Design and Development of Integral Broadband Matching of Stacked Patches Microstrip Antenna with Coplanar Feed Structure

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Abstract

This paper investigates the concept of cascading microstrip patch antennas to form the broadband frequency operation. Stacked patches microstrip antennas with and without coplanar feed structure have been designed, developed and field-tested at the operating frequencies of 1800 MHz mobile phone system. Analysis methods are based on rigorous and approximation techniques, which are employed for determining the antenna characteristics and total impedance between antenna layers, respectively. The results illustrate that the stacked patches microstrip antenna without coplanar feed structure have two resonant frequencies. In the case of stacked patches microstrip antenna with coplanar feed structure, it shows that the two resonant frequencies are shifted closer to each other resulting in wider operation frequency.

Keywords – Microstrip antennas, Stacked patches, Impedance matching, Integral broadband matching, Coplanar feed structure.

1. Introduction

Microstrip antenna beyond the UHF application has a number of dominant characteristics compared to wire antennas, for example, its electrical size that expanded along the horizon which is easily and precisely controlled by the etching technique. Moreover, it can also be flexible and attachable to any active devices in order to match the requirement concerning the physical and electrical constraints, i.e. amplification and oscillation point of view. However, major disadvantages of the microstrip antenna are its inefficiency and very narrow bandwidth, which is typically a few percent compared to the operational frequency. [1]

Broadening the operation frequency is a solution to accomplish the flexibility of the microstrip antenna usage. It should be mentioned that there are various methods to broaden the operating bandwidth. Firstly, the simplest structure, multi-layer antenna patches [2-3]: this structure provides the resonant frequencies in accordance with the layers of the dielectric. The limitation of this antenna type is the fractional percent of the operating frequency. Secondly, multi-layer patches with a matching impedance network [4-9]: matching impedance can be applied into two solutions, the "on-board" and the "off-board" matching network. On-board structure is a unique design, i.e. merging the radiation and matching network on the same board. The etching process can be simply applied in one shot. The limitation of on-board structure is the feeder line, which may interfere the antenna radiation pattern. On the other hand, the off-board structure also provides some advantages compared to on-board one regarding the ease of impedance adjustment which can be held up on the other side of the patches, i.e. behind the ground plane. This method can isolate the radiation and matching element independently.

So far, there has never been a research work that integrates both the stacked patches microstrip antenna and matching impedance network together to improve the bandwidth and the matching impedance between the antenna and transceiver. Therefore, this paper presents the combination of multi-layer antenna (stacked patches) and on board matching network to enhance the operating bandwidth by utilizing a single stacked patches which operates multiple frequencies. Step by step of the hardware design will be described in the following section.

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2. Design and Development of Stacked Patches

2.1 Stacked Patches with Common Feed

As illustrated below, Figure 1 represents the stack patches with a common feed. Two or more patches are layered using a common feed. The upper patches exhibit as the radiation element, while the lower ones exhibit as the ground plane of the upper patches. The simplest structure is as shown in Figure 1. It should be mentioned, however, that the feeding system can be accomplished by using 1) common feed, 2) parasitically feed and 3) individual feed [1] or the combination of 1 to 3.

Stacked patches antenna with common feed utilizing the transmission line model is described by Pues and Van de Capelle [10]. The patch length, L can be determined by using the equation below:

$$L = \frac{0.5\lambda_0}{\sqrt{\varepsilon_r}} - 2\Delta l \qquad (1)$$

where λ_0 is called the free space wavelength, ε_r is the dielectric constant, Δl is the open-end-effect extension which can be determined as in [1].

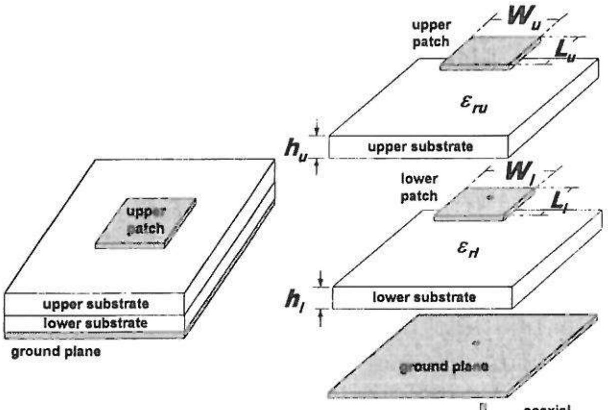


Figure 1 Stacked patches microstrip antenna with common feed (without coplanar feed structure on ground plane).

The input impedance ($Z_{in} = 1/Y_{in}$) of the antenna can be expressed as

$$Y_{in} = 2Y_0\left[\frac{Y_0^2 + Y_s^2 - Y_m^2 + 2Y_sY_0\coth(\gamma L) - 2Y_mY_0\csc h(\gamma L)}{(Y_0^2 + Y_s^2 - Y_m^2)\coth(\gamma L) + (Y_0^2 - Y_s^2 + Y_m^2)\cosh(2\gamma\Delta)\csc h(\gamma L) + 2Y_sY_0}\right] \qquad (2)$$

where Y_o is the characteristic admittance of the microstrip patches, Y_s is the self admittance of main radiating slots, Y_m is the mutual radiative admittance of the main radiating slots, γ is the complex propagation constant and Δ is the distance between the feed point and the center of the patch. The parameters mentioned above are described in [10].

At this stage, the important parameters, which are mainly used in determining the characteristic impedance/admittance of the antenna have been known. To analyze the stacked patches antenna, one must consider that one patch which sits on the other can result in both the electromagnetic interaction in a capacitance form which decreases the resonant frequency, and changing the input impedance (Z_{in}) of the antenna. Analytical method utilizing the modified transmission line model is described by Shavit [11]. The input impedance (Z_{in}) of microstrip antenna which is coated by the upper layer dielectric can be estimated from equation (2), where G_s is the self conductance and Y_m is the mutual admittance of the combining antenna and can also be determined in the same manner as in the case of a typical antenna without superstrate (upper covered dielectric material) [1]. The added superstrate layer varies the self susceptance value (B_s) which can be determined approximately from

$$C_s = \frac{W}{2}\left[\frac{\varepsilon_{re}(L)}{cZ_0(L)} - \varepsilon_0\varepsilon_1\frac{L}{h_1}\right] \quad , \qquad (3)$$

$$B_s = \omega C_s \quad , \qquad (4)$$

and

$$Y_s = G_s + jB_s \qquad (5)$$

where C_s is the capacitance among slots, W is the patch width, $\varepsilon_{re}(L)$ and $Z_0(L)$ are the effective dielectric constant and the characteristic impedance of the microstrip with the width L, respectively, c is the free-space light velocity, ε_0 is the free-space permitivity, and ε_1 and h_1 are the effective dielectric constant and substrate thickness, respectively.

Design and integration of the stacked patches at the operating frequency of 1,700 and 1,900 MHz are pointed out in Figure 2. Upper patch is designed for the upper operating frequency: 1,900 MHz, using Epoxy-Glass as a dielectric material, which has the dielectric constant about 4.4, the tangential loss (tan δ) about 0.01 [1], and the height (h) of 0.21 cm. On the other hand, lower patch is assigned for the lower operating frequency: 1,700 MHz by using the same dielectric parameters excepted for the height of 0.1 cm instead.

Figure 2 shows the dimension of the associated elements which are consisted of the upper patch, lower patch and ground plane. Stacked patches is simply analyzed step by step by determining the input impedance of the upper and lower patches which are considered as a "series network". After the input impedance is known, the return loss, S11 can also be determined as a consequence.

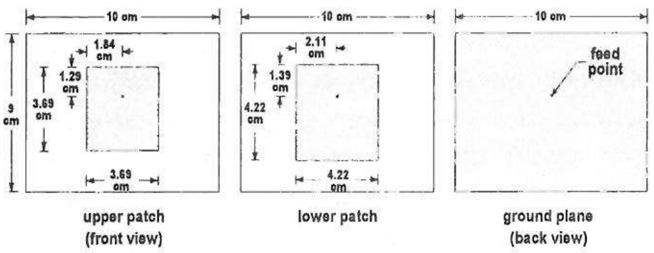


Figure 2 Dimension of stacked patches microstrip antenna with common feed.

It should be noted that epoxy-glass applied in this experiment is widely used and much cheaper than any other high frequency printed circuit boards, PCBs.

2.2 Stacked Patches with Common Feed and Coplanar Structure

Design and integration of the stacked patches with coplanar structure are illustrated in Figure 4. The extra coplanar feeding components are introduced in Figure 3(a), covered coplanar waveguide without lower ground plane and Figure 3(b) with lower ground plane. Analytical technique of both coplanar feed structures utilizing the conformal mapping method is described in [12].

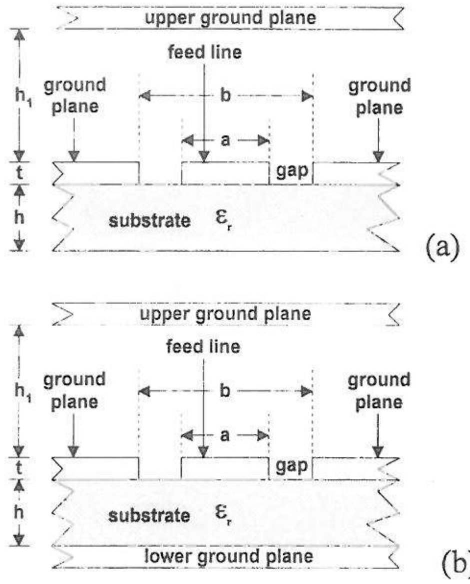


Figure 3 Cross section of covered coplanar waveguide (a) without lower ground plane and (b) with lower ground plane.

Characteristic impedance of the coplanar transmission line has been stated in [13]. The characteristic impedance of the coplanar without lower ground plane (Figure 3(a)) can be determined by

$$Z_0 = \frac{\eta_0}{2.0\sqrt{\varepsilon_{eff}}} \frac{1.0}{\frac{K(k_2)}{K(k'_2)} + \frac{K(k)}{K(k')}} \quad (6)$$

Also, coplanar with lower ground plane (Figure 3(b)) can be expressed as

$$Z_0 = \frac{\eta_0}{2.0\sqrt{\varepsilon_{eff}}} \frac{1.0}{\frac{K(k_3)}{K(k'_3)} + \frac{K(k_4)}{K(k'_4)}} \quad (7)$$

where $\frac{K(k)}{K(k')}$ is the ratio of completed elliptic integrals of the first kind and k, k_2, k_3, k_4, k', k_2',

k_3', k_4' and ε_{eff} can be estimated as in [13].

To broaden the operating frequency, the additional coplanar feed structure is integrated to the stacked patches microstrip antenna as shown in Figure 4. The size of the upper and lower patches are kept the same as the one shown in Figure 2 (stacked patches with common feed). The dimension of stacked patches microstrip antenna with common feed and coplanar feed structure on ground plane is illustrated in Figure 5.

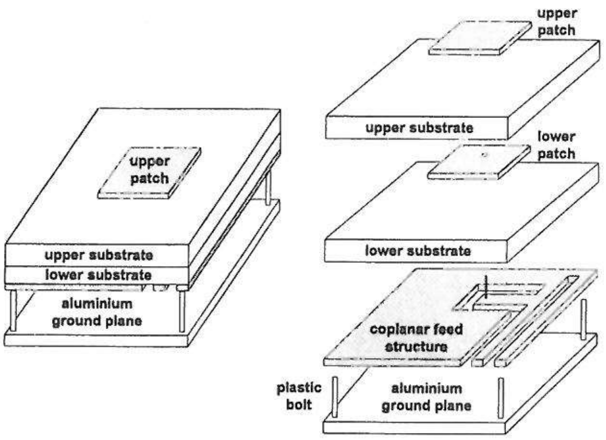


Figure 4 Stacked patches microstrip antenna with common feed and coplanar feed structure on ground plane.

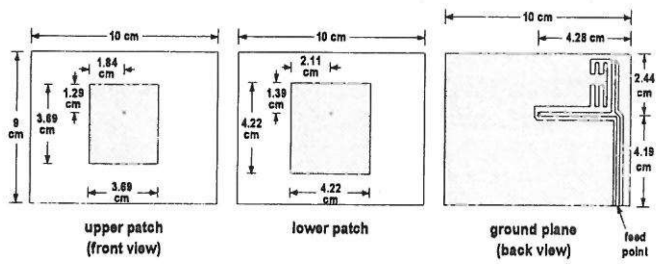


Figure 5 Dimension of stacked patches microstrip antenna with common feed and coplanar feed structure on ground plane made in this work.

An analysis of the stacked patches with coplanar feeder is made by dividing the coplanar structure into 7 segments as demonstrated in Figure 6. The total input impedance under the coplanar transmission is determined by equation (6) from transmission

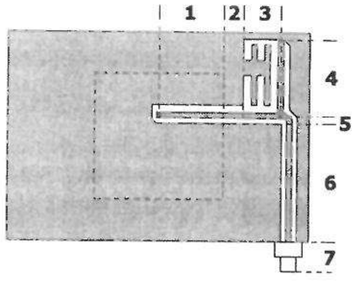


Figure 6 The 7 segments of coplanar feed structure on ground plane for calculating the total input impedance.

line section 1 to 7. Section 1 represents the feeder impedance from the known upper and lower patches (using CAD in [1]) including the straight coplanar transmission line. Section 2 and 3 are the same as section 1 except for the additional electrical length. Section 4 is the parallel short stub applied in the system to widen the operating bandwidth. Section 5, 6 and 7 (plus a coaxial feeder) are the additional electrical length. When the total input impedance is obtained, the return loss of an antenna can be calculated as mentioned in [14-15].

For simplicity, the antenna gain is obtained approximately by using the radiation pattern [16]. The pattern is plotted in different axes which are consisted of E-plane and H-plane. To acquire the gain, θ_E : the half power beamwidth of the E-plane and ϕ_H : the half power beamwidth of the H-plane radiation patterns must be prepared before substituting into equation (8) [16] as follows

$$Gain \cong \frac{30{,}000}{\theta_E \phi_H} \quad . \tag{8}$$

It should be noted that this equation can be applied to calculate the antenna gain when the main lobe of radiation pattern is greater than the minor lobe about 10 dB.

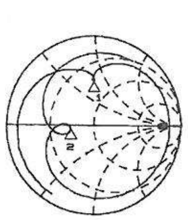
3. Experimental Results

The test results are divided into three

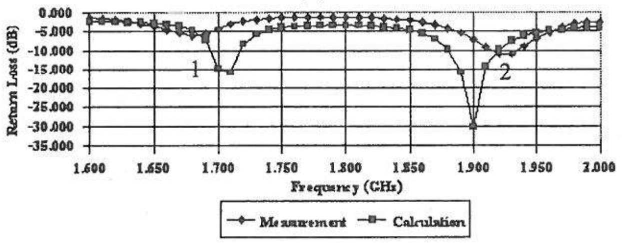
parts.

3.1 Stacked Patches without Matching Structure

The simplest structure, a stacked patches structure without any matching structure shown in Figure 2. The Smith chart and return loss of such an antenna obtained from the experiment by using RF Network Analyzer (Hewlett-Packard, model 8720c) are pointed out in Figure 7. The return loss at the frequencies of 1,685 and 1,925 MHz is -5 and -10 dB, respectively. The frequencies between 1,685 and 1,925 MHz are not applicable due to the excessive mismatch.



(a)

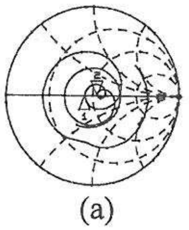


(b)

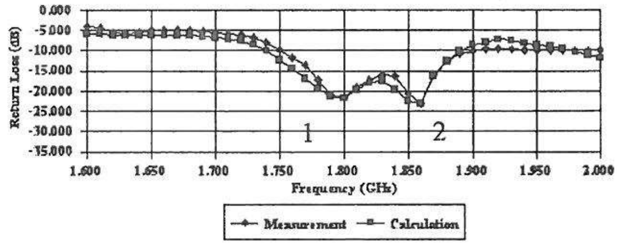
Figure 7 (a) Smith chart from the experiment and (b) return loss as a function of antenna frequencies in Figure 2.

3.2 Stacked Patches with Coplanar Feed Matching Structure

To improve the efficiency of the antenna mentioned above, coplanar feeder must be added in the antenna structure as shown in Figure 5. The Smith chart and return loss of such an antenna are pointed out in Figure 8. At this point, a lot of progressive is observed. Firstly, the input impedance (observed from Figure 8(a)) is located nearer to the center point (50 Ohms). Secondly, the graphs in Figure 8(b) show that the return loss at frequencies 1,795 and 1,865 MHz is –17 and –15 dB, respectively. Both resonance frequencies are moved closer. And lastly, the total bandwidth is considerably increased to 6 % (at -15 dB return loss). Note that the antenna operating frequency may not cover the entire range, from 1,725 to 1,925 MHz. More researches, such as stacked patches taper microstrip antenna have to be done to cover the entire band.



(a)



(b)

Figure 8 (a) Smith chart from the experiment and (b) return loss as a function of frequencies of antenna in Figure 5.

3.3 The Radiation Pattern of the Antenna with Coplanar Feed Matching Structure

The E-plane and H-plane radiation patterns at the frequency of 1,800 MHz are pointed out in Figures 9(a) and 9(b), respectively. The main lobe of the E-plane is wider than that of the H-plane. The half power beamwidth of the E-plane and H-plane is 85° and 67.5°, respectively. It should be stated that the similar patterns could be obtained in the frequency range of 1,750 – 1,810 MHz. The patterns outside the range are degraded. The pattern bandwidth and impedance bandwidth tradeoff is needed in practical design. Due to the lack of a standard antenna to perform gain measurement, the gain of this antenna is estimated from equation (8) by substitution. It is approximately 7.18 dB.

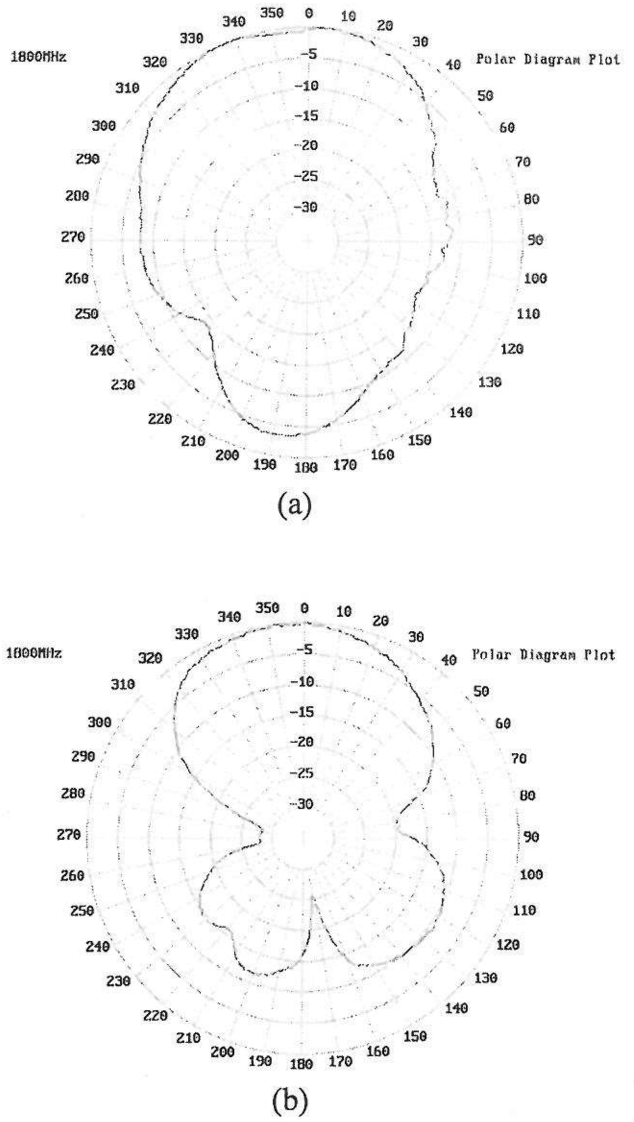


Figure 9 (a) The E – plane and (b) the H – plane radiation patterns of single element stacked patches microstrip antenna with common feed and coplanar feed structure on ground plane (in Figure 5).

4. Conclusions

In summary, two categories can be described.

1) Stacked patches microstrip antenna with common feed, without coplanar feed structure: Antenna could apply two frequencies simultaneously into a single stacked patches antenna. Resonant frequencies are pointed at 1,685 and 1,925 MHz, which the error compared to theoretical calculation is 0.88 % and 1.32 %; respectively. The limitation of using the antenna is the operating frequency which must be specified at two particular frequencies and also specified the operating bandwidth depending on the transmission rate. Moreover, the frequencies between the resonance are not usable because of the high reflection.
2) Stacked patches microstrip antenna with common feed and coplanar feed structure : At this stage, the operation bandwidth is broaden significantly to 6 % from the frequency of 1,750 MHz to 1,875 MHz. Return loss is guaranteed more than -10 dB between 1,750 and 1,875 MHz.

It should be pointed out that the pattern bandwidth is not as wide as that of impedance one. Hence, there should be a tradeoff in the design.

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