Progress In Electromagnetics Research M, Vol. 9, 215–226, 2009

COMPACT HALF U-SLOT LOADED SHORTED RECTANGULAR PATCH ANTENNA FOR BROADBAND OPERATION

J. A. Ansari, N. P. Yadav, P. Singh, and A. Mishra

Department of Electronics and Communication
University of Allahabad
Allahabad 211002, India

Abstract—In this paper, analysis of half U-slot loaded patch antenna with shorting wall is presented. The parameters of the antenna significantly depend on slot and notch dimensions. Bandwidth of the proposed antenna is found to be 21.59%. The 3 dB beamwidth of the antenna is found to be 90° at the central frequency of 2.6 GHz. The theoretical results are compared with IE3D simulated and experimental ones which are in good agreement.

1. INTRODUCTION

Intensive research has been carried out to develop the bandwidth-enhancement techniques by keeping the size of the patch antenna as small as possible. One of the effective methods to improve the bandwidth is to employ a thick substrate [1]. A broadband microstrip antenna is very useful in the commercial applications such as 2.5 GHz and 3.0 GHz wireless systems, wireless local area networks (WLAN), and bluetooth personal networks. Therefore, various designs have been proposed to improve their bandwidth including different shapes of patch [2–4], stacked patch [5, 6] and shorted patch antenna [7].

In this article, a half U-slot loaded rectangular patch ($L \times W$) is analyzed using equivalent circuit theory based on model expansion cavity model, in which the performance of half U-slot loaded patch is studied as a function of slot length (L_s), slot width (W_s), notch length (L_n) and notch width (W_n). The theoretical results obtained are compared with the simulated [8] and experimental ones [9].

Corresponding author: J. A. Ansari (jaansari@rediffmail.com).

2. THEORETICAL CONSIDERATIONS

2.1. Antenna Structure and Its Equivalent Circuit

Figure 1 depicts the geometry of the proposed antenna. It consists of a rectangular patch with dimensions ($L \times W$). The rectangular patch is separated from ground plane with a foam substrate ($\varepsilon_r = 1.0$) of thickness h.

Microstrip patch is considered as a parallel combination of capacitance (C_1), inductance (L_1) and resistance (R_1) as shown in Fig. 2(a).

The values of R_1, L_1, and C_1 can be given as [10].

$$C_1 = \frac{\varepsilon_0 \varepsilon_e LW}{2h} \cos^{-2}\left(\frac{\pi y_0}{L}\right) \tag{1}$$

$$L_1 = \frac{1}{\omega^2 C_1} \tag{2}$$

$$R_1 = \frac{Q_r}{\omega C_1} \tag{3}$$

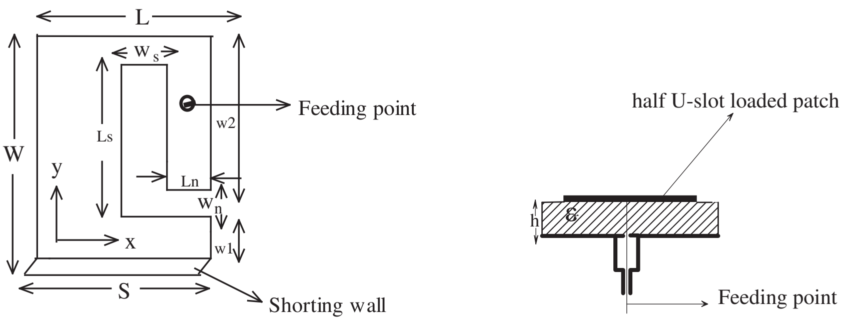
in which L = length of the patch, W = width of the patch, y_0 = feed point location, h = thickness of the substrate material.

$$Q_r = \frac{c\sqrt{\varepsilon_e}}{4fh}$$

where c = velocity of light, f = the design frequency, ε_e is effective permittivity of the medium which is given by [10].

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10h}{W}\right)^{-1/2}$$

where, ε_r = relative permittivity of the substrate material.



(a) Top view of the proposed antenna (b) Side view of the proposed antenna

Figure 1. Geometry of the half U-slot loaded shorted patch antenna.

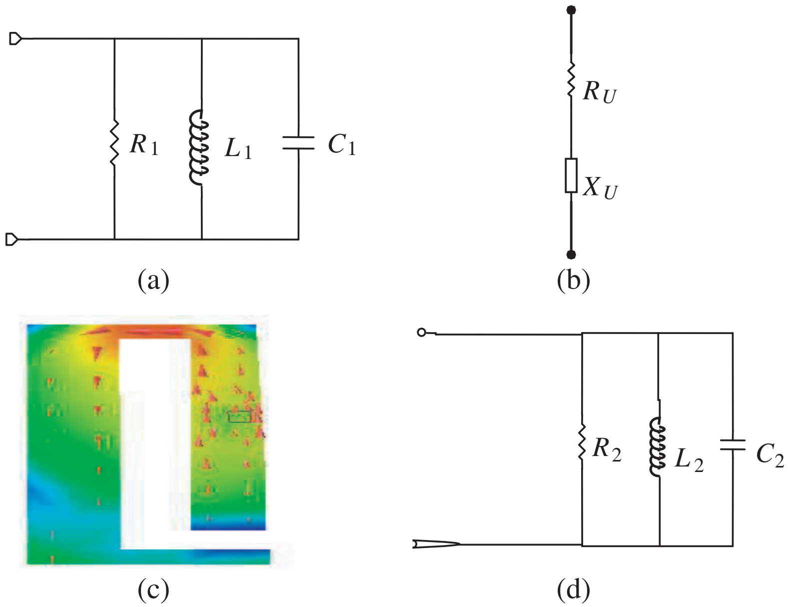


Figure 2. (a) Equivalent circuit of the patch. (b) Equivalent circuit of the vertical slot. (c) Current distribution for the antenna at the centre frequency of 2.6 GHz. (d) Equivalent circuit of notch loaded rectangular patch antenna.

Therefore, the impedance of the patch can be derived using Fig. 2(a) as

$$Z_P = \frac{1}{\frac{1}{R_1} + \frac{1}{j\omega L_1} + j\omega C_1} \tag{4}$$

Half U-slot in the patch is analyzed by assuming it as a combination of a slot with dimension $(L_s \times W_s)$ and a notch with dimension $(L_n \times W_n)$.

The equivalent circuit of a vertical slot in the patch can be given as (Fig. 2(b)).

The equivalent circuit of a narrow slot comprises a series combination of the radiation resistance (R_U) and the reactive components (X_U) [11] as shown in Fig. 2(b). Therefore, the impedance of the vertical slot can be given as

$$Z_U = R_U + jX_U \tag{5}$$

where,

$$R_U = 60C + \ln(kL_S) + \frac{1}{2}\sin(kL_S)\left[S_i(2kL_S)2S_i(kL_S)\right] + \frac{1}{2}\cos(kL_S)C + \ln\frac{kL_S}{2} + C_i(2kL_S)2C_i(kL_S)$$

and

$$X_U = 30\cos^2\alpha\Big\{2S_i\left(kL_S\right) + \cos(kL_S)\left[2S_i\left(kL_S\right) - S_i\left(2kL_S\right) - \sin\left(kL_S\right)\right] \left[2C_i\left(kL_S\right) - C_i\left(2kL_S\right) - C_i\left(\frac{2kW_S^2}{L_S}\right)\right]\Big\}$$

in which C is Euler's constant $= 0.5772$; k is propagation constant in free space; S_i and C_i are the sine and cosine integrals defined as

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

and

$$C_i(x) = -\int_x^\infty \frac{\sin(x)}{x}dx$$

The notch is introduced along one of the radiating side, which is shorted by the shorting wall. Due to the effect of notch, two currents flow in the patch. One is the normal patch current, and another is around the notch (Fig. 2(c)).

The second resonant circuit is shown in Fig. 2(d) in which

$$L_2 = L_1 + \Delta L$$

and

$$C_2 = \frac{C_1 \Delta C}{C_1 + \Delta C}$$

where series inductance (ΔL) and capacitance (ΔC) are calculated as [12, 13].

$$\Delta L = \frac{Z_1 + Z_2}{16\pi f \cos^{-2}\left(\frac{\pi y_0}{L_n}\right)}\tan\left(\frac{\pi f L_n}{c}\right) \tag{6}$$

where L_n is the length of notch, and Z_1, Z_2 are the characteristic impedance of microstrip lines with length L_n and widths of w_1 and w_2, respectively.

The values of Z_1 and Z_2 are given as

$$Z_1 = \frac{120\pi}{\frac{w_1}{h} + 1.393 + 0.667\log\left(\frac{w_1}{h} + 1.44\right)}$$

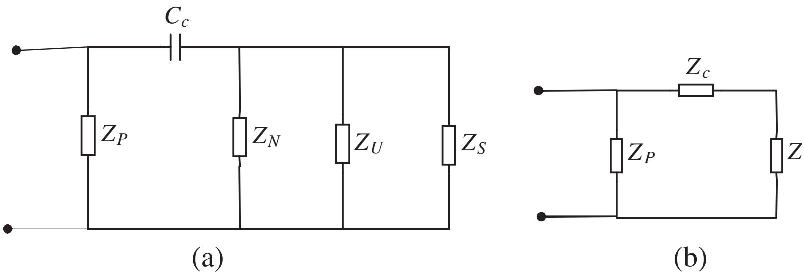


Figure 3. (a) Equivalent circuit of the proposed antenna. (b) Modified equivalent circuit of the proposed antenna.

$$Z_2 = \frac{120\pi}{\frac{w_2}{h} + 1.393 + 0.667 \log\left(\frac{w_2}{h} + 1.44\right)}$$

and

$$\Delta C = 2 \ln \frac{\varepsilon_0}{\pi} \left[\ln \frac{1+\sqrt{k_1}}{1-\sqrt{k_1}}\right] \ln\, \coth\left(\frac{\pi W_n}{4h}\right) + 0.013 \frac{h}{W_n} \tag{7}$$

where $k_1 = \sqrt{1-k^2}$ and $k^2 = \frac{1+\frac{w_1}{W_n}+\frac{w_2}{W_n}}{(1+\frac{w_1}{W_n})(1+\frac{w_2}{W_n})}$.

The coupling factor C_c between the two resonators is given by [14]. The equivalent circuit of the proposed antenna is given in Fig. 3(a) which is modified to Fig. 3(b).

Using this circuit the total input impedance of the proposed antenna can be given as

$$Z_T = \frac{Z_P\left(Z_c + Z\right)}{Z_P + Z_c + Z} \tag{8}$$

where Z_P is the impedance of the simple patch and

$$Z = \frac{Z_U Z_S + Z_N Z_S + Z_N Z_U}{Z_N Z_U Z_S}$$

in which $Z_N = \frac{1}{\frac{1}{R_1} + \frac{1}{j\omega L_2} + j\omega C_2}$, Z_S = input impedance of shorted patch, $Z_S = j\omega l_s$, l_s = Inductance due to shorting wall [15],

$$l_s = h\left[0.2 \log\left(\left(\frac{2h}{S}\right)\right) + (0.2235)\left(\frac{S}{h}\right) + 0.5\right]$$

where

S = Length of the shorting wall, h = Thickness of the substrate

$$Z_C = \frac{1}{j\omega C_c}$$

where

$$C_c = \frac{-\left(C_1 + C_2\right) + \sqrt{\left(C_1 + C_2\right)^2 - C_1 C_2 \left(1 - \frac{1}{k_c^2}\right)}}{2}$$

k_c = coupling coefficient.

2.2. Calculation of Various Antenna Parameters

The reflection coefficient of the patch can be calculated as

$$\Gamma = \frac{Z_0 - Z_T}{Z_0 + Z_T} \tag{9}$$

where Z_0 = characteristic impedance of the coaxial feed (50 ohm).

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{10}$$

and

$$\text{Return loss} = 20 \log |\Gamma| \tag{11}$$

2.3. Radiation Pattern

The radiation pattern of half U-slot loaded shorted patch antenna can be calculated as [15]

$$\begin{aligned} E(\theta) \; &= \; \frac{-jk_0 W V e^{-jk_0 r}}{\pi r} \cos\left(kh_1 \cos\theta\right) \frac{\sin\left(\frac{k_0 W}{2} \sin\theta \sin\phi\right)}{\frac{k_0 W}{2} \sin\theta \sin\phi} \\ &\quad \times \cos\left(\frac{k_0 L}{2} \sin\theta \sin\phi\right) \cos\phi \quad \left(0 \le \theta \le \pi/2\right) \end{aligned} \tag{12}$$

$$\begin{aligned} E(\phi) \; &= \; \frac{-jk_0 W V e^{-jk_0 r}}{\pi r} \cos(kh_1 \cos\theta) \frac{\sin\left(\frac{k_0 W}{2} \sin\theta \sin\phi\right)}{\frac{k_0 W}{2} \sin\theta \sin\phi} \\ &\quad \times \cos\left(\frac{k_0 L}{2} \sin\theta \sin\phi\right) \cos\phi \sin\phi \quad \left(0 \le \theta \le \pi/2\right) \end{aligned} \tag{13}$$

where V is radiating edge voltage; r is the distance of an arbitrary point, $k = k_0 \sqrt{\varepsilon_{e1}}$, $k_0 = \frac{2\pi}{\lambda}$.

3. DESIGN SPECIFICATIONS FOR THE PROPOSED ANTENNA

Table 1. Design specifications for the proposed antenna.

Dielectric constant of the material used (ε_r)	1.05 foam
Thickness of substrate used (h)	10.0 mm
Length of the rectangular patch (L)	30.0 mm
Width of the rectangular patch (W)	15.0 mm
Length of the slot (L_s)	26.0 mm
Width of the slot (W_s)	4.0 mm
Length of the notch (L_n)	5.0 mm
Width of the notch (W_n)	2.0 mm
Feed point (X_0, Y_0)	(7.0 mm, 3.0 mm)
Length of the Shorting wall (S)	15.0 mm

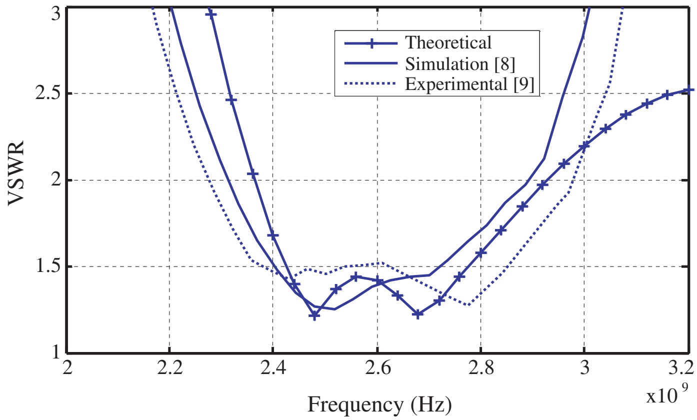


Figure 4. Comparative plot of theoretical, simulated and experimental results for given value of slot length (L_s) = 26.0 mm, slot width (W_s) = 4 mm, notch length (L_n) = 5.0 mm, notch width (W_n) = 2.0 mm.

4. DISCUSSION OF RESULTS

Figure 4 shows the variation of VSWR with frequency for the half U-slot loaded patch. The theoretical bandwidth is found to be

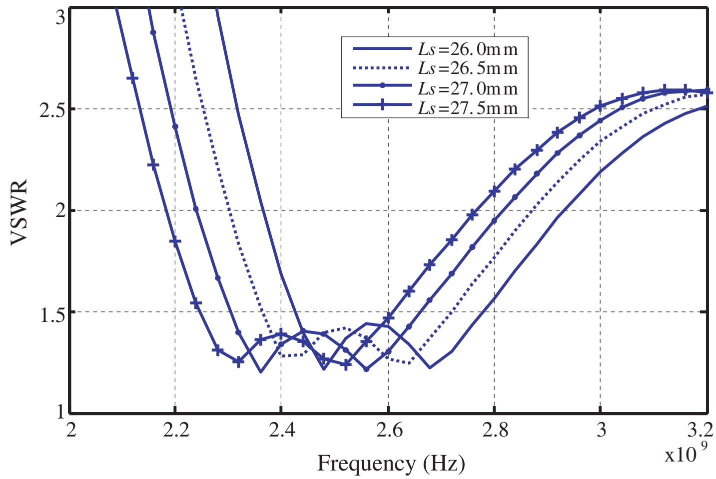


Figure 5. Variation of VSWR with frequency for different Slot length (L_s).

Table 2. Calculated value of bandwidth for different value of slot length (L_s).

S. No.	Slot length (L_s)	Operating frequency band (GHz)	Centre frequency (GHz)	bandwidth
1.	26.0 mm	2.364–2.936	2.6500	21.58%
2.	26.5 mm	2.301–2.873	2.5870	22.11%
3.	27.0 mm	2.240–2.820	2.5300	22.92%
4.	27.5 mm	2.182–2.769	2.4755	23.71%

21.59% VSWR ≤ 2 which shows almost agreement with the simulated (bandwidth 22.31%) and experimental (bandwidth 27.10%) results.

The variation of slot length (L_s) has increasing effect on bandwidth which shifts the entire bandwidth towards lower side as the value of L_s increases (Fig. 5). The obtained result is also corroborated from Table 2.

In Fig. 6, the variation of VSWR as a function of frequency is shown for different values of slot width (W_s) and for given values of $L_s = 26.0$ mm, $L_n = 5.0$ mm, $W_n = 2.0$ mm. It is found that up to a certain value the antenna shows broadband nature. However beyond $W_s = 6.0$ mm dual band characteristic is observed.

The bandwidth of the antenna increases as the value of notch

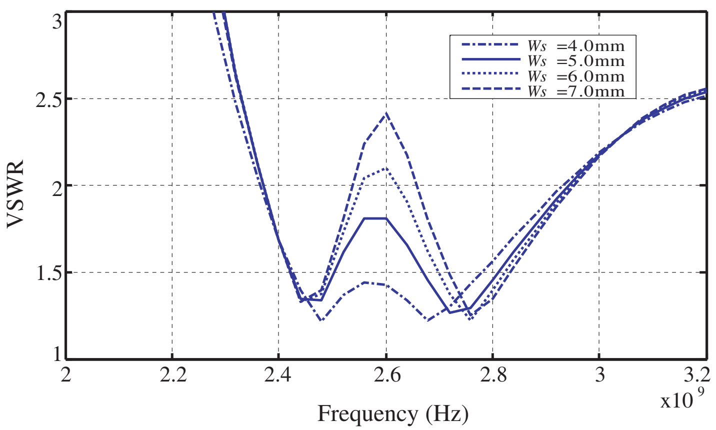


Figure 6. Variation of VSWR with frequency for different slot width (W_s).

Table 3. Calculated value of bandwidth for different value of notch length (L_n).

S. No.	Notch length (L_n)	Operating frequency band (GHz)	Centre frequency (GHz)	bandwidth
1.	5.0 mm	2.364–2.936	2.6500	21.58%
2.	6.0 mm	2.377–2.987	2.6820	22.77%
3.	7.0 mm	2.387–3.036	2.7115	23.94%
4.	8.0 mm	2.392–3.088	2.7400	25.40%

Table 4. Calculated value of bandwidth for different value of notch width (W_n).

S. No.	Notch length (W_n)	Operating frequency band (GHz)	Centre frequency (GHz)	Bandwidth
1.	2.0 mm	2.364–2.936	2.6500	21.58%
2.	3.0 mm	2.390–2.922	2.6560	20.0%
3.	4.0 mm	2.420–2.918	2.6690	18.66%
4.	5.0 mm	2.453–2.907	2.6800	16.94%
5.	6.0 mm	2.498–2.891	2.6945	14.59%

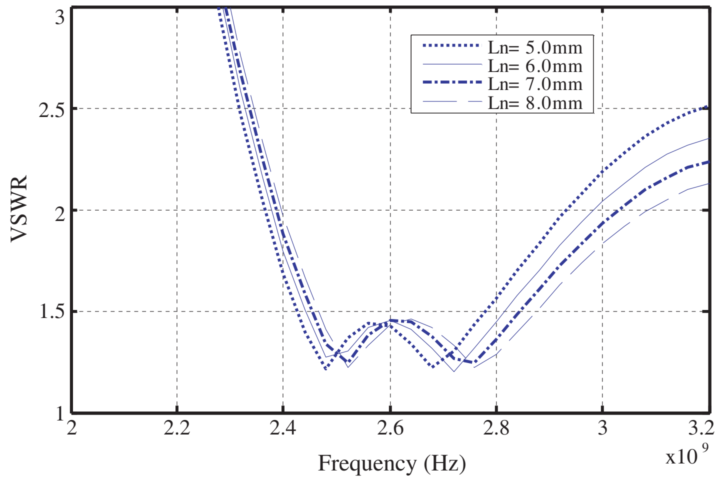


Figure 7. Variation of VSWR with frequency for different notch length (L_n).

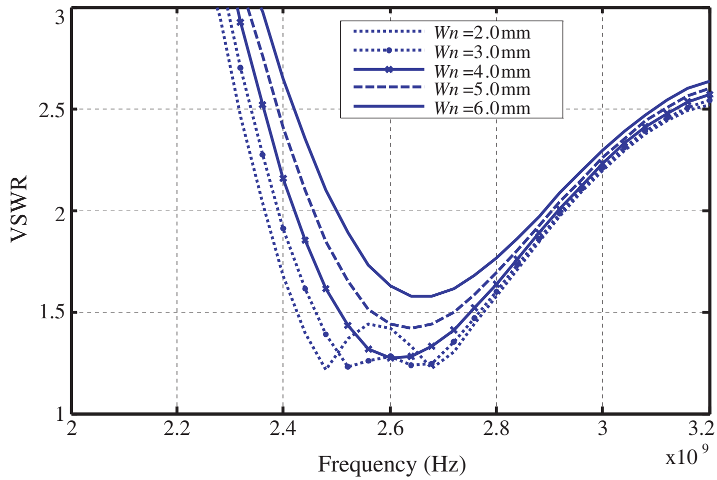


Figure 8. Variation of VSWR with frequency for different notch width (W_n).

length (L_n) increases (Fig. 7). The maximum bandwidth is found to be 25.40% at $L_n = 8.0$ mm (Table 3).

The variation of notch width (W_n) (Fig. 8) shows significant effect on the antenna bandwidth. Typically, the bandwidth is found to be

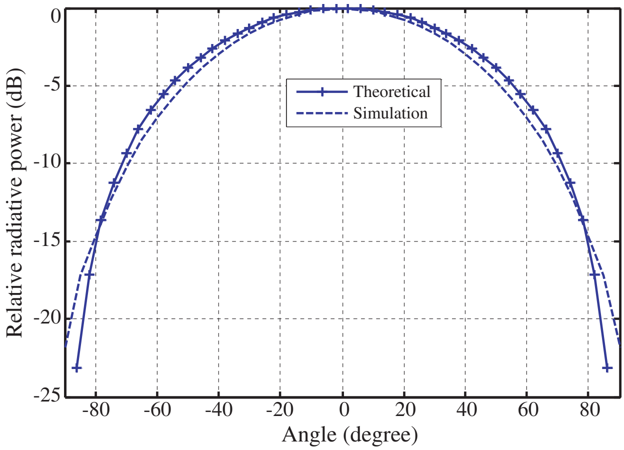


Figure 9. Radiation pattern of proposed antenna.

14.59% at maximum value of $W_n = 6.0$ mm whereas it is maximum at 21.58% at $W_n = 2.0$ mm as shown in Table 4.

The radiation pattern of the proposed antenna is shown in Fig. 9. The theoretical result (beamwidth, 90°) shows the deviation of 3 dB beamwidth around 4 degree as compared to simulated results(beamwidth, 82°).

5. CONCLUSION

From the analysis it is found that the bandwidth of the antenna is highly dependant on the dimension of slot and notch incorporated in the patch. Such antenna can be used for the Bluetooth application.

ACKNOWLEDGMENT

The authors thank Prof. Babau R. Vishvakarma, Emeritus professor, Department of Electronics Engineering, Institute of Technology, Banaras Hindu University, Varanasi, India, for providing valuable suggestions.

REFERENCES

1. Chang, E., S. A. Long, and W. F. Richards, "An experimental investigation of electrically thick rectangular microstrip antenna," *IEEE. Trans. Antenna. Propag.*, Vol. 34, 767–772, 1986.

2. Ali, A., L. Neyestanak, et al., "W-shaped enhanced bandwidth patch antenna for wireless communication," *Wireless Pers. Communication*, Vol. 43, 1257–1265, 2007.
3. Sanad, M., "Double C-patch antennas having different aperture shaped," *Proceeding of IEEE AP-S Symposium*, 2116–2119, Newport Beach, CA, 2003.
4. Abbaspour, M. and H. R. Hassani, "Wideband star shaped microstrip patch antenna," *Progress In Electromagnetic Research Letters*, Vol. 1, 61–68, 2008.
5. Ansari, J. A. and R. B. Ram, "Broadband stacked U-slot microstrip patch antenna," *Progress In Electromagnetic Research Letters*, Vol. 4, 17–24, 2008.
6. Ansari, J. A., R. B. Ram, and P. Singh, "Analysis of a gap-coupled stacked annular ring microstrip antenna," *Progress In Electromagnetic Research B*, Vol. 4, 147–158, 2008.
7. Ansari, J. A., P. Singh, N. P. Yadav, and B. R. Vishvakarma, "Analysis of shorting pin loaded half disk patch antenna for wideband operation," *Progress In Electromagnetics Research C*, Vol. 6, 179–192, 2009.
8. IE3D simulation software, Zeland, version 14.05, 2008.
9. Mak, C. L., R. Chair, K. F. Lee, K. M. Luk, and A. A. Kishk, "Half U-slot patch antenna with shorting wall," *Electronics Letters*, Vol. 39, 1779–1780, 2003.
10. Bahal, I. J. and P. Bhartia, *Microstrip Antennas*, Artech House, Boston, MA, 1985.
11. Shivnarayan, S. S. and B. R. Vishkarma, "Analysis of slot loaded rectangular microstrip patch antenna," *Indian Journal of Radio and Space Physics*, Vol. 34, 424–430, 2005.
12. Zhang, X. X. and F. Yang, "Study of slit cut microstrip antenna and its application," *Microwave and Optical Tech. Lett.*, Vol. 18, 297–300, 1998.
13. Bahal, I. J., *Lumped Elements for RF and Microwave Circuits*, Artech House, Boston, 2003.
14. Lu, J. H., C. L. Tang, and K. L. Wong, "Single feed slotted equilateral triangular microstrip antenna," *IEEE. Trans. Antenna. Propag.*, Vol. 47, 1174–1178, 1999.
15. Bahal, I. J. and P. Bhartia, *Microstrip Antenna*, Artech House, Massachuaetts, 1980.
16. Carver, K. R. and J. W. Mink, "Microstrip antenna technology," *IEEE. Trans. Antenna. Propag.*, Vol. 29, 2–23, 1981.