Analysis of slot-loaded rectangular microstrip patch antenna

Shivnarayan, Shashank Sharma & Babau R Vishvakarma
Department of Electronics Engineering, Institute of Technology, Banaras Hindu University, Varanasi 221005, India
E-mail: brvish@bhu.ac.in

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In the present paper, the analysis of a slot-loaded rectangular microstrip patch antenna using equivalent circuit concept is presented. The slot is taken as a capacitive reactance on the patch. It is found that the resonance frequency decreases with increasing slot width for a given slot length. The decrease in the resonance frequency is in the higher side for longer slot length, whereas it is on the minimum side for the lower slot length. It is found that VSWR remains almost invariant with slot width and slot length. The impedance increases almost linearly with the slot width, but inversely with the slot length.

Keywords: Slot-loaded patch, Rectangular microstrip antenna, Microstrip antenna

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1 Introduction
Narrow bandwidth is the major disadvantage of microstrip antenna in practical applications. For present day wireless communication systems, the required operating bandwidth for antennas is about 7.6% for a global system for mobile communication, 9.5% for a digital communication system and 12.2% for universal mobile telecommunication system. Several bandwidth enhancement or broadbarding techniques are recently employed, such as coplanar directly gap-coupled patches, use of a thick air or foam substrate, etc. It may be mentioned that bandwidth can also be improved by loading of suitable slots along the radiating edges of patch. By embedding suitable slots in the radiating patch, compact and dual band microstrip antennas can be realized. Multiple slots are also used to control the impedance of the microstrip antennas. These days, many methods such as FDTD method and Hybrid multiport theory, etc. are used for the analysis of slot-loaded microstrip antenna.

This paper presents the analysis of a slot-loaded rectangular microstrip antenna (Fig. 1) using equivalent circuit concept in which patch and slot on the patch are represented in terms of equivalent circuit parameters. In this circuit the slot is taken as a capacitive reactance on the patch to counteract the inductive reactance of the probe. It may be added that the analysis of slot on the patch has been done by using duality relationship between the dipole and slot. The aim of the work is to study the effect of narrow slot on the performance of the rectangular microstrip antenna such as input impedance, VSWR and return loss.

2 Theoretical considerations
Slot on the patch can be analyzed by using the duality relationship between the dipole and the slot. In
the present work, the patch is fed by co-axial cable (50 ohm). Since the slot is thin, the voltage can be sinusoidal with zero voltage across the ends of slot. In this case, the voltage across the slot is given as

\[ V_\phi(z) = V_m \sin \left( k \left( \frac{L}{2} - |z| \right) \right), \quad |z| \leq 1 \quad \ldots (1) \]

where

- \( L \) = Length of the slot
- \( k = \frac{2\pi}{\lambda} \) = Propagation constant in free space
- \( V_m \) = Maximum input voltage
- \( |z| \) = Distance along the length of the slot

The current distribution of long dipole is given by

\[ I(z) = I_m \sin \left( k \left( \frac{L}{2} - z \right) \right), \quad z > 0 \]

\[ = I_m \sin \left( k \left( \frac{L}{2} + z \right) \right), \quad z < 0 \quad \ldots (2) \]

where \( I_m \) is the maximum input current in the dipole antenna.

The total electric field at the far-field point from the antenna is given by

\[ E_0 = \frac{jk\eta_0 e^{-jkr} \sin \theta}{4\pi r} \left[ \int_{-l/2}^{l/2} I(z) e^{jk \cos \theta \sin \theta \sin \theta} \right. \]

Performing integration yields

\[ E_0 = \frac{jn_m I_m e^{-jkr}}{2\pi r} \left[ \cos \left( \frac{kl \cos \theta}{2} \right) - \cos \left( \frac{kl}{2} \right) \right] \quad \ldots (3) \]

where

- \( \eta_0 \) = Characteristic impedance of free space
- \( = 120\pi \ \Omega \)
- \( r \) = Distance of far-field from centre of the dipole

The Poynting vector can be written as

\[ P_r = \frac{1}{2} |E_0| |H_\phi| = \frac{|E_0|^2}{2\eta_0}, \text{ since } H_\phi = \frac{E_0}{\eta_0} \]

Therefore, the total power radiated from the dipole antenna is given by

\[ W_t = \int pds \]

\[ = \int P_r 2\pi r^2 \sin \theta \, d\theta \]

\[ = \frac{n_m I_m^2}{4\pi} \left[ \frac{\cos \left( \frac{kl \cos \theta}{2} \right) - \cos \left( \frac{kl}{2} \right)}{\sin \theta} \right] \, d\theta \quad \ldots (5) \]

If the radiation resistance is defined in terms of maximum current, then it may be given as

\[ R_t = \frac{2W_t}{I_m^2} = \frac{n_m}{2\pi} \int_0^{\pi/2} \left[ \frac{\cos \left( \frac{kl \cos \theta}{2} \right) - \cos \left( \frac{kl}{2} \right)}{\sin \theta} \right] \, d\theta \]

On solving the above equation one gets

\[ R_t = 60 \left\{ C + l_n (kl) - C_i (kl) \right\} \]

\[ + \frac{1}{2} \sin kl [S_1 (2kl) - 2S_1 (kl)] \]

\[ + \frac{1}{2} \cos (kl) \left\{ C + l_n \left[ \frac{kl}{2} \right] + C_i (2kl) - 2C_i (kl) \right\} \]

The input impedance of the dipole (slot) is given by

\[ Z_\infty = \frac{V}{I_m} = \int_{-h}^{h} E_z \sin k (h - |z|) \, dz \quad \ldots (7) \]
The electric field along the z-direction is given by

\[ E_z = \frac{(j - kl_m)}{4 \pi \omega c} \left( \frac{e^{-j \beta_l}}{r_1} + \frac{e^{-j \beta_r}}{r_2} - 2 \cos k h \frac{e^{-j \beta_0}}{r_0} \right) \quad \ldots (8) \]

where

\[ r_1 = \left[ y^2 + (h + z)^2 \right]^{1/2} \]

= Distance of far-field point from the upper end of the slot (dipole)

\[ r_2 = \left[ y^2 + (h - z)^2 \right]^{1/2} \]

= Distance of far-field point from lower end of the slot (dipole)

\[ r_0 = \left[ y^2 + z^2 \right]^{1/2} \]

= Distance of far-field point from centre of the slot (dipole).

Now substituting the value of \( E_z \) from Eq. (16) in Eq. (15), one gets the expression for input impedance as

\[ Z_{in} = j 0.30 \int _{z=0} ^{h} \left( \frac{e^{-j \beta_l}}{r_1} + \frac{e^{-j \beta_r}}{r_2} - 2 \cos k h \frac{e^{-j \beta_0}}{r_0} \right) \times \sin k (h - |z|) \, dz \quad \ldots (9) \]

The above expression for impedance consists of both real and imaginary parts and can be written as

\[ Z_{in} = R_s + j X_s \quad \ldots (10) \]

where real part is \( R_s \) equivalent to the radiation resistance of dipole (i.e. slot) and imaginary parts \( X_s \) is input reactance of the slot which is given by

\[ X_s = 30 \left( 2 S_h (kL) + \cos kL [2 S_h (kL) - S_i (2kL)] - \sin kL \left[ 2 C_i (kL) - C_s (2kL) - C_s \left( \frac{ka^2}{2L} \right) \right] \right) \quad \ldots (11) \]

where, \( a = \) Width of the slot.

On substituting the value of all the parameters in Eq. (11), one gets the value of \( X_s \) with negative sign. This shows that the reactance of the slot on the patch is capacitive. In this study, the capacitive reactance is taken parallel to the reactance of the patch for the analysis of the slot-loaded rectangular microstrip patch antenna.

### 3 Equivalent circuits

The slot-loaded rectangular microstrip patch antenna can be considered as a parallel combination of capacitance \( C_1 \), inductance \( L_1 \) and resistance \( R_1 \) of the patch and capacitive reactance of the slot, where \( R_1, L_1, C_1 \) of patch are given by

\[ C_1 = \frac{\varepsilon_r \varepsilon_0 L W}{2h} \cos^{-1} \left( \frac{\pi z_0}{L} \right) \quad \ldots (12) \]

where

\[ h = \] Thickness of substrate

\[ \varepsilon_r = \] Effective dielectric constant

\[ \varepsilon_0 = \] Permittivity of free space

\[ z_0 = \] Feed point location along z-axis

\[ L_1 = \frac{1}{C_1 \omega_0} \quad \ldots (13) \]

\[ R_1 = \frac{Q}{\omega C_1} \quad \ldots (14) \]

The equivalent circuit of slot-loaded rectangular microstrip patch antenna is presented in Fig. 2.

It may be noted that input impedance \( (Z_{in}) \) of the circuit in Fig. 2(a) excluding slot can be expressed as

\[ Z_{in} = \frac{1}{R_1 + j \omega C_1 + \frac{1}{j \omega L_1}} \]

\[ = \frac{R_s (\omega L_s)^2}{(\omega L_s)^2 + R_s^2 (\omega^2 L_s C_s - 1)^2} \]

\[ -j \left( \frac{R_s^2 \omega L_s (\omega^2 L_s C_s - 1)^2}{(\omega L_s)^2 + R_s^2 (\omega^2 L_s C_s - 1)^2} \right) \quad \ldots (15) \]

The above equation can be expressed as

\[ Z_{in} = R - jX \quad \ldots (16) \]

where, \( R \) and \( X \) are the real and imaginary part of \( Z_{in} \) respectively.

The input impedance of the slot-loaded patch can be calculated from Fig. 2 (b) as

\[ Z_{in} = \frac{(R - jX)(jX_s)}{R - jX + jX_s} \]
Using this value, the reflection coefficient, VSWR and return loss can be computed as

Reflection coefficient \((\Gamma) = \frac{Z_0 - Z_{in}}{Z_0 + Z_{in}} \)  \(\ldots (18)\)

Where

- \(Z_0\) = Characteristic impedance of the co-axial feed (50 ohm)
- \(VSWR = S = \frac{1 + |\Gamma|}{1 - |\Gamma|} \)  \(\ldots (19)\)
- \(R\) = Resistance
- \(C\) = Capacitance
- \(X\) = Reactance

4 Design parameters

For designing the slot-loaded rectangular microstrip patch antenna, following parameters were used

- Design frequency = 3.0 GHz
- Free space wavelength \((\lambda)\) = 100 mm
- Dielectric constant (R-T Duroid) = 2.2
- Loss tangent (\(\tan \delta\)) = 0.0033
- The thickness of the substrate \((h)\) = 0.0159\(\lambda\)
- Length of the patch \((L)\) = 0.329\(\lambda\)
- Width of the patch \((W)\) = 0.395\(\lambda\)

5 Calculations

The input impedance of the slot-loaded patch was calculated using Eq. (17) for different values of slot width and slot length. The data thus obtain are shown in Fig. 3. The value of VSWR and return loss were calculated using Eqs (19) and (20) for different slot widths and slot lengths. The resulting data are shown in Figs 4 and 5. The variations of resonance frequency, VSWR, \(R_c (Z_{in})\) and bandwidth with slot width for different slot lengths are shown in Figs 6, 7, 8 and Table 1, respectively.
Results and discussion

The variation of input impedance with different slot widths and slot lengths is shown in Fig. 3. It is observed that the resonance frequency decreases with increasing slot width for a given slot length. A similar result has been also reported by Fan Yang. The range of frequency variation with slot width for a given slot length is found to be maximum (0.040 GHz) for the lowest slot length ($L_s=16$ mm), whereas it is minimum (0.016 GHz) for the largest slot length ($L_s=30$ mm). It is important to note that there is a significant change in resonance frequency with the slot on the patch as compared to patch without slot.
The variation in the resonance frequency with slot width is attributed to the fact that increasing dimension of the slot modifies the effective values of capacitive reactance, which renders the change in the resonance frequency.

The variation of VSWR with frequency for different slot width and slot length is shown in Fig. 4. It is found that the resonance frequency decreases with increasing slot width for a given slot length. The decrement occurs in resonance frequency, i.e., 1.31% for \( L_s = 16 \text{ mm} \) and 0.59% for \( L_s = (26-30 \text{ mm}) \) with the variation of slot width. This is also corroborated from Fig. 6.

It may be noted that the decrease in the resonance frequency is on the higher side for higher slot length, whereas it is on the lower side for the lower slot length. Further, it may be noted that the change in the resonance frequency is minimum (0.016 GHz) for the longest slot length (30 mm), whereas it is maximum (0.040 GHz) for the minimum slot length (16 mm). This is also corroborated from return loss data shown in Fig. 5.

The variation of VSWR with slot width for different slot length is shown in Fig. 7. It is observed that the value of VSWR remains around 1.03 for different slot widths and slot lengths which is slightly higher as compared to the value for patch without slot, i.e., 1.02.

The variation of real part of input impedance with slot width for a given slot length is shown in Fig. 8. It is found that the real part of the input impedance at resonance increases minutely with increasing slot width for all slot lengths considered. However, it may be noted that the values are slightly higher with
decreasing slot length. From Fig. 8, it is also observed that the real part of input impedance increases almost linearly with slot width but inversely with the slot length.

7 Conclusions

It may be concluded that loading of patch with narrow slot affects significantly the resonance frequency, input impedance and bandwidth increase with slot width for a given slot length (Table 1).

References