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# Slots and Notches Loaded Microstrip Patch Antenna for Wireless Communication

**Ashish Singh*, Kamakshi, Mohd. Aneesh, J.A. Ansari**
Department of Electronics and Communication, University of Allahabad, Allahabad, India
*Corresponding author, e-mail: ashsin09@rediffmail.com

***Abstract***

*In this article, the theoretical investigations are carried out on slots and notches loaded microstrip patch antenna for dual-band operations. The antenna parameters are calculated such as return loss, VSWR and radiation pattern. It is observed that antenna resonates at three distinct modes of frequencies of 1.490/1.953/2.941 GHz. The characteristics behaviors of the proposed antenna are compared with other coaxial fed microstrip patch antennas. The bandwidth of the proposed antenna at modes $TM_{01}$ is 2.01 %( simulated) and 3.42 % (theoretical), $TM_{02}$ is 1.10 %( simulated) and 3.81 % (theoretical) and $TM_{03}$ is 1.01 %( simulated) and 4.80 % (theoretical). The theoretical results are compared with IE3D simulation results as well as reported experimental results and they are in close agreement.*

***Keywords***: *dual-band, slots, notches, rectangular microstrip patch antenna*



## 1. Introduction

In the recent development of microstrip patch antenna in wireless communication. These antennas are used in wider range of devices in various applications such as mobile satellite, terrestrial cellular, personnel communication system [1-3] etc. As these antennas plays vital role in efficient reception and transmission of the signal in wireless communication. These antennas become more fruitful when single antenna can be used for both transmission and reception of the signal as well as can be used for dual band operation having more than two bands of frequencies. This motivated the researcher to design microstrip patch antenna for dual band operation having multiband of frequencies.

Dual band microstrip patch antenna was first reported by Wang and Lo [4] in 1984. Thereafter, plenty of dual band microstrip antennas have been reported [5-17] in which maximum research papers reported are experimental and simulated results. Only few researchers provide theoretical analysis based on circuit theory concept of their radiating structures. The theoretical analysis based on circuit theory concept us helps to comprehend on which parameter the characteristics behavior of antenna depends on such as length, width, height of the substrate, dielectric substrate, length and width of notch and slot etc. There are some researchers that have reported on dual band microstrip patch antenna having triple-band such as microstrip patch antenna using a spur-line filter [18], multi-frequency and broadband hybrid coupled [19], GSM/DCS/IMT-2000 triple-band built-in antenna for wireless terminals [20], broadband triple-frequency microstrip patch radiator combining [21], a folded planar inverted-f antenna for GSM/DCS/Bluetooth triple-band application [22], internal triple-band folded planar antenna design for third generation mobile handsets [23], design and operation of dual/triple-band asymmetric m-shaped microstrip patch antennas [24], dual-band miniaturized patch antennas for microwave breast imaging [25], the use of u-slots in the design of dual-and triple-band patch antennas [26], compact UWB printed slot antenna with extra Bluetooth, GSM and GPS bands [27], stacked-patch dual-polarized antenna for triple-band handheld terminals [28] etc. All these above reported paper of triple band having dual band operation has only experimental and simulated results. They have not explained their theoretical behavior of the antenna based on circuit theory concept as well as not provided the comparison with theoretical, experimental and simulated results.

In this article, theoretical analysis of microstrip patch antenna with three slots and notches for dual band /triple band operation is presented. The theoretical analysis of dual band antenna for triple band frequency operation is not reported in past. The theoretical comparison

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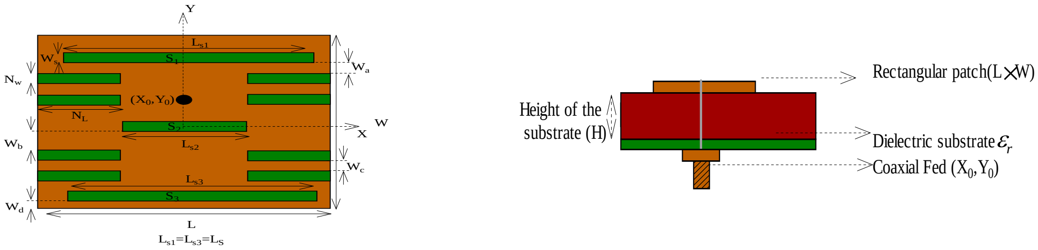
of proposed antenna with similar radiating structures as well as the theoretical, experimental and simulated comparison of results for proposed antenna has been presented. Detail description of antenna and their theoretical analysis has been presented in next section.

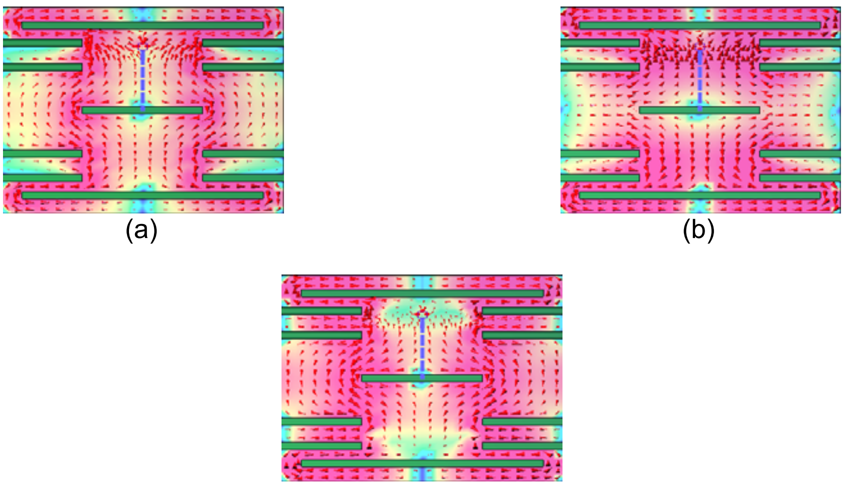
## 2. Antenna Design

The proposed antenna structure is shown in Figure 1. It consists of rectangular patch of dimension (L×W) with three slots $S_1$, $S_2$ and $S_3$ of dimensions $L_{S1}$×$W_s$, $L_{S1}$×$W_s$ and $L_{S1}$×$W_s$ respectively as well as, four notches of equal dimension ($N_L$×$N_W$) is loaded on both side of the radiating edges. The rectangular patch is fed via coaxial feeding at ($X_0$,$Y_0$) and it is separated from ground plane with substrate ($\varepsilon_r$=2.65) of thickness H. Detail design specification of antenna is given in Table 1.




(a) (b)

Figure 1. Geometry of rectangular microstrip patch antenna (a) top view, (b) side view



(a) (b) (c)

Figure 2. Current distribution of proposed antenna at (a) $TM_{01}$, (b) $TM_{02}$, and (c) $TM_{03}$ modes

Table 1. Design Specification of proposed antenna structure

| | |
|---|---|
| Length of the patch (*L*) | 29 mm |
| Width of the patch(*W*) | 28 mm |
| Dielectric substrate $\varepsilon_r$ | 2.65 |
| Length of the slots $S_1$ and $S_3$ ($L_{S1}$=$L_{S3}$=$L_S$) | 24 mm |
| Length of the slot $S_2$($L_{S2}$) | 12 mm |
| Width of the slots($W_S$) | 1 mm |
| Width of the notches($N_W$) | 1 mm |
| Length of Notches($N_L$) | 10 mm |
| Distance between slots ($S_1$&$S_3$) and notches ($W_a$) | 1.5 mm |
| Distance between slot ($S_2$) and notches ($W_b$) | 5.125 mm |
| Distance between two notches ($W_c$) | 2.375 mm |
| Distance between non radiating edges of patch and slot ($S_1$ &$S_3$) ($W_d$) | 2 mm |
| Feeding point($X_0$, $Y_0$) | (0, 4.5) |

**3. Theoretical Analysis**

According to the Modal expansion cavity modal the rectangular patch is considered as parallel combination of resistance $R_P$, capacitance $C_P$ and inductance $L_P$ as shown in Figure 3. The values of $R_P$, $L_P$, and $C_P$ are given as [29],

$$C_p = \frac{\varepsilon_0 \varepsilon_e LW}{2H} \cos^{-2}\left(\frac{Y_0 \pi}{L}\right) \quad (1)$$

$$L_p = \frac{1}{\omega^2 C_p} \quad (2)$$

$$R_p = \frac{Q_r}{\omega C_p} \quad (3)$$

$$Q_r = \frac{c\sqrt{\varepsilon_r}}{4fH} \quad (4)$$

And,

$$f = \frac{c}{2\pi L\sqrt{\varepsilon_e}} \quad (5)$$

$f$ is the design frequency of rectangular patch,
$L$ is the length of the patch,
$W$ is the width of the patch,
$H$ is height of the substrate,
$Y_0$ is the feeding point on y axis,
$\varepsilon_r$ is the relative permittivity of the substrate,
$c$ is the velocity of light,
$\varepsilon_e$ is the effective permittivity of the medium [29]

The total input impedance $Z_p$ of rectangular patch is given as:

$$Z_p = \frac{1}{\frac{1}{R_p} + j\omega C_p + \frac{1}{j\omega L_p}} \quad (6)$$

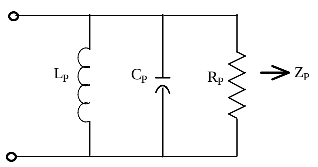



Figure 3. Equivalent circuit of simple rectangular patch

Three parallel slots loaded on the patch is considered as parallel combination of impedance $Z_{S1}$, $Z_{S2}$ and $Z_{S3}$ as shown in Figure 4. The input impedance $Z_S$ of the slots is calculated as [30-33],

$Z_S = R_S + jX_S$,

$$R_S = 60[C + In(kL_S) + \frac{1}{2}\sin(kL_S)\{S_i(kL_S) - 2S_i(kL_S)\} + \frac{1}{2}\cos(kL_S)\{C - \frac{In(kL_S)}{2} - C_i(2kL_S) - 2C_i(kL_S)\}]\cos\psi \quad (7)$$

$$X_s = 30[2S_i(kL_s) + \cos(kL_s)\{2S_i(kL_s) - S_i(2kL_s)\} - \sin(kL_s)\{2C_i(kL_s) - C_i(2kL_s) - c(2kW_S^2 / L_s)\}] \quad (8)$$

Here *C* is the Euler's constant, ψ is the inclination of the slot from radiating edge, *k* is the propagation constant and function $S_i(x)$ and $C_i(x)$ are defined as:

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

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

Where $W_s$ is width of slots and $L_S$ is the Length of the slots.

Now, input impedance of corresponding slots $Z_{S1}$, $Z_{S2}$ and $Z_{S3}$ can be calculated from above Equation (7) and (8) by putting the value of length and width of their corresponding slot. The total input impedance of slots on the patch is given as:

$$Z_S = \frac{1}{\frac{1}{Z_{S1}} + \frac{1}{Z_{S2}} \frac{1}{Z_{S3}}} \quad (9)$$

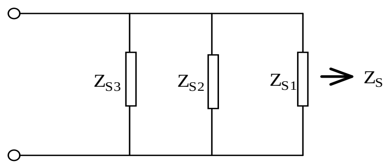



Figure 4. Equivalent circuit of slots

When a four notches is loaded to the patch on both side of the radiating edges of the antenna. Due to the effect of notches and slots, three current flows on the patch of different length, one current flows normal to the patch and resonates at the design frequency of the initial patch, and other two current flows around the notches and slots as shown in Figure 2. Figure 2 (a-c) shows the current distribution at three distinct resonance frequencies are 1. 490GHz, 1.953GHz and 2.941GHz respectively. Therefore, this perturbation modifies the equivalent circuit of the initial patch with an additional series inductance *ΔL* and series capacitance *ΔC* [34] as shown in Figure 5.

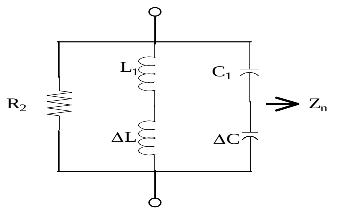



Figure 5. Equivalent circuit of notch

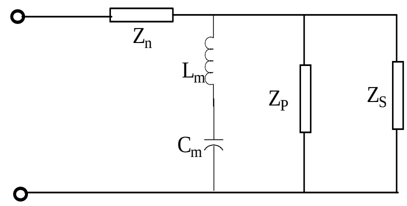



Figure 6. Equivalent circuit of proposed antenna

$$\Delta L = 8.(\frac{H\eta\pi}{8}(N_L / N_W)),$$

$$\Delta C = 8.(\frac{N_L}{N_W})C_g,$$

Where $\mu = 4\pi \times 10^{-7}$ H/m, $C_g$ is the gap capacitance [35].

$$C_g = 0.5.H.Q_1 \exp(-1.86(\frac{N_W}{H})\left[1 + 4.09\{1 - \exp(0.75\sqrt{\frac{H}{W}})\}\right]$$

$$Q_1 = 0.04598\left\{0.03 + \left(\frac{W}{H}\right)^{Q_4}\right\}(0.272 + \varepsilon_r\, 0.07),$$

$$Q_2 = 0.107\left[\frac{W}{H} + 9\right]\left(\frac{N_W}{H}\right)^{3.23} + 2.09\left(\frac{N_W}{H}\right)^{1.05} + \left[\frac{1.5 + 0.3(\frac{W}{H})}{1 + 0.6(\frac{W}{H})}\right]$$

$$Q_3 = \exp(-0.5978) - 0.55$$

$$Q_4 = 1.23$$

Where $N_W$ is the width of the notches and $N_L$ is the length of the notches.

The impedance of notch loaded on the as shown in Figure 5 is given as:

$$Z_n = \frac{1}{\frac{1}{R_2} + j\omega C_2 + \frac{1}{j\omega L_2}}, \tag{10}$$

The value of $R_2$ resistance [36] after cutting the notch is calculated similarly as $R_1$. Thus the equivalent circuit of proposed antenna can be given as shown in Figure 6, in which $L_m$ and $C_m$ are mutual inductance and capacitance [36-37] between the two resonators.

$$\mathrm{L_m} = \frac{\mathrm{k_c^2}(L_1 + L_2) + [k_c^4(L_1 + L_2)^2 + 4k_c^4(1 - k_c^2)L_1L_2]^{1/2}}{2(1 - k_c^2)},$$

$$C_m = \frac{-(C_2 + C_1) + [(C_2 + C_1)^2 + (1 - 1/k_c^2)C_1C_2]^{1/2}}{2},$$

The mutual impedance from Figure 5 can be given as:

$$Z_m = jwL_m + \frac{1}{j\omega C_m}, \tag{11}$$

Where,

$$L_2 = L_1 + \Delta L,\ C_2 = \frac{C_1.\Delta C}{\mathrm{C_1} + \Delta C},\ k_c = \frac{1}{\sqrt{Q_1Q_2}},$$

$$Q_1 = R_1\sqrt{\frac{C_1}{L_1}},\ Q_2 = R_2\sqrt{\frac{C_2}{L_2}},$$

$Q_1$ and $Q_2$ are quality factor for both the resonators.

Therefore, the total input impedance of the proposed antenna for Figure 6 is:

$$Z = Z_n + (\frac{Z_m.Z_s.Z_p}{Z_m.Z_s + Z_s.Z_P + Z_m.Z_P}), \tag{12}$$

Now using Equation (12), one can calculate the total input impedance of the proposed antenna and various antenna parameters such as reflection coefficient, voltage standing wave ratio (VSWR) and return loss (RL) is given as:

Reflection Coefficient $\Gamma = \frac{Z - Z_0}{Z + Z_0}$.

Where $Z_0$ is the input impedance of the coaxial feed (50 Ω),

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|},$$

And RL=20 log |r|

**4. Radiation Pattern**

The radiation pattern for three parallel slots and eight notches loaded single layer patch antenna is calculated by considering it as rectangular patch. The normalized patterns in the E-plane ($E_\theta$ in $\phi$ =0˚ plane) and the H-plane ($E_\phi$ in $\phi$ =90˚ plane) [34-37] are given by:

$$E_\theta = \frac{-jk_0WVe^{-jk_0r}}{\pi r}\cos(kH\cos\theta)\frac{\sin(\frac{k_0W}{2}\sin\theta\sin\phi)}{\frac{k_0W}{2}\sin\theta\sin\phi}\times$$

$$\cos\left(\frac{k_0L}{2}\sin\theta\sin\phi\right)\cos\phi \quad (0 \le \theta \le \pi/2)$$

$$E_\phi = \frac{-jk_0WVe^{-jk_0r}}{\pi r}\cos(kH\cos\theta)\frac{\sin(\frac{k_0W}{2}\sin\theta\sin\phi)}{\frac{k_0W}{2}\sin\theta\sin\phi}$$

$$\times\cos\left(\frac{k_0L}{2}\sin\theta\sin\phi\right)\cos\phi\sin\phi \quad (0 \le \theta \le \pi/2)$$

Where, V is radiating edge voltage
r is the distance of an arbitrary point.

$$k = k_0\sqrt{\varepsilon_r}$$

$$k_0 = \frac{2\pi}{\lambda}$$

**5. Discussion of Results**

Figure 7 shows the variation of reflection coefficient with frequency for various antennas configurations for simple rectangular patch without notches and slots, only slots, only notches, and with notches and slots (proposed) antenna. The characteristics of various antenna configurations are summarized in Table 2. From figure it is observed that simple rectangular patch antenna without notches and slots is resonating at 3.105GHz offers a band width of 131MHz (3.034GHz-3.195GHz) this meets the frequency band of S–band applications. For only notches antenna is resonating at two distinct modes 2.605GHz and 3.075GHz for lower and higher resonance frequencies. This antenna meets the requirement S-band applications for an ISM bands. For slots only antenna resonates at 1.483GHz and 1.953GHz, which meets the requirement of L-band applications for GPS and GSM mobile phones. For proposed microstrip patch antenna (with slots and notches) is resonating at 1.490GHz, 1.953GHz and 2.941GHz, which covers different applications of L and S bands frequency for GSM mobile phones, GPS and in biomedical applications for tumor detection.

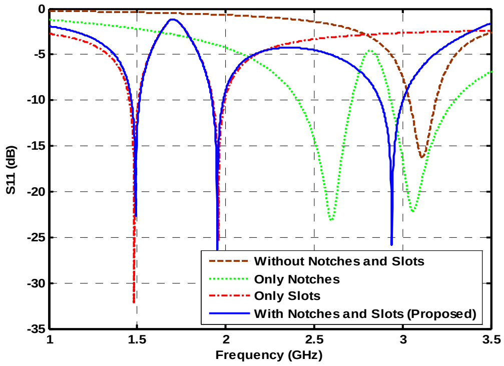



Figure 7. Comparative plot of simple rectangular patch (without notches and slots), only notches, only slots and proposed patch antenna with notches and slots

Table 2. Characteristics of Antennas

| Antenna | Frequency (GHz) | Band(GHz)<br>Bandwidth(MHz) |
|---|---|---|
| Without notches and Slots<br>(single band) | 3.105 | 3.034-3.195<br>131<br>4.2% |
| Only Notches<br>(dual band) | 2.605 | 2.404-2.715<br>311 |
| | 3.073 | 12.15%<br>2.935-3.307<br>372<br>11.91% |
| Only slots<br>(dual band) | 1.483 | 1.416-1.515<br>99<br>6.7% |
| | 1.953 | 1.900-2.002<br>102<br>5.22% |
| With notches and Slots (Proposed)<br>(triple band) | 1.490 | 1.465-1.515<br>50<br>3.7% |
| | 1.953 | 1.900-2.002<br>102<br>5.22% |
| | 2.941 | 2.875-3.012<br>137<br>4.65% |

Figure 8 shows the comparison of the theoretical results along with simulated [38] and experimental [25] results for proposed antenna. It is found that theoretical and simulated results are in close agreement with the reported experimental results.

From Figure 9, it is observed that on decreasing the length $L_s$ of slots $S_1$ and $S_3$ simultaneous from 24mm to 12mm, $TM_{03}$ and $TM_{02}$ resonating modes of the antenna shift towards lower resonance side whereas fine shifting in $TM_{01}$ mode is observed.

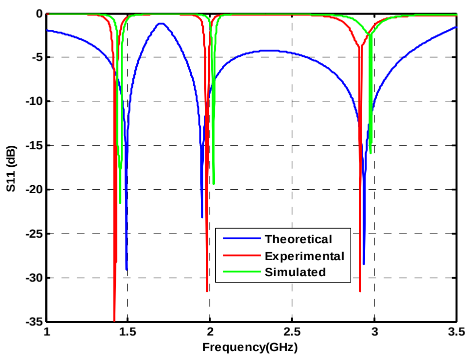
Figure 10 shows the variation of reflection coefficient with frequency for different length of the slot $S_2$. On increasing the length $L_{s2}$ of the slot from 12mm to 24mm, fine variation is observed on first and second order frequencies shift towards higher side whereas third order frequency shift towards higher side with higher variation in comparison with first and second order frequencies.

Figure 11 shows the variation of reflection coefficient with frequency for width of the slots ($S_1$ $S_2$ and $S_3$). On increasing the width of the slots $W_s$ from 1mm to 2.5mm, third and first order resonance frequencies shift towards lower resonance side where as second order resonance frequency shift towards higher side. This is happens due to length of slot $S_2$ which is the half of the slots $S_1$ and $S_3$.

Figure 12 shows the variation of reflection coefficient with frequency on varying the length of the notches. On decreasing the notches length $N_L$ form 10mm to 7mm, it is observed that third and second order frequencies shift towards higher side whereas on increasing the length $N_L$ form 10mm to 13mm, third and second order frequencies shifts toward lower side and no variation is observed at first order resonance frequency.

Figure 13 shows the variation of reflection coefficient with frequency on varying the width of the notches. On increasing the width of the notches $N_W$ from 1mm to 5mm, it is observed that third, second, and first order resonance frequencies shift towards lower side. There is slight or negligible variations are observed at first order resonance frequency in most of the variations because first order resonance frequency is consider to be resonance frequency of the simple rectangular patch which shifts toward lower resonance side as notches and slots are incorporated into the patch whereas second and third order resonance frequencies are due notches and slots respectively. Thus, the variations of the width and length of slots and notches are observed on second and third order resonance frequencies. On variation of length and width of notches the input impedance of notches $Z_n$ varies whereas on variation of width and length of slots the input impedance of slots varies which affects the total input impedance $Z_{in}$ of proposed antenna.

Figure 14 shows the radiation pattern of simulated [38] and theoretical results for proposed antenna. From Figure14 (a)-(c) shows radiation pattern of proposed antenna of $E_\theta$ at $TM_{01}$, $TM_{02}$ and $TM_{03}$ modes respectively. It is found that simulated and theoretical results are in close agreement.




Figurev8. Comparison of the theoretical, simulated [38] and experimental [13] results

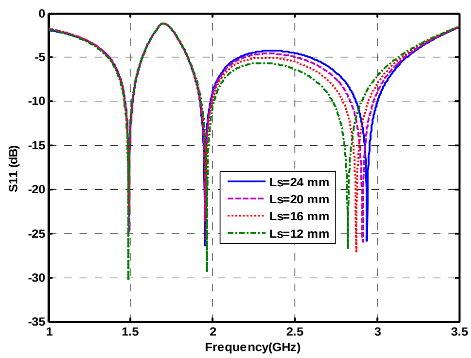



Figure 9. Variation of reflection coefficient with frequency on varying the length of the slots $S_1$ and $S_3$

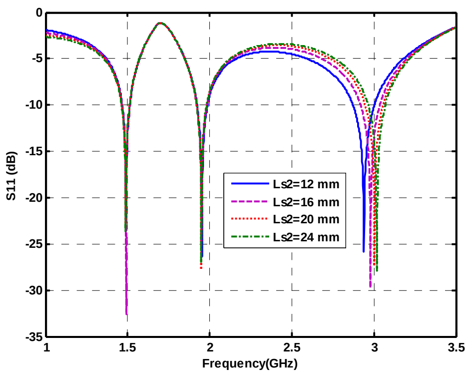



Figure 10. Variation of reflection coefficient with frequency on varying the length of the slot $S_2$

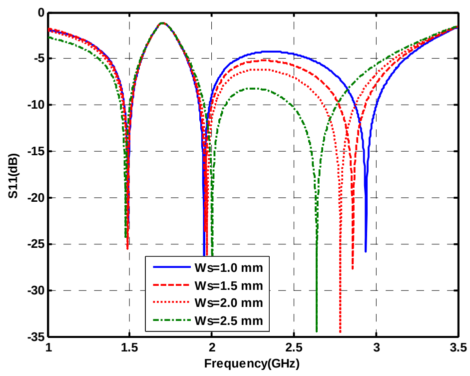



Figure 11. Variation of reflection coefficient with frequency on varying the width of the slots ($S_1$ $S_2$ and $S_3$)

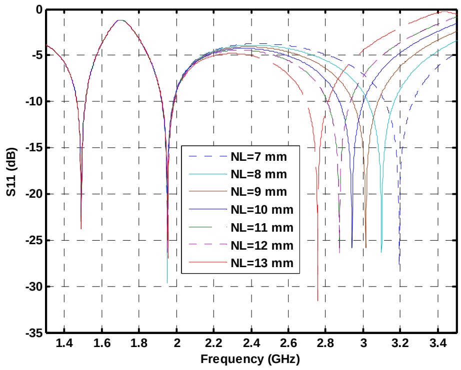



Figure 12. Variation of reflection coefficient with frequency on varying the length of the notches

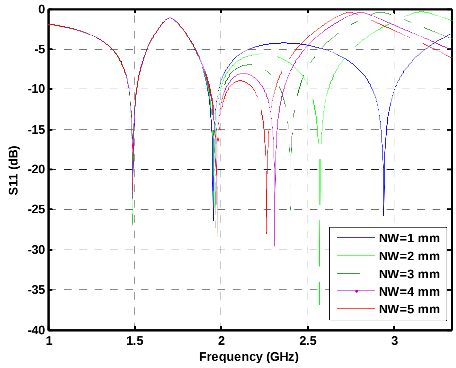
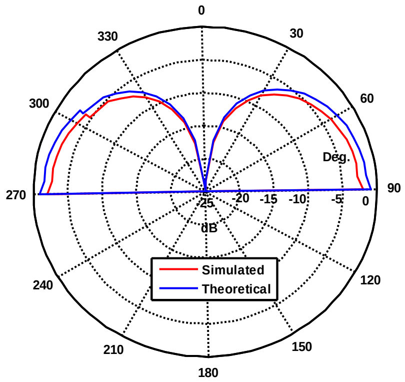
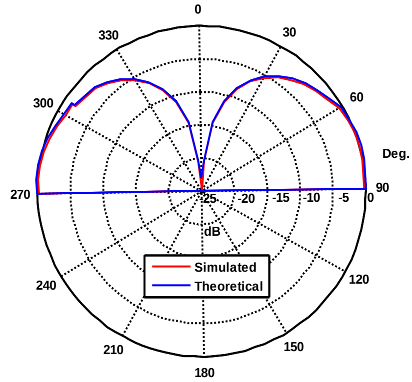


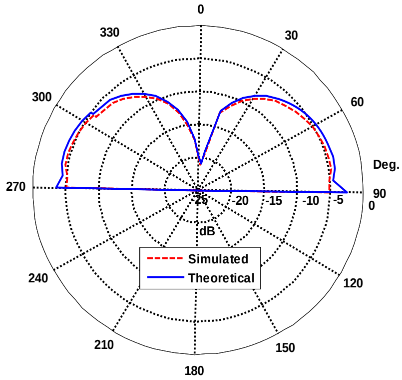

Figure 13. Variation of reflection coefficient with frequency on varying the width of the notches $N_W$




(a)




(b)




(c)

Figure 14. Radiation pattern at (a) 1.490 GHz, (b) 1.953 GHz, and (c) 2.941 GHz for E-plane

## 6. Conclusion

The theoretical investigation of proposed radiating structure has been carried out along with their similar radiation structures. It has been observed that triple band can be obtained by incorporating slots and notches together on simple rectangular patch. The proposed rectangular patch antenna depends on notches width and length and slots width and length. The proposed radiating antenna lies in L and S frequency bands. This antenna can be utilized in various wireless communication systems such as GSM (mobile phones), GPS and biomedical (tumor detection) applications.

## References


[1] Wu WW, Miller EF, Pritchard WL, Pickholtz RL. Mobile satellite communication. *Proc. IEEE*. 1997; 82: 1431-1448.
[2] Elbert BR. The Satellite Communication Applications Handbook. Norwood, MA, Artech House. 1997.
[3] Miller B. Satellite free the mobile phone. *IEEE spectrum*. 1998; 35:26-35.
[4] Wang B, Lo Y. Microstrip antennas for dual frequency operation. *IEEE Tran. Antenna Propagat.* 1984; 32: 938-934.
[5] Singh A, Ansari JA, Kamakshi, Aneesh M, Sayeed S S, Mishra A. Analysis of slots and notches loaded patch antenna for dualband operation. Multimedia, Signal Processing and Communication Technologies (IMPACT). Allahabad, 2013; 168-171.
[6] Huang CY, Ling CW, Kuo JS. Dual-band microstrip antenna using capacitive loading. *IEEE Trans. Antennas Propagt.*, 2003;150: 401-404.
[7] Polivka M, Drahovzal M, Mazanek M. Synthesis of dualband broadside radiated microstrip patch antenna operating with $TM_{10}$ and $TM_{21}$ modes. *IEEE Antenna Propagat. Soc. Int. Symp*. 2004; 1: 245-248.
[8] Hwang SH, Kwak W, Moon JI, Park SO. An internal Dualband printed antenna for CDMA/PCS handsets. *Microw. Opt. Technol. Lett.*, 2005; 45: 537-540.
[9] Ningsih Y K, Hadinegoro R. Low Mutual Coupling Dualband MIMO Microstrip Antenna with Air Gap Parasitic. *TELKOMNIKA.* 2014; 12(2), 405-410.
[10] Lau KL, Kong KC, Luk KM. Dual-band stacked folded patch antenna. *Electronic Lett.* 2007; 43: 789-790.
[11] Chen W-S, Ku K-Y. Band-rejected design of the open slot antenna for WLAN/WiMAX operation. *IEEE Trans. Antennas Propagt.*, 2008; 56: 1163 – 1169.
[12] Sung YJ. Simple tunable dual-band microstrip patch antenna. *Electronics Lett.* 2009; 45: 666-667.
[13] Al-Joumayly MA, Aguilar SM, Behdad N, Hagness SC. Dual-Band miniaturized patch antennas for microwave breast imaging. *IEEE Antennas and Wireless Propagation Letters*. 2010; 9: 268-271.
[14] Singh P. Rectangular Notch Loaded Dual Band Annular Ring Patch Antenna. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*. 2014; 13: 85-96.
[15] Singh A, Ansari JA, Kamakshi, Aneesh M, Sayeed SS. Analysis of Slot Loaded Compact Patch Antennas for Dualband Operation. *International Journal of Applied Electromagnetics and Mechanics*. DOI-10.3233/JAE-140020, 2014.
[16] Li Y, Xue Q, Tan HZ, Long Y. A dual frequency microstrip antenna using a double sided parallel strip line periodic structure. *IEEE Trans., Antenna Propag.*, 2012; 60: 3016-3019.
[17] Singh A, Aneesh M, Kamakshi K, Mishra A, Ansari JA. Analysis of F-shape microstrip line fed dualband antenna for WLAN applications. *Wireless Netw.* 2014; 20: 133-140.
[18] Sanchez Hernandez D, Robertson I. Triple band microstrip patch antenna using a spur-line filter and a perturbation segment technique. *Electronics Lett*. 1993; 29: 1565-1566.
[19] Ray KP, Kumar G. Multi-frequency and broadband hybrid coupled circular microstrip antennas. *Electronics Lett.*, 1997; 33: 437-438.
[20] Fayadh AR, Malek MFA, Fadhil AH, Wee HF. Planar Finger-Shaped Antenna used in Ultra-Wideband Wireless Systems. *TELKOMNIKA.* 2014; 12(2), 419-428.
[21] Anguera J, Martinez-Ortigosa E, Puente C, Borja C, Soler J. Broadband triple-frequency microstrip patch radiator combining a dual-band modified sierpinski fractal and a monoband antenna. *Antennas and Propagation, IEEE Trans.,* 2006; 54: 3367-3373.
[22] Kwak WIl Park, SO, Kim JS. A Folded Planar Inverted-F Antenna for GSM/DCS/Bluetooth Triple-Band Application. *IEEE Trans. Antennas and Wireless Propagation Letters*. 2006; 5: 18-12.
[23] See CH, Abd-Alhameed R A, Excell PS, McEwan NJ, Gardiner JG. Internal triple-band folded planar antenna design for third generation mobile handsets. *Microwaves, Antennas & Propagation, IET*. 2008; 2: 718 – 724.
[24] Peng L, Ruan CLi, Wu XH. Design and operation of dual/triple-band asymmetric M-shaped microstrip patch antennas. *Antennas and Wireless Propagation Letters, IEEE*, 2010; 9: 1069-1072.
[25] Al-Joumayly Mudar A, Aguilar SM, Behdad N, Hagness SC. Dual-band miniaturized patch antennas for microwave breast imaging *IEEE Trans. Antennas Wirel. Propag. Lett*. 2010; 9: 268-271.

[26] Lee KF, Luk KM, Mak KM, Yang SLS. On the Use of U-Slots in the Design of Dual-and Triple-Band Patch Antennas. *Antennas and Propagation Magazine, IEEE*, 2011; 53: 60–74.
[27] Bod M, Hassani HR, Taheri MMS. Compact UWB Printed Slot Antenna With Extra Bluetooth, GSM, and GPS Bands. *Antennas and Wireless Propagation Letters, IEEE*, 2012; 11: 531–534.
[28] Falade OP, Gao Y, Chen X, Parini C. Stacked-Patch Dual-Polarized Antenna for Triple-Band Handheld Terminals. *Antennas and Wireless Propagation Letters, IEEE.* 2013; 12; 202-205.
[29] Garg R, Bhartia P, Bahl I, Ittipiboon A. *Microstrip Antenna Design Handbook*. Artech House, Boston, London. 2003.
[30] Bahl I J, Bhartia P. Microstrip Antenna. Artech House Massachuaetts.1980.
[31] Anasari JA, Ram RB. Analysis of Broad Band U-Slot Microstrip Patch Antenna. *Microwave and Optical Technology Letters*. 2008; 50: 1069-1073.
[32] Pandey VK, BR Vishvakarma. Analysis of an E-shaped patch antenna. *Microwave and Optical Technology Letters,* 2007; 49: 4–7.
[33] Shivnarayan, Sharma S, Vishvakarma B R. Analysis of slot-loaded rectangular microstrip patch antenna. *Indian Journal of Radio & Space Physics*, 2005; 34 (6): 424-230.
[34] Bahl IJ. *Lumped Elements for RF and Microwave Circuit*. Artech House 2003; 456-459.
[35] Meshram MK, Vishvakarma BR. Gap-coupled microstrip array antenna for wideband operation. *Int. J. of Electronics*. 2011; 88: 1161-1175.
[36] Balanis CA. *Antenna Theory Analysis and Design*. 2nd edition, Wiley, New York, 1997.
[37] Terman FE. Electronic and Radio Engineer. 15, Kagakasha Tokyo, Japan, 1995.
[38] Zeland, IE3D simulation software, Version 14.05, Zeland Inc., USA, 2008.