and \( X_r \) is the input reactance of the inclined slot given by

\[
X_r = 30\cos^2 \alpha \left[ 2S_i(kL_y) + \cos(kL_y) \left[ 2S_i(kL_y) - S_i \right] \left( 2kL_y - \sin(kL_y) \right) \right]
\]  
(11)

Now the input impedance due to inclined slot can be given as [16].

\[
Z_{slot} = \frac{\eta_0^2}{4Z_{cy}}
\]  
(12)

Similarly the impedance for the base length \( L_b \) is calculated by substituting the value of \( \alpha \) and \( L_y \) by \( 90 + \alpha \) and \( L_y \), respectively.

The equivalent circuit of the proposed V-slot embedded patch can be calculated in similar way as U-slot loaded disk shown in Fig. 3, in which \( Z_{u1} \) and \( Z_{u2} \) are replaced by \( Z_{v1} \) and \( Z_{v2} \) respectively. \( Z_{v1} \) is the impedance due to two V-arm length and \( Z_{v2} \) is the impedance due to base length of the V-slot. The values of \( Z_{v1} \) and \( Z_{v2} \) are calculated using equation (12).

Now the total input impedance of the proposed antenna can be calculated from Fig. 3 as

\[
Z_T = \frac{Z_rZ_{v1}Z_{v2}}{Z_{v1}Z_{v2} + 2Z_rZ_{v2} + Z_pZ_{v1}}
\]  
(13)

Using equations (8) and (13) one can calculate the various antenna parameters for both proposed antennas as

Reflection Coefficient

\[
(\Gamma) = \frac{Z_0 - Z_T}{Z_0 + Z_T}
\]  
(14)

where \( Z_0 = \) characteristic impedance of coaxial feed (50 \( \Omega \))

\[
VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}
\]  
(15)

and

Return loss = 20 log (\( |\Gamma| \))

\( \) (16)

IV RADIATION PATTERN

The radiation pattern for the U-slot and V-slot loaded disk patch antenna are given by considering these antennas equivalent to circular disk patch as [17]

\[
E(\theta) = J^n k_0 V_0 e^{-j\phi} [J_{n+1}(k_0 R \sin \theta) - J_{n-1}(k_0 R \sin \theta)] \cos n\phi
\]  
(17)

\[
E(\phi) = J^n k_0 V_0 e^{-j\phi} [J_{n+1}(k_0 R \sin \theta) - J_{n-1}(k_0 R \sin \theta)] \cos \theta \sin n\phi
\]  
(18)

where \( V_0 = \) radiating edge voltage

\[
h_1 E_0 J_n(R)
\]

\( r = \) distance of an arbitrary far-field point

\( R = \) radius of fed disk patch
V. DESIGN SPECIFICATIONS

Table-1 Design specifications for U-slot loaded disk patch antenna

<table>
<thead>
<tr>
<th>Substrate material used</th>
<th>Thickness between ground and fed patch (h)</th>
<th>Radius of fed disk patch (R)</th>
<th>Length of U-slot (L_s)</th>
<th>Width of the slot (T)</th>
<th>Base length of U-slot (L_b)</th>
<th>Feed location (x_0,y_0)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>(ε_r = 2.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.575 mm</td>
<td>10.65 mm</td>
<td>11.0 mm</td>
<td>2.0 mm</td>
<td>6.0 mm</td>
<td>(0,-1 mm)</td>
</tr>
</tbody>
</table>

Table-2 Design specification for V-slot loaded disk patch antenna

<table>
<thead>
<tr>
<th>Substrate material used</th>
<th>Thickness between ground and fed patch (h)</th>
<th>Radius of fed disk patch (R)</th>
<th>Arm angle (α)</th>
<th>V-arm length (L_s)</th>
<th>Base length (L_b)</th>
<th>V-slot thickness (T)</th>
<th>Feed location (x_0,y_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ε_r = 2.2)</td>
<td></td>
<td>7°</td>
<td>11.0 mm</td>
<td>4.0 mm</td>
<td>2.0 mm</td>
<td>(0,-1 mm)</td>
</tr>
</tbody>
</table>

VI. DISCUSSION OF RESULTS

In fig.5, it is shown a marginal improvement in antenna bandwidth. Similar variation in antenna bandwidth is observed when U-slot length (L_s) and base length (L_b) vary (Fig.6 & 7). In Fig.8 theoretical results are compared with simulated and experimental results. The theoretical bandwidth is found to 24.21 %, (simulated 23.84 % and experimental 21.5 %).

It is found that the theoretical results obtained from the analysis exhibit good agreement with simulated and experimental results.

Fig. 5 Variation of return loss with frequency for different value of slot width (T) in U-slot loaded disk

Fig.6. Variation of return loss with frequency for different value of slot length (L_s) in U-slot loaded disk
Variation of slot length (Ls) for V- slot loaded disk is shown in Fig. 9. From the figure it is clear that the bandwidth of the antenna increases comprehensively with the increasing value of Ls. After a certain value of Ls antenna shows dual frequency behavior however the bandwidth is found inversely proportional to the V- slot thickness (T) (Fig.10).

The variation of V-slot base length (Lb) on antenna bandwidth is almost ineffective but the antenna matching improves as the base length (Lb) decreases and a shift in frequency band of operation towards lower side is observed as the value of Lb decreases (Fig 11). Fig.12 shows that there is no significant effect of V-arm angle (α) on antenna bandwidth. However as the value of (α)
increases up to a certain value of ($\alpha$), it exhibits wideband antenna and dual-band radiator thereafter.

Fig11. Variation of return loss with frequency for different value of base length ($L_b$) in V-slot loaded disk

Fig12. Variation of return loss with frequency for different value of arm angle ($\alpha$) in V-slot loaded disk

Fig13. Theoretical plot with simulated results of V-slot loaded disk patch antenna ($R=10.65\text{mm}$, $h=1.575\text{mm}$, $L_a=11\text{mm}$, $L_b=4\text{mm}$, $W_s=2\text{mm}$)

A comparative plot of theoretical results along with simulated one is shown in Fig. 13. for the validity of the proposed theory. Good agreement between theoretical and simulated results has been observed.

The radiation pattern for both U-slot and V-slot loaded disk antenna are shown in Figs. 14 and 15. Both results are showing close agreement with the simulated results for the corresponding given frequencies i.e. 4.52 GHz for U-slot and 4.50 GHz for V-slot loaded disk.

Fig.14. Radiation pattern for U-slot loaded disk
VII. CONCLUSIONS

From the analysis it is found that U-slot and V-slot loaded disk patch exhibit wide bandwidth characteristics and the antenna bandwidth also depends on the various parameters of U-slot and V-slot. Broadband / dualband behavior of the antenna can be achieved by varying the V-slot width (T) and V-slot arm angle (α).

REFERENCES