Study of the Combination Method and Its Application to Shrink a Patch Antenna Operating in the UHF Band

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Abstract – This work is focused on how to efficiently shrink a patch antenna operating in the UHF band. Five typical independent methods are first introduced that were solely used to realize a small patch antenna. A potential combination method is further discussed utilizing two or more of these five methods. One miniature patch antenna is experimentally demonstrated operating at 735 MHz using the combination method, in which both of shorting wall and complementary split ring resonators are applied in a reconciling way. A two-step optimization procedure is given to show how the antenna sizes can be significantly reduced with this combination method. The antenna is fabricated on a simple dielectric with a low εr of 2.2. The patch size is only 0.127λ × 0.123λ. The antenna efficiency is considerably high as 77% in measurement.

Index Terms – Combination method, patch antenna, small-sized, UHF band.

I. INTRODUCTION

Patch antennas are widely used in several gigahertz (GHz) range. Due to the resonance condition, the patch length is generally at the order of half guided wavelength (0.5λg) [1,2]. The patch length is, however, physically large for an antenna operating below 1 GHz in the UHF band due to the long wavelength. In this work, we aim to shrink a patch antenna in the UHF band. We notice that a variety of miniaturization methods have been reported [3] to realize a compact patch antenna including: (I) shorting/folding technique [4–7]; (II) etching slots on the patch and/or ground planes [8–10]; (III) using natural magneto-dielectric with a higher relative permittivity εr, and/or permeability µ, [11–14]; (IV) using planar metamaterials [15–18]; (V) bulky metamaterials with effective permittivity εreff, and/or permeability µreff [19,20], etc. Most of them were nevertheless solely used.

Inspired by these technologies, a combination method by incorporating two or more of the five methods can be utilized to reduce the antenna size as well. The combination method is more effective than a single technique used on its own. Here, with the technologies of shorting wall and planar metamaterial structures, a combination method is demonstrated to significantly compact a patch antenna operating in the UHF band. The size reduction effect is numerically examined in a two-step optimization procedure. The first step is to add a shorting wall that makes the half-wave patch reduced to quarter-wave. The second step is to further shorten the quarter-wave length by loading periodic complementary split ring resonators (CSRRs) [16,17,27] on the patch. One shorted patch antenna with 2 × 2 CSRRs is experimentally studied resonating at 735 MHz. The patch antenna is fabricated on a simple dielectric with a low εr of 2.2. The patch size is only 0.127λ × 0.123λ (λ is free space wavelength). The measured efficiency is 77%, which is in good agreement with the simulated value. The small shorted metamaterial patch antenna can be applied in the UHF band communications.

II. CONCEPT OF THE COMBINATION METHOD

The typical five methods to shrink patch antennas are given in Table 1. The five size multipliers from M_I to M_V are also given, which are used to measure how the antenna length is reduced from the original half-wave. Note that the first three methods [3,14] have been widely used in previous decades. The latter two methods [15–26] are, however, using new conceptual metamaterials. According to the metamaterial structures, they are further differentiated into planar and bulky types. The planar metamaterials are 2D structures [15–18], e.g., CSRRs, loaded on the patch or ground plane, which are similar with etched slots on the planes since they both need metal planes to make functional patterns. Hence,
the second and fourth methods are sometimes incompatible. The bulky metamaterials are, however, 3D structures embedded in the dielectric substrate $[19–26]$. They are physically inhomogeneous included with composite subwavelength structures but work as homogeneous natural materials as if $\varepsilon_{\text{reff}} \approx \varepsilon_{rh}$ and $\mu_{\text{reff}} \approx \mu_r$.

Considering a conventional patch antenna with length $L$ fabricated on a low loss nonmagnetic substrate with dielectric constant $\varepsilon_r$, the resonant frequency $f_0$ is predicted using a simple formula $[1, 2]$

$$f_0 \approx c / (2L\sqrt{\varepsilon_r}) , \quad (1)$$

where $c$ is the light speed in free space. Note that the margin effects are not accounted in eqn (1) for simplicity. The associated electric patch length is calculated as

$$L_{\lambda} = \frac{L}{\lambda} = \frac{c}{f_0} . \quad (2)$$

From eqn (2), we see that the electric patch length is proportional to $f_0$. Hence, for a given $L$, the key issue to compact the antenna is to downshift $f_0$ with the five methods listed in Table [I]

We now discuss the multipliers for these methods. On the basis of the conventional antenna discussed above, if the antenna size is kept unchanged when using these compacting methods, it will resonate at a new but lower frequency $f_1$. Therefore, multiplier is approximately equal to $f_1/f_0$, which is smaller than 1. For the first method of the shorting/folding technique, the multiplier is $M_I \approx 0.5^n$, where $n$ is an integer. If only a shorting wall is added to the antenna $[4–6]$, the half-wave antenna evolves to quarter-wave, e.g., $n = 1$ in this case. For more complex folding techniques $[7]$, $n$ can be 2, 3, or even larger.

The multipliers $M_{II}$ for the second method of adding slots on the patch or ground, and $M_{IV}$ for the fourth method are both highly dependent on the shape and parameters of functional structures. Therefore, it will be difficult to give empirical solutions for $M_{II}$ and $M_{IV}$.

For the third method when the patch antenna is loaded with a natural magneto-dielectric with $\varepsilon_{rh}$ and $\mu_r$, the resonant frequency becomes

$$f_1 \approx c / (2L\sqrt{\varepsilon_{rh}\mu_r}) . \quad (3)$$

The associated multiplier is $M_{III} \approx \left[\varepsilon_r/(\varepsilon_{rh}\mu_r)\right]^{1/2}$.

The case for the fifth method is similar with eqn (3) but using effective $\varepsilon_{\text{reff}}$ and $\mu_{\text{reff}}$, which is

$$f_1 \approx c / (2L\sqrt{\varepsilon_{\text{reff}}\mu_{\text{reff}}}) . \quad (4)$$

The associated multiplier is $M_V \approx \left[\varepsilon_r/(\varepsilon_{\text{reff}}\mu_{\text{reff}})\right]^{1/2}$.

By incorporating all the five methods, we obtain

$$f_1 = f_0 \cdot M_I(f_1) \cdot M_{II}(f_1) \cdot M_{III}(f_1) \cdot M_{IV}(f_1) \cdot M_V(f_1) = f_0 \cdot M_{\text{total}}(f_1) . \quad (5)$$

The new resonant frequency $f_1$ in eqn (5) is now the product of $f_0$ multiplied by a new size reduction operator $M_{\text{total}}$, which represents the total effect of the five methods. Considering the second and fourth methods are sometimes incompatible in a practical antenna design, we use a square bracket including these two multipliers, in which only one multiplier can be chosen for the same time. The case is similar for the second square bracket where the third and fifth methods are included. If the size reduction effects vary with frequency, these multipliers should be dispersive as well that only the effects around $f_1$ need to be taken into account.

By utilizing the five methods in a combining way, the antenna length can be reduced more significantly than only one method used solely. In the following parts, one compact patch antenna will be demonstrated by incorporating two methods, in which both of a shorting wall and planar metamaterial structures are utilized.

### III. ANTENNA DESIGN

#### A. Step 1: From half-wave to quarter-wave

We start from a conventional rectangular patch antenna. The prototype of the conventional antenna is given in Figure [I] (a) with patch size of $L \times W$ and ground plane length $G$. In the side view of Figure [I] (b), we see that dielectric substrate is with thickness $h$, dielectric constant $\varepsilon_r$, and loss tangent $\tan \delta$. The patch and ground planes are both made of copper with conductivity of $5.8 \times 10^7$ S/m and thickness $t$. The shorted patch antenna is shown in Figure [I] (c). A shorting wall composed of numerous conducting vias is added at the end of the shorted antenna. The shorting wall connects the patch and ground planes, making the half-wave patch length ($\lambda_d/2$) reduced to quarter-wave ($\lambda_d/4$). Note that the sizes for both antennas are identical. And they are both coaxially fed with characteristic impedance of $50 \, \Omega$.

Assuming $L = 52$ mm, $W = 50$ mm, $G = 100$ mm, $h = 12$ mm, $t = 0.035$ mm, $\varepsilon_r = 2.2$, and $\tan \delta = 0.001$, we obtain the reflection coefficients (S11s) for the conventional and shorted patch antennas in Figure [2] using the numerical HFSS solver.
Fig. 1. Antenna prototypes. (a) Top view. (b) Side view of a conventional patch antenna. (c) Top view of a shorted patch antenna.

Fig. 2. The simulated S11s for the conventional and shorted patch antennas.

It is seen that the resonant frequency is 1.788 GHz for the conventional antenna and 0.885 GHz for the shorted one. The patch lengths are 0.46 $\lambda_g$ and 0.23 $\lambda_g$, respectively. If the margin effects for the patches are accounted, the lengths should be better near $\lambda_g/2$ and $\lambda_g/4$.

B. Step 2: Beyond quarter-wave

To make the antenna smaller, the planar CSRRs are further added on the shorted patch. The scheme for one CSRR element is given in Figure 3 (a). They are excited by the electric fields perpendicular to the structures \[16, 17\], working as electric metamaterials. The mechanisms for the CSRRs can be explained using a lumped-element model (see Figure 13 in \[27\]) that the effective capacitance for the CSRR patch is increased than the original integrated one. The period for the CSRR element is $p$. Two slots are etched on the square structure. The length of the outer slot is $a$, while the width is $g$. These parameters can be tuned and adapted for different antenna applications. An array including $2 \times 2$ CSRRs is designed on the patch, as shown in Figure 3 (b). The metamaterial antenna size is kept the same as the aforementioned one without CSRRs.

The geometry parameters for the CSRR structure are: $p = 25$ mm, $a = 20$ mm, $g = 1$ mm, $d = 0.5$ mm, and $b = 2.5$ mm. The shorted antennas loaded with CSRRs are subsequently calculated in HFSS. The simulated S11s are shown in Figure 4. As is mentioned above, the original shorted antenna without CSRRs resonates at 885 MHz. However, by adding $2 \times 2$ CSRRs, the antenna resonant frequency is downshifted to 737 MHz. The patch length is about 0.19 $\lambda_g$, which is beyond the quarter-wave limitation for a conventional shorted patch antenna.

The two-step results provide an evident evolution map for the combination method to show its capability to effectively reduce the antenna resonant frequency. Considering the antenna volumes for these antennas are identical, it implies that the antenna with a lower resonant frequency has a smaller electrical size. Hence, a better size reduction effect can be achieved by the combination technique than only one method used solely.
The designed shorted patch antenna with $2 \times 2$ CSRRs is experimentally demonstrated. The substrate is a kind of F4BMX dielectric with nominal $\varepsilon_r = 2.2$ and $\tan \delta = 0.001$, provided by Taizhou Wangling Corp. The measured $S_{11}$, in contrast to the simulated one, is given in Figure 5. The fabricated shorted antenna with the CSRR metamaterial patch is also shown in the inset picture. It is fed by a 50-Ω coaxial probe. From the measured $S_{11}$, it is observed to resonate at 735 MHz ($\lambda = 408.16$ mm) with the $-10$ dB bandwidth (BW) of 6.8 MHz (0.93%). They agree well with the simulated results. The simulated resonant frequency from HFSS is 737 MHz with BW of 6.2 MHz (0.84%). The limited BW is resulted from the small antenna size [28, 29], which can also be found in other miniature antennas [12].

The normalized antenna size is $0.127 \times 0.123\lambda$ (or $0.189\lambda_g \times 0.182\lambda_g$). The substrate thickness is 12 mm or $0.03\lambda$. Considering the dielectric is with a low index of $\varepsilon_r = 2.2$, the size-reduction effect is remarkable.

The radiation patterns for the shorted metamaterial antenna at the resonant frequency are given in Figure 6. For the shorted antenna, there is only one slot radiating the electromagnetic waves. Hence, its patterns on the $E$-plane as shown in Figure 6(a) exhibit quasi-omnidirectional characteristics. They are much different from the conventional patch antenna in which two parallel slots work together. The $H$-plane patterns in Figure 6(b) are yet similar with the conventional antenna.

The miniature antenna is with a notable backlobe. It is due to the electrically small ground plane. To suppress the backlobe, an effective method is to increase the ground size. Another limitation for the antenna is that the cross-polarizations are seen very large on the $H$-plane. They seem inevitable for shorted patch antennas that were also found in other designs with shorting walls [5-7]. Fortunately, the radiation fields in the broadside are still with good polarization purity.

The peak antenna gain is at the level of 2 dBi at the resonant frequency. The antenna gain can be moderately enhanced to about 3-4 dBi by increasing the directivity. It can be realized by enlarging the ground plane as to suppress the backlobe.

Figure 7 shows the simulated and measured antenna efficiency ($\eta$). They are obtained with the G/D (gain/directivity) method. The directivity is calculated from the measured 3D radiation pattern data. The peak efficiency in measurement is about 77%. The simulated one is slightly higher as 82%. It proves that, although the new shorted antenna with CSRRs is very small, the total radiated power is still kept at an acceptably high level.

The performances for the shorted metamaterial antenna in this work are finally summarized in Table 2.
in comparison with some other compact patch antennas operating in the UHF band below 1 GHz.

We have realized a small-sized UHF band patch antenna using the combination method of adding both a shorting wall and CSRRs. To make the antenna more compact, some other ways, e.g., a higher permittivity host substrate [12], [13] or magnetic material [14] may be incorporated into this powerful technique in future.

V. CONCLUSION

In conclusion, a small patch antenna is designed by combining two size-reduction methods as adding a shorting wall and CSRRs. Numerical calculations show that the resonant frequency can be significantly reduced by utilizing the combination method. One particular shorted patch antenna loaded with $2 \times 2$ CSRRs is experimentally studied, which is fabricated on a low permittivity substrate. The antenna resonates at 735 MHz. The patch size is $0.127\lambda \times 0.123\lambda$. The measured efficiency is acceptably high as 77% that can meet the demands of the UHF band communications.

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REFERENCES


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