# An Enhanced Bandwidth Design Technique for Electromagnetically Coupled Microstrip Antennas

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***Abstract*—This paper describes a method of enhancing the bandwidth of two different electromagnetically coupled microstrip antennas by utilization of a tuning stub. An approximate theory and equations are developed to demonstrate the potential bandwidth improvement and required stub impedance characteristics. A novel dual-stub design is presented that achieves better characteristics than a conventional quarter wavelength open-end stub. As examples, the bandwidth $(\mathrm{VSWR} < 2)$ of a conventional proximity-coupled microstrip antenna is increased from 4.8 to 8.4% and the bandwidth of a stacked aperture-coupled microstrip antenna is increased from 27.5 to 34.5% using this technique.**

***Index Terms*—Broad-band antennas, microstrip antennas.**

## I. INTRODUCTION

MICROSTRIP antennas are used in a wide range of applications [1], but narrow impedance bandwidth often limits their more widespread use. The straightforward approach to improving bandwidth is increasing the thickness of the substrate supporting the microstrip patch. However, limitations still exist on the ability to effectively feed the patch on a thick substrate and radiation efficiency can degrade with increasing substrate thickness [1]. Techniques of overcoming this problem include using parasitic tuning elements, external matching, and separating the antenna and feed [1]. Coplanar parasitic elements are often not desirable due to the increased difficulty of design and usually add to the size of the antenna.

This paper describes an approach utilizing a combination of the second two techniques. Pues and Van de Capelle [2] described an approach using external matching alone, but it is difficult to get a substantial improvement in bandwidth without several matching sections. The electromagnetically (EM) coupled feed methods such as proximity coupling and aperture coupling can exhibit better bandwidth characteristics than traditional coaxial probe-fed and coplanar microstrip edge-fed methods due to the possibility of individual placement of the feed and patch on thin and thick substrates, respectively [1]. In this paper, a simple easy-to-design matching structure is utilized, along with separated feed and antenna substrates to achieve enhanced bandwidth behavior. The method treats the stub in an EM coupled antenna as an integral reactive tuning element to achieve broad-band performance. The approach is similar to a single stub tuned proximity-coupled patch [3], except that the stub tuning takes place directly under the patch in this technique such that additional substrate space is not required and good cross-polarization characteristics are displayed.

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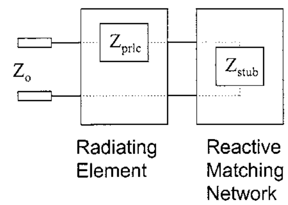


Fig. 1. Broad-band matching problem with equivalent circuit model for proximity-coupled and aperture-coupled microstrip antennas.

A novel stub design is presented with simple design equations that provide a useful starting point when combined with an EM simulator. The bandwidth improvement is outlined in an approximate theory. Two examples, a proximity-coupled microstrip patch antenna and an aperture-coupled microstrip patch antenna are provided that illustrate the technique.

## II. BANDWIDTH IMPROVEMENT AND STUB CHARACTERISTICS

A broad-band matching design procedure with external matching was presented in [2] to improve the bandwidth characteristics of several microstrip antennas. Similar broad-band matching problems exist for EM coupled antennas such as the aperture-coupled microstrip antenna [4] and proximity-coupled microstrip antenna [5]. At the proper reference plane, both of these antennas exhibit a parallel resistor-inductor capacitor (RLC) response with an equivalent circuit shown in Fig. 1 (note that the model is valid for both proximity and aperture coupling). Improvements in the total impedance bandwidth can be obtained by using the stub as an integral reactive tuning element. It is assumed that the stub does not interact with the antenna except at the slot discontinuity [4] or the edge of the patch [5], so the initial antenna design does not have to be altered to accommodate the application of this technique. A simple design procedure is outlined: design a proximity-coupled or aperture-coupled microstrip antenna using existing techniques and tools [1], design the tuning stub using approximate expressions presented below, and finally, iterate for an optimized design using simulations or measurements.

In [3], an expression relating the bandwidth $B$ and the resonator quality factor $Q$ of a simple RLC circuit was derived. This relationship is dependent on the degree of matching desired, as given by $R_{\mathrm{norm}} = R_{\max}/Zo$, where $R_{\max}$ is the maximum (resonant) resistance for a parallel RLC with a system impedance of $Z_o$ and the acceptable mismatch as given by the maximum standing wave ratio $S$ and is written as

$$Q = \frac{1}{B}\sqrt{\frac{(SR_{\text{norm}}-1)(S-R_{\text{norm}})}{S}}. \tag{1}$$

The bandwidth $B$ is defined as $(f_2 - f_1)/f_r$ where $f_1$ and $f_2$ are the frequencies where $\text{VSWR}(f_1) = \text{VSWR}(f_2) = S$ and $f_r$ is the resonant frequency.

An expression for the impedance of a parallel RLC resonance about a narrow band of frequencies can be approximated as [6]

$$\begin{aligned} Z_{\text{pric}}(f_r + \Delta f) &= R_{\text{pric}} - jX_{\text{pric}} \\ &\cong \frac{R_{\text{norm}} - 2jR_{\text{norm}}Q\left(\frac{\Delta f}{f_r}\right)}{1 + 4Q^2\left(\frac{\Delta f}{f_r}\right)^2} \end{aligned} \tag{2}$$

where $\Delta f = f - f_r$ or the frequency shift from resonance.

In (1) and in the following expressions, it is assumed that the antenna input impedance is close to the system impedance such that additional matching to the input feed line is not necessary. This requirement is not overly restrictive when considering EM coupled antennas [1] since the input impedance can be made near 50 Ω (for a 50-Ω system) through proper choice of substrate thickness and feed height or slot size.

Therefore, an antenna at resonance results in $1/S < R_{\text{norm}} < S$ and the frequency for which $R_e(Z_{\text{pric}}) = 1/S$ gives the maximum possible band edge $\Delta f_{\max}$, which is found from (2) to be

$$\frac{\Delta f_{\max}}{f_r} = \frac{1}{2Q}\sqrt{SR_{\text{norm}} - 1}. \tag{3}$$

At this band edge, if a reactive matching network were to present the conjugate reactance of (2) so that

$$Z_{\text{stub}}(f_r + \Delta f_{\max}) = jX_{\text{pric}} \tag{4}$$

then the total input impedance of the parallel RLC network and a reactive load would be

$$Z_{\text{total}}(f_r + \Delta f_{\max}) = Z_{\text{pric}} + Z_{\text{stub}} = 1/S. \tag{5}$$

In (4) and (5), an assumption that a symmetric impedance locus is obtained about $f_r$ such that a solution for one band edge is adequate. Therefore, (3) represents half the achievable bandwidth and the total new bandwidth is

$$B_{\text{new}} \cong 2\frac{\Delta f_{\max}}{f_r} > B. \tag{6}$$

This improvement in bandwidth can be found using (1), (3), and (6).

Most EM coupled microstrip antenna designs use a quarter wavelength open-ended stub, illustrated in Fig. 2(a), for providing maximum power transfer to the radiating resistance, although odd multiples of a quarter wavelength as shown in Fig. 2(b) can also be used [7]. Applying this enhanced bandwidth technique with a simple open-ended stub is difficult since the only design parameters are the characteristic impedance of the stub and the length of the stub.

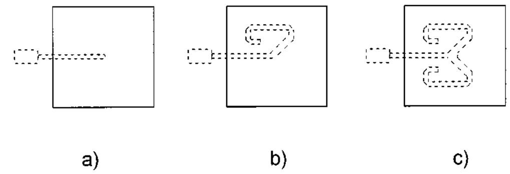


Fig. 2. Layout and geometry of proximity-coupled microstrip antennas. (a) Quarter wavelength stub. (b) Three quarter wavelength stub. (c) Dual stub.

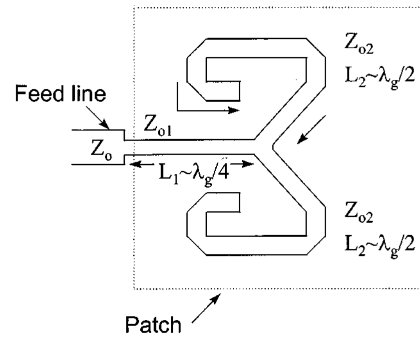


Fig. 3. Detail of symmetric dual-stub design.

Considering these factors, a design better suited to achieving the requirements given by (4) than a quarter or three-quarter wavelength stub seems desirable. This new design, the dual-stub design, shown in Fig. 2(c), incorporates a section of quarter wavelength line and dual-symmetric half-wavelength open-ended stubs that use impedance transformations to achieve greater frequency variation. In the design (shown in detail in Fig. 3), $L_1$ is a quarter wavelength long with characteristic impedance of $Z_{o1}$ and $L_2$ is a half wavelength long with characteristic impedance of $Z_{o2}$. The input impedance of such a stub configuration is

$$Z_{\text{stub}} \cong jZ_{01}\left\{\frac{2Z_{o1}}{Z_{o2}}\tan(\beta L_2) - \cot(\beta L_1)\right\}. \tag{7}$$

Unknowns $Z_{o1}$ and $Z_{o2}$ can be easily adjusted to obtain the $Z_{\text{stub}}$ value of (4). An approximate expression is derived below to solve for these unknowns; this expression is then further reduced to account for narrow bandwidth cases.

A simple expression for $Z_{o2}$ is found by taking a Taylor series expansion about the appropriate argument for the tangent and cotangent expressions, and then retaining only the first terms. For $L_1$ and $L_2$ as quarter and half wavelengths, respectively, and using $Z_{\text{stub}}$ of (4) at $\Delta f_{\max}$, (7) can be solved for $Z_{o2}$ to obtain

$$Z_{o2} \cong \frac{2Z_{o1}^2}{\frac{X_{\text{pric}}}{\pi}\left(\frac{f_r}{\Delta f_{\max}}\right) - \frac{Z_{o1}}{2}}. \tag{8}$$

Since $Z_{o1}$ is the feed line characteristic impedance at the antenna, in many cases iteration of the original antenna design is not required to apply this stub design directly. To minimize the possibility of having the stubs impacting the antenna characteristics, as a practical rule, 50-Ω lines are the minimum characteristic impedance used for these designs. For narrow-band cases, an even simpler expression for (8) results. In cases where $\Delta f_{\max}/f_r$ is small, (8) can be written as

$$Z_{o2} \cong \frac{2Z_{o1}^2}{\frac{X_{\text{pric}}}{\pi}\left(\frac{f_r}{\Delta f_{\max}}\right)}. \tag{9}$$

Using (8) or (9) results in the feed-line characteristic impedances that can be used to satisfy the requirement given by (4). However, further comments on these design equations are warranted. As shown in the layout of Fig. 2(c), a number of discontinuities, including the bends, junction, and open end as well as the effect of the bonding film exist and would have to be accounted for in any actual design. The actual lengths of $L_1$ and $L_2$ are not exact quarter and half wavelengths as assumed in the derivation due to these discontinuities. Also, due to the number of approximations, a practical guide for (8) and (9) is that (8) has been found to work well for bandwidths <10% and (9) for bandwidths <25%. Regardless, (8) and (9) give an excellent starting point for use with EM simulations and an EM solver [8] can be used for more accurate design optimization.

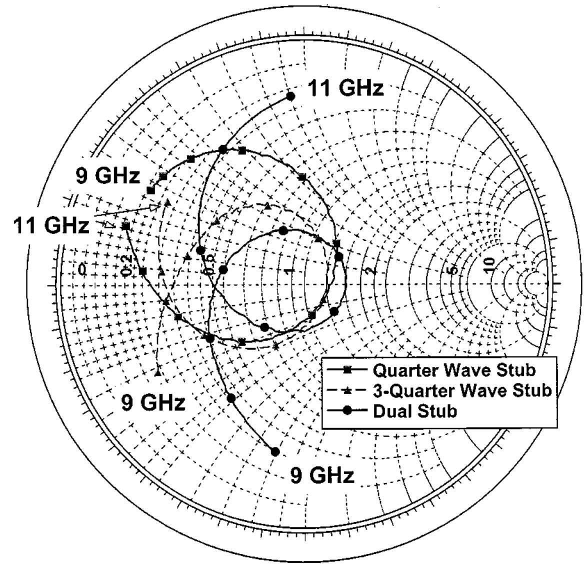


Fig. 4. Smith chart plot of measured input impedance for three stub cases for proximity-coupled patch. Dimensions: substrate thickness 0.107 cm, dielectric constant 2.94, patch length 0.8 cm, patch width 0.8 cm, feedline width at antenna 0.025 cm, system feedline width 0.114 cm, feedline height 0.0508 cm, reference plane 0.051 cm from edge of patch.

## III. Examples

### A. Design Example #1: Proximity-Coupled Microstrip Antenna

The proximity-coupled microstrip antenna best demonstrates the advantages of this technique. First, the tuning stub takes up no excess substrate real estate since the reactive tuning takes place directly under the patch. Second, since the stub is under the patch, any radiation from the stub is shielded and potentially reradiated by the patch, leading to good cross-polarization characteristics. Third, achieving improved bandwidth in this manner instead of by increasing the thickness of the substrate, results in antennas with higher radiation efficiencies and more attractive scanning capabilities. Finally, the use of thinner substrates leads to reduced material costs and weight.

Three antenna designs with the layouts shown in Fig. 2 are considered to illustrate the use of this technique. In these examples, the bandwidth of interest is assumed to be $\text{VSWR} < 2$. The baseline design of a typical proximity-coupled microstrip antenna with a quarter-wavelength stub yields a 4.8% bandwidth. The second design is a proximity-coupled patch with a three-quarter-wavelength stub which results in 6.1% bandwidth. The third case uses the dual-stub design for enhanced bandwidth performance and achieves 8.4% bandwidth. The input impedance of these three designs are plotted in Fig. 4.

The method described above of optimizing the novel dual-stub design can be effectively illustrated with this example. Beginning with the baseline design, the $R_{\text{norm}}$ is 1.3 as illustrated in Fig. 4. The $Q$ found by (1) for $S = 2$ is 15.6 and $\Delta f_{\max}/f_r$ using (3) is 0.041. Applying the design procedure should yield a new bandwidth of 1.7 times the original 4.8% according to (6). The calculated stripline impedances are $Z_{o1} = 82\ \Omega$ and $Z_{o2} = 55\ \Omega$. In comparison, to achieve the same degree of broad-band matching using a simple quarter-wave open-end stub would require the stub's characteristic impedance to be approximately 600 $\Omega$. The actual fabricated characteristic impedances are $Z_{o1} = 82\ \Omega$ and $Z_{o2} = 59\ \Omega$. The improvement in bandwidth is 75%.

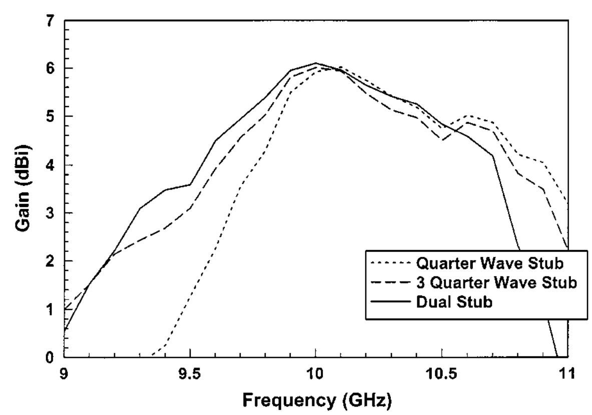


Fig. 5. Measured gain of three proximity-coupled microstrip antenna designs.

It should be noted that the $R_{\text{norm}}$ of the dual-stub design is slightly higher than the original. The model of [5] for the proximity-coupled patch assumes no interaction between the stub and the patch, which is not rigorously correct. The currents on the patch are perturbed by the stub discontinuities as the EM solver predicts, however, its overall effect can be quite small. The increase of $R_{\text{norm}}$ from the baseline design value of 1.3 to the dual-stub design value of 1.4 is a direct consequence of this effect.

The gain was measured and is shown in Fig. 5 for the three designs. The results show that the gain of all three designs are the same so the extra line lengths under the patch does not add to extra losses. Also, the extra impedance bandwidth shows up in the gain as would be expected. The radiation patterns were measured across the bands for copolarization and cross-polarization

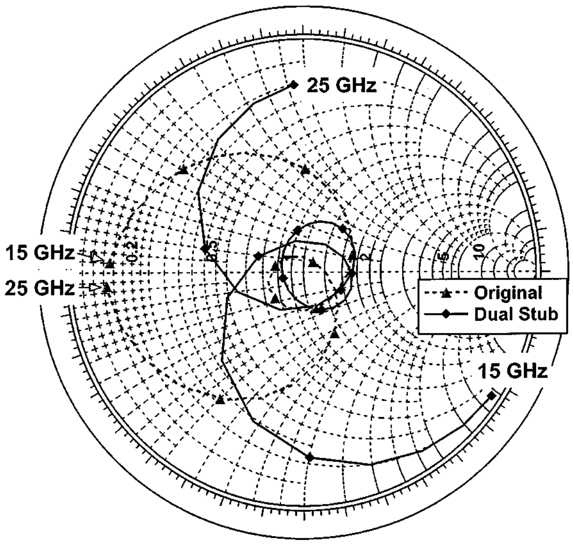


Fig. 6. Smith chart plot of simulated input impedance for original aperture-coupled stacked patch [9] and case with optimized dual-stub design. Dimensions as given in [9]: $W_1 = 3.5$ mm, $W_2 = 3.8$ mm, $\varepsilon_{r1} = \varepsilon_{r2} = \varepsilon_{rf} = 2.20$, $H_1 = 0.50$ mm, $H_2 = 1.0$ mm, $A_1 = 3.2$ mm, $A_w = 0.4$ mm, $H_f = 0.508$ mm, $W_f = 1.55$ mm, $L_s = 1.8$ mm.

levels. In all designs, the measured cross-polarization is below −20 dB from copolarized levels over its impedance bandwidth.

### *B. Design Example #2: Aperture-Coupled Microstrip Antenna*

The dual-stub matching technique can also be applied to other EM coupled feed methods such as aperture coupling. A wide-band aperture-coupled patch design is examined that uses stacked patches (parasitic tuning element) to achieve large bandwidths [9]. The stub bandwidth enhancement is applied to this design to further improve the resulting bandwidth. However, using the dual-stub design with aperture coupling eliminates some of the advantages inherent in the proximity-coupled patch case. Radiation from the stubs should be examined with the use of this technique since an increased backlobe is a potential consequence of stub radiation. However, a thinner feed substrate could alleviate the increase to the backlobe. Also, the dual-stub can use more substrate space than the quarter-wavelength stub in this topology since it is no longer hidden under the patch.

The design in [9] was simulated using an EM simulator [8] at a reference plane $0.05\lambda_o$ from the center of the slot and shown in Fig. 6. The calculated bandwidth $(\mathrm{VSWR} < 2)$ is 27.5%. Values of $\Delta f_{\max}/fr = 0.17$ and $-jX_{\mathrm{pric}}(f_r + \Delta f_{\max}) = 46\,\Omega$ are obtained from Fig. 6. Using (8) for the stub characteristics, we calculate $Z_{o1} = 50\,\Omega$ and $Z_{o2} = 82\,\Omega$. Using the EM simulator leads to an optimum value of $Z_{o2} = 110\,\Omega$. The anticipated increase is 1.24 times the original 27.5% bandwidth. The simulated dual-stub design had a bandwidth of 34.5%, resulting in a 1.25 times increase.

Using the dual stub with aperture-coupled patch antennas has the potential to increase backlobe radiation. This arises from spurious radiation from the stub due to the half wavelength sections. The simulated backlobe level for the dual-stub design leads to a maximum increase in the band of 1.5 dB over the original design.

## IV. Conclusion

A simple and practical method of enhancing the bandwidth of electromagnetically coupled microstrip antennas using a tuning stub was presented. The application of this technique involves the development of a new stub design that had better impedance characteristics than a quarter wavelength open-ended stub. Basic design equations were derived to aid in the optimization using EM simulation. This basic procedure of enhancing the bandwidth of EM coupled antennas from proper design of the stub is shown to achieve better performance due to efficient utilization of the available circuit structures.

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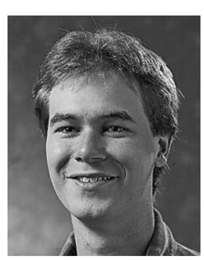

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