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A WIDEBAND MINIATURIZED DIPOLE ANTENNA ON A PRINTED CIRCUIT BOARD

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Abstract—This paper investigates a miniaturized resonant antenna that comprises a meandered monopole and a partial ground plane. A bandwidth enhancement is found using the ground plane on the back side of the circuit board where the entire communication system resides. The meandered monopole together with the ground plane forms a wideband dipole antenna. The design shows over 25% 10 dB impedance bandwidth at 2.5 GHz ISM band with a monopole area of 300 mils by 166 mils on a small circuit board and a backside ground plane 1500 mils by 600 mils. The wire length is about one third and the Q factor is about twice as compared against the case of using a straight quarter-wave microstrip monopole. The antenna Q factor as a function of the ground plane area is characterized. The use of circuit ground as a part of an antenna should find useful applications in portable wireless systems. Good agreements are found between simulated and measured antenna gain patterns and return loss.

1. INTRODUCTION

In portable wireless communications where the entire system resides on a small circuit board, the area reserved for an integrated antenna is often much smaller than a wavelength [1]. A fundamental issue that limits antenna size reduction is the impedance bandwidth (or the quality factor Q). In addition to the necessary gain, an antenna should be resonant with sufficient surface for radiation.

Common integrated antennas for wireless systems are suspended monopoles on the substrate surface. The metal ground plane right underneath the antenna on the back side is removed to enhance the

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bandwidth. However, the conductor on the backside is also necessary to serve as the ground for the chips and board circuits. A printed inverted F antenna (PIFA) mounted on the edge of the circuit board with a truncated ground plane underneath is a typical example [2]. The edge of the ground plane adjacent to the antenna traces also contributes to the radiation.

Due to the recent advancement of material technology, it becomes very feasible to fabricate complicated electronic devices in multi-layer integrated circuit structures, at a sub-micron scale on silicon microelectronics or at a millimeter-scale on printed circuit boards (PCB) or low-temperature co-fired ceramics (LTCC). There have been significant efforts in 3D microwave circuits including filters, resonators, branch-line couplers, antennas, matching circuits, and power splitters on multi-layer integrated circuits [3–4] and growing research activities on the electromagnetic applications of engineered materials such as metamaterials, where the material characteristics can be tailored [5–7].

Recently, there has been much research effort in the bandwidth (or Q factor) optimization of electrically small antennas [8–10]. Using left-handed/right-handed metamaterial structures for antenna size reduction is also addressed in [11–15] as examples. Although such an electrically small antenna could be self tuned to resonance, the radiation resistance is usually small due to a small useful radiation area, corresponding to a large Q factor and a small bandwidth. This paper explores the use of truncated ground plane as part of the antenna. The design treats the whole circuit board as an antenna structure. The ground plane is designed as a monopole forming half of the dipole. A wire antenna is constructed from a section of a meandered transmission line with proximity coupled inter-digital strips. An example of the antenna prototype is fabricated and tested. The antenna impedance and Q factor are also characterized using the fundamental antenna limit as a bench mark. The bandwidth enhancement (or Q reduction) due to the controlled radiation at the backside conductor ground plane is also verified.

2. THE DESIGN OF A MINIATURIZED WIRE ANTENNA

The initial design is for a dipole antenna on a FR-4 ($\varepsilon_r = 4.2$ and $\tan\delta = 0.01$) slab (no ground plane). The meandered wire with coupled strips and substrate parameters are shown in Fig. 1. The design is originated from the design of a slow-wave transmission line [13]. Per unit cell, the meandered wires enhance the inductance

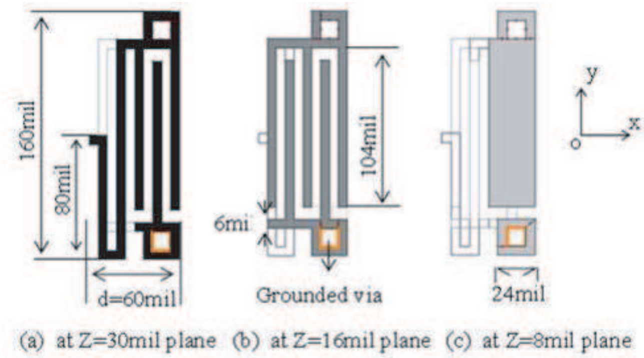


Figure 1. The drawing of a unit cell in the meandered dipole. Note that for antenna application, the ground plane at $z = 0$ is partially removed.

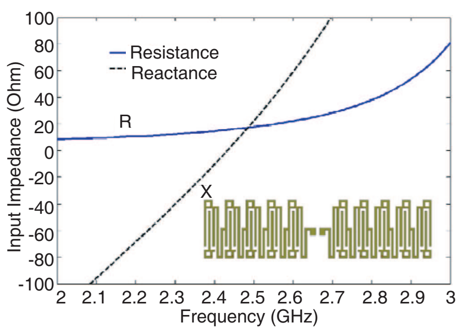


Figure 2. Input impedance of a meandered dipole antenna on a FR4 slab.

and the coupled strips enhance the capacitor, in order to reduce the transmission line wavelength. However, for antenna applications where the ground underneath is removed, the floating capacitance has less effect and the monopole is more or less like a meandered line. HFSS is adopted as the simulation tool for this work. The antenna traces and their gaps are at 8 mils and other parameters are indicated in Fig. 1. The simulation results of the dipole antenna input impedance are shown in Fig. 2. It is observed that for antenna resonance at around 2.44 GHz, 10 unit cells (60 mils and 5 unit cells on each side) are needed for this half-wave length dipole. The resonant resistance is about 15 Ω. In comparison, a normal printed dipole, the resonant length is about 3 times (1800 mils). Although the meandered resonant dipole is much smaller, the antenna bandwidth is also reduced according to the fundamental antenna limit [16]. Antenna fractional bandwidth (FBW_v) is roughly inverse proportional to its Q factor (Q_z) through the formula in [16],

$$FBW_v(\omega) \approx \frac{s-1}{\sqrt{s} \cdot Q_z}, \tag{1}$$

where s is the voltage standing-wave ratio (VSWR).

The Q factor can be found from the frequency dependent antenna impedance according to the formula in [16],

$$Q_z(\omega) = \frac{\omega}{2R(\omega)} \sqrt{\left(\frac{dR(\omega)}{d\omega}\right)^2 + \left(\frac{dX(\omega)}{d\omega} + \frac{|X(\omega)|}{\omega}\right)^2} \tag{2}$$

The antenna input impedance $Z_{in} = R + jX$ can be obtained from the EM simulation or measurement. Antenna bandwidth is usually based on VSWR = 2 (10 dB return loss). The Q factor could provide the bandwidth information if the antenna is tuned to a designed impedance.

Figure 3 shows the simulated Q factor of two half-wave length dipoles, one with a regular microstrip and the other with a meandered wire (shown in Fig. 2). It is observed that the Q factor at the designed frequency (2.44 GHz) is about 4 times larger for the meandered wire case that has a 10 dB bandwidth of about 2.8%. Such a narrow bandwidth is insufficient for most portable wireless systems and is much worse than a PIFA. For a monopole (half of the dipole), the bandwidth is much worse and proper ground is needed for current balancing.

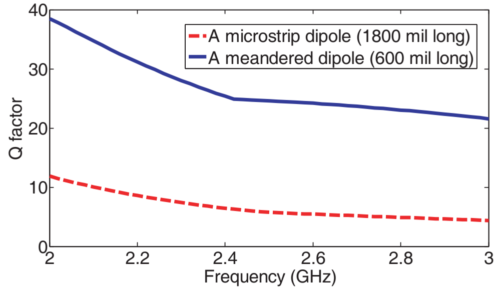


Figure 3. Q factor comparison of a miniaturized dipole (600 mils long) and a straight microstrip dipole (1800 mils long) with no bottom ground conductor.

The lower bound of the radiation Q factor (Q_{lb}) according to the antenna fundamental limit is ([16])

$$Q_{lb} = \eta_r \left(\frac{1}{1+\gamma}\right)\left(\frac{1}{(ka)^3} + \frac{1}{ka}\right), \tag{3}$$

where η_r is the radiation efficiency, γ ($0 \leq \gamma \leq 1$) is the ratio of power between orthogonal polarizations, $k = 2\pi/\lambda$ (λ is the free space wavelength), and a is the radius of an imaginary sphere enclosing the maximum dimension of the antenna. It is of interest to check the miniaturized wire design against the fundament limit given in (3). At the design resonant frequency of 2.5 GHz, the efficiency η_r is found about 0.5, polarization factor is $\gamma = 0$ (linearly polarized), and the radius a is about half of the dipole (300 mils). The lower bound of the Q factor is about 10 as compared to 25 shown in Fig. 2. This calculation shows that the miniaturized wire dipole is far from the fundamental antenna limit and there could have much more potential improvement. This improvement could come from the increase in the vertical antenna dimension. In the present design, the substrate thickness is only 30 mils. Increasing the substrate thickness to the antenna radius could help pushing the Q factor to its lower bound, although it may not be practical for small and low-profile potable wireless systems.

A novel approach is proposed here to achieve a large antenna bandwidth with such an electrically small monopole. Half of the dipole in Fig. 2 is replaced by a rectangular patch (wide strip) that also served as the circuit ground. The layout and picture of such an antenna are shown in Fig. 4. The dark area is a ground copper plate on the backside. There is a clearance area underneath the remaining monopole.

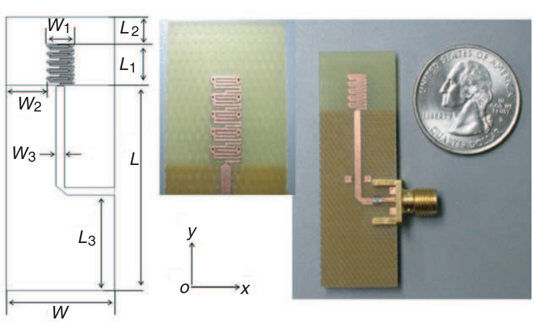


Figure 4. Miniaturized printed wire antenna on a FR4 substrate. Note that wire-and ground patch form a dipole.

Table 1. Resonant frequency and resistance versus Ground length L ($W = 17$ mm) (miniaturized wire is half of the dipole in Fig. 4).

L (mm)	5	20	30	36	38	40	45	50
F: GHz	2.61	2.42	2.35	2.35	2.40	2.61	2.68	2.64
R_r (Ω)	8.5	8.5	28.2	46.1	58.3	70.0	46.5	32.1

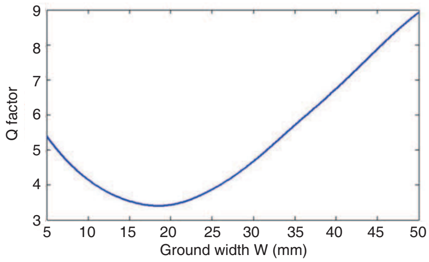


Figure 5. Q factor of the centered wire-patch antenna versus the ground width (W) with $L =$ 1500 mils.

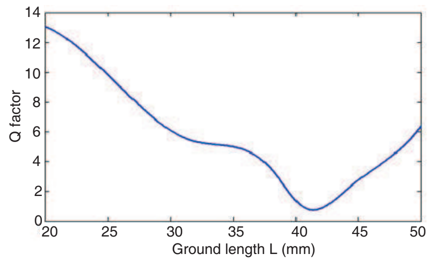


Figure 6. Q factor of the wire-patch antenna versus the ground length L. Other dimensions are given in Fig. 1 ($W = 666$ mils).

Interestingly, the structure shown in Fig. 4 is in effect a dipole antenna, where the ground plane shared with the rest of the systems is the other half of the dipole. This ground area on a circuit board is usually flexible and "practically" not counted as part of antenna real estate. It could however enlarge the overall antenna volume to enhance the bandwidth. The antenna length is effectively reduced by half (compared to a symmetric dipole in Fig. 1) excluding the pre-existed ground plane.

The antenna design concept here is very different from that of a PIFA whose tuning arm provides the current return path and its ground plane area is insignificant to the antenna characteristics. The choice of ground patch dimensions is based on the overall Q factor optimization. For example, the simulation result of the Q factor versus the ground patch width (W) is shown in Fig. 5 at 2.5 GHz, where the ground length is fixed at 1500 mils (38.1 mm). It is observed from Fig. 5 that for a small ground width ($<$ 30 mm), the Q factor is below 5 and the Q factor gradually increases as the width increases. This is due to the decrease of the radiation resistance as the patch width increases. Antenna resonant frequency and resistance for several ground patch lengths are shown in Table 1, where the width is 17 mm (666 mils). From Table 1, it is observed that the resonant frequency is not very sensitive to the patch length. It is mostly dictated by the miniaturized monopole (as shown in Fig. 2). The ground seems to contribute the resonant resistance and helps the impedance bandwidth. The observation implies that the miniaturized monopole functions as L-C tuning elements, while the ground patch serves as the main radiator, excited partially by the monopole. A reason of insignificant influence of the ground patch on the resonant frequency is that the main L-C value of the dipole is coming from the monopole. The patch is much wider, so its inductance value is much smaller. Also extended ground length is farther away from the monopole and would not affect much of the overall capacitance much.

The Q factor versus the ground length (L) is shown in Fig. 6 at 2.5 GHz, where the ground width is fixed at 666mils and the monopole is centered as the case in Fig. 3. It is observed that the Q factor drops below 5 for a wide range of the ground plane length ($30 \sim 50$ mm) and even for a small ground 20 mm, the Q factor of 13 (8% bandwidth) is still quite good for such a small structure. The Q factor plot in Fig. 6 explains that the stored energy is mostly on the CTF monopole and the radiation resistance comes from the patch. The optimized patch length is in between 38 to 40 mm where there the resistance is highest (the lowest Q factor). It is interesting to note that this optimized length is roughly half of a wavelength for a patch on the FR4 slab surface. The ground patch is in effect a half-wave length low Q resonator.

For a given circuit board, Figs. 5 and 6 suggest that it is possible to design the circuit ground layer metal profile to enhance the radiation and decrease the Q factor. The circuit board layout in Fig. 3 resembles a dongle with an edge-mounted SMA connector. The board design parameters are $W_1 = 166$ mils, $W_2 = 250$ mils, $W_3 = 52$ mils, $L_1 = 300$ mils, $L_2 = 200$ mils, and $L_3 = 698$ mils. The ground patch

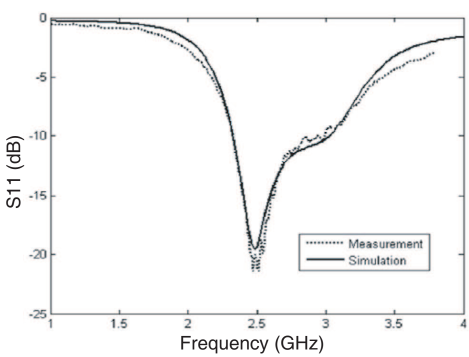


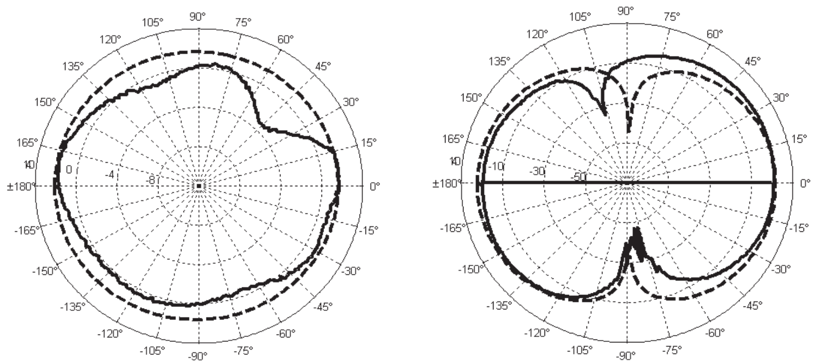
Figure 7. Reflection coefficient of the antenna shown in Fig. 4.

dimension, is designed as $W = 666$ mils (17 mm) and $L = 1500$ mils (38 mm) based on the results in Figs. 5 and 6.

Figure 7 shows the reflection coefficient plot of the proposed antenna structure. The simulation shows 10 dB impedance bandwidth of 25.3% (680 MHz from 2.38 GHz to 3.04 GHz) at the center frequency 2.68 GHz. The SMA connector and the feed location shift the center frequency slightly away from the designed frequency 2.5 GHz. The simulation agrees very well with the measured data. The simulation of a microstrip monopole (same structure, but with the monopole replacement) shows a similar 10 dB impedance bandwidth of 23.9% (610 MHz) with 900 mils in length, but about three times longer (compared to 300 mils here).

Figure 8 shows the overall antenna gain patterns at 2.5 GHz in both the E- (Y-Z) and H- (X-Z) planes. The net wire current is in the E-plane and transverse to the H-plane. The overall radiation pattern is pretty much a donut-shaped pattern of a linear wire antenna. The peak gain is about 2 dB at 2.5 GHz, consistent with the gain of a resonant dipole. In simulation, the cross-polarization is at least 20 dB less than the co-polarization. Simulated radiation efficiency is slightly above 90% in band (2.28 GHz to 2.94 GHz). The efficiency at 2.5 GHz based on the measured gain patterns shown in Fig. 8 is about 80%, using a free-space lossless monopole as a reference (2.15 dB gain omni-direction in H-plane). From the simulation, it is found that there is significant current crowded on the upper edge and the side corners of the partial ground plane that attributes to the radiation. The overall antenna performance is similar to a printed inverted F antenna (PIFA) [4, 5] but much smaller in size.

It is noted that the regular microstrip monopole is about 3 times longer (900 mils) than the meandered wire (300 mils) at resonance. The Q factor comparison of the two antennas shown in Fig. 9 is interesting. It is observed that the Q factor of the meandered wire is about twice larger at the design frequency (2.5 GHz) with the same ground plane dimensions (1500 mils long and 666 mils wide). Furthermore, for frequency above 2.7 GHz, the straight microstrip monopole has a larger Q factor. The Q factor curve in Fig. 9 explains the fairly large bandwidth ($> 25\%$) of the designed antenna even though it is only 0.06λ long and 0.03λ wide. It is noted that a straight quarter-wave monopole is by itself an effective radiator and the ground plate has less an impact to it as to the meandered monopole.



(a) (b)

Figure 8. Simulated and measured radiation patterns. Dot-line: Simulation and solid line: measurement. (a) H-plane (x-z plane in Fig. 4). (b) E-plane (y-z plane in Fig. 4).

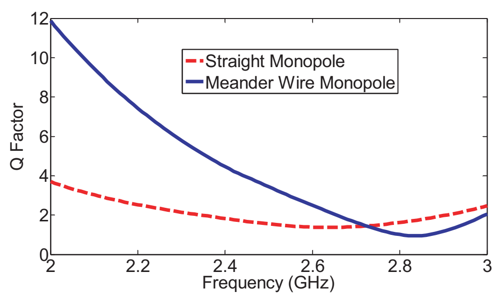


Figure 9. The Q factor of the designed miniaturized wire (300 mils long) in Fig. 4 and a straight microstrip monopole (900 mils long).

3. CONCLUSIONS

This paper proposed a miniaturized printed wire antenna comprising meandered lines with proximity coupled strips. The quarter-wave monopole length was found one third of a normal microstrip quarter-wave monopole. The antenna length reduction corresponds to the increase in Q factor (the reduction in the bandwidth). A technique for bandwidth enhancement (or Q reduction) was proposed, by designing the existing backside circuit ground as part of the radiating element. The monopole and the ground patch together form a dipole antenna and increase effectively the overall antenna volume and enhance the bandwidth. The prototype design demonstrated 25% antenna bandwidth by a proper choice of the ground plate dimensions; while without the backside conductor, the Q factor is found around 25 (2.8% bandwidth). The bandwidth increases effectively by a factor of 9. In contrast, in many surface-mounting microstrip antenna structure with a ground underneath, the use of the ground plane descreases the bandwidth.

Antenna prototype built on a 2000 mils by 666 mils FR4 circuit board showed 25% bandwidth and 2 dB peak gain at 2.5 GHz ISM band. The effect of the ground size to the bandwidth and the Q factor was also characterized. The idea proposed in this paper on 3D substrate metalilization to provide better radiation within a given volume offers potentially useful applications.

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