Miniaturized Printed Wire Antenna for Wireless Communications

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Abstract—**Miniaturized printed-circuit-board wire antennas are investigated for wireless local access network (WLAN) and Bluetooth applications. The proposed wire antenna in F shape could have a much smaller area than an inverted F antenna with similar bandwidth. It is found an F antenna can usually be inductively tuned but the bandwidth decreases if the size is reduced from a quarter wave length. The bandwidth as a function of the antenna vertical and parallel arm lengths is characterized with numerical simulations. The antenna with an area of about 14 mm by 6 mm for 2.4 GHz industrial, scientific, and medical (ISM) band, similar to the size of a chip, is designed and tested with a bandwidth of about 200 MHz. The antenna range and blind spot are also discussed.**

Index Terms—**Printed circuits, radiation, wire antennas, wireless communication.**

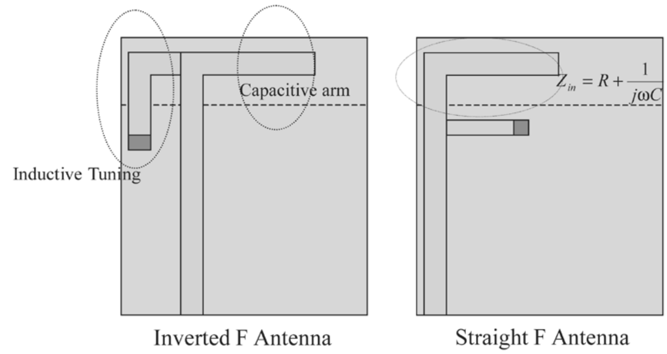

Fig. 1. Top view of a printed inverted F and a straight F antenna on a printed circuit board (dash line shows the backing conductor cut).

I. Introduction

RECENTLY, there is a worldwide demand for the development of wireless communication systems for local access networks (WLAN) including Bluetooth, IEEE 802.11a, and 802.11b. This demand has stirred significant renewed interest in antenna designs at the industrial, scientific, and medical (ISM) band. Many novel antenna structures for single, dual, or multiple bands have been proposed [1], [2]. Commercial products including Murata chip antennas (by Murata Co.), blue-chip antennas (by Centurion Co.), etc. are readily available. However, in a cost-effective personal communication system, the front-end antenna should be integrated on the circuit board with a minimum area and with more than 100 MHz bandwidth at 2.4 GHz ISM band. Printed circuit antennas are desirable for their low cost, low profile, and conformality [3]. A common drawback is the narrow bandwidth, when a conductor backing is presented. Parasitic elements may be used to provide multiple resonances to enhance the bandwidth. Recently, inverted printed F antennas were proposed that provide a much wider bandwidth and smaller size [4] by removing the ground backing underneath the wire antenna. An inverted F antenna [5], [6] is similar to a freestanding quarter-wave monopole above a ground plane, rather than the usual half-wave wire antennas. Much larger bandwidth is a result of a lower Q-factor as compared to the resonant microstrip elements. Inverted F antennas on a circuit board provide a broadband miniaturized antenna solution. In WLAN or Bluetooth applications where the complete communication system is in a single chip built on a small circuit board, it usually allows very small area for an antenna. There is a demand that the antenna area be less than 10 mm by 10 mm on a FR-4 substrate (dielectric constant 4.2). This presents a design and impedance matching problem. The inductive and capacitive arms of a printed inverted F antenna add up as the total antenna length that is usually much larger than what is desired. The inductive arm limits the flexibility in miniaturization. In this letter, a straight F antenna is investigated for further size reduction. The arm lengths of the F-shape wire antenna are optimized for bandwidth. The design and test results show that this antenna is much smaller than the usual inverted F antenna with sufficient bandwidth for the ISM band. Numerical results based on Ansoft high frequency structure simulator (HFSS) characterize the antenna characteristics and provide a design guide line of the tradeoff between the antenna size and bandwidth.

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II. Printed Straight F Antenna and Its Design Considerations

An example of a printed inverted F antenna is shown in Fig. 1(a). A distinctive feature of this wire antenna is that its antenna portion is in F shape and the opposite side of the surface is without conductor backing. It can be viewed as a suspended inverted F antenna collapsing on the substrate surface. Without conductor on the back to form a resonator, it maintains the low-Q feature of a suspended antenna and is broadband in nature. A 50 Ω trace extends into antenna central arm and it requires a conductor backing to form a microstrip transmission line. The conductor on the backside is also necessary as the ground for the chips and board circuits. A printed inverted F antenna is typically placed at the edge (corner) of a circuit board where only near the corner edge part of the metal ground is removed. The right arm of the feed trace acts as a capacitor, while the left arm is used for inductive tuning. This wire antenna is similar to a wire travelling-wave antenna [5] and at the resonance the input resistor is close to 50 Ω, the

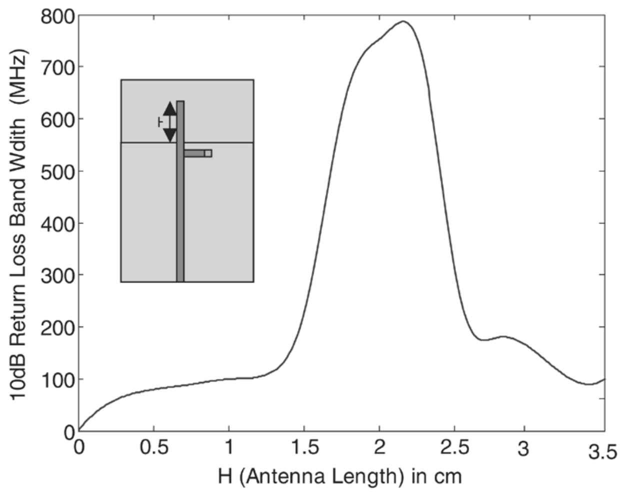

Fig. 2. Impedance bandwidth versus the antenna length (the length is measured from the truncated ground plane to the open trace). The center frequency is at 2.4 GHz.

characteristic impedance of the feed trace. The capacitive arm length is designed as a quarter-wave monopole.

For WLAN and Bluetooth personal communication systems applications, the dimensions of overall communication systems are fairly small, while the required bandwidth is 80 MHz (2.4 to 2.48 GHz). The board space left for an antenna is usually very limited. In this letter, we discuss a straight printed F antenna to further reduce the antenna dimension. The top view of a printed straight F is shown in Fig. 1(b). For an inverted F antenna, capacitive and inductive arms are on either side of the feed line resulting in a longer lateral antenna dimension. For a straight F, the inductive tuning arm is placed inside the L-shape capacitive arm. The inductive arm is printed right above the ground plane edge as a board circuit element. The wire antenna is bent in an F shape such that the antenna could be placed effectively on the corner of a circuit board. An interesting design problem is to determine the smallest antenna area to satisfy minimum bandwidth requirement. The bandwidth as a function of the antenna length (the wire extension beyond the ground plane edge) for a straight wire antenna is investigated using Ansoft HFSS. The numerical results are shown in Fig. 2 for a 30 mil FR-4 substrate and a 50 Ω transmission line tuned at 2.4 GHz. It is seen that maximum bandwidth (800 MHz or 33%) occurs when the antenna length is about a quarter wavelength long. The increase or decrease of the antenna length reduces the bandwidth. The input impedance of the monopole antenna ($\leq 1/4\lambda$) shown in Fig. 2, excluding the tuning inductor is given as

$$Z_{\text{in}} = R + \frac{1}{j\omega C}. \tag{1}$$

When the *RC* time constant is sufficiently large as is usually the case when the monopole is close to a quarter of a wavelength (quarter-wave transformer from an open), the admittance [inverse of (1)] is approximated as

$$Y_{\text{in}} = \frac{1}{R} + j\frac{1}{\omega}\frac{1}{R^2 C} \approx \frac{1}{R}. \tag{2}$$

It is seen from (2) that the antenna admittance is frequency insensitive (imaginary part is very small). This observation explains the broadband nature of the antenna. For wireless applications at ISM bands, the required bandwidth is only about 3% (80 MHz at 2.4 GHz) and the design should be at least 5% to accommodate the environmental factors, suggesting that the antenna length can be much smaller than a quarter of a wavelength as seen in Fig. 2.

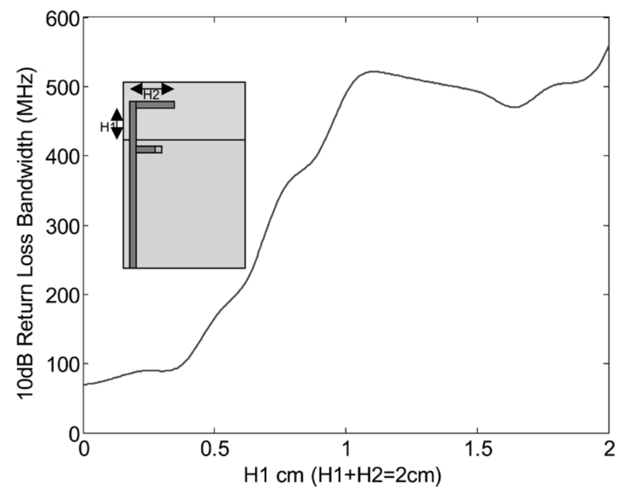

Fig. 3. Impedance bandwidth versus the antenna vertical length H1 (total length is fixed). The center frequency is at 2.4 GHz.

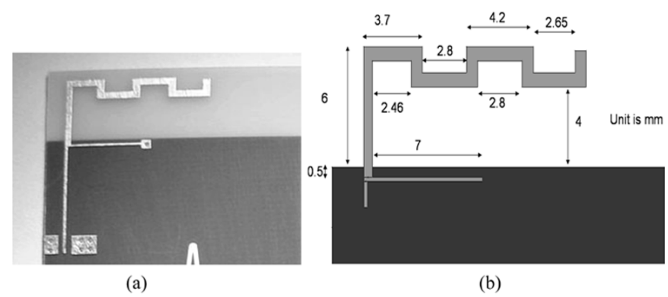

Fig. 4. Printed straight F antenna on a FR-4 substrate with the detail antenna dimensions. Microstrip line width is 0.24 mm and substrate thickness is 5 mil.

There are further design considerations when the wire antenna is bent in an F shape at the board corner. In general, the electrical length is shorter when the antenna is moved toward the board edge from the middle, a result of the less effective dielectric constant. This implies that for the same bandwidth, the antenna is larger when it is placed at the corner. In addition, the area without the ground backing is strictly for antenna purpose and should be as small as possible. The part of a PCMCIA card extended out of a laptop computer is an example. It is desirable to have most of the antenna traces bent toward and in parallel to the ground. However, the parallel arm creates an opposite image current and forms a high Q resonator with the ground. As a result, the longer the parallel arm (smaller antenna area with the same total antenna length), the smaller the bandwidth will be. An example of the HFSS numerical results of bandwidth versus the bend length is shown in Fig. 3. It is observed that the bandwidth decrease significantly if the vertical arm H1 is small (or the parallel arm H2 is too close to the ground) when the total antenna length is fixed. The results in Fig. 3 provide a design guide line on how much bend one could afford for a given desired bandwidth.

III. A Design Example

A design example of a meandered straight F antenna is shown in Fig. 4. The parallel arm is meandered to further reduce the antenna area. The overall antenna area is reduced down to below

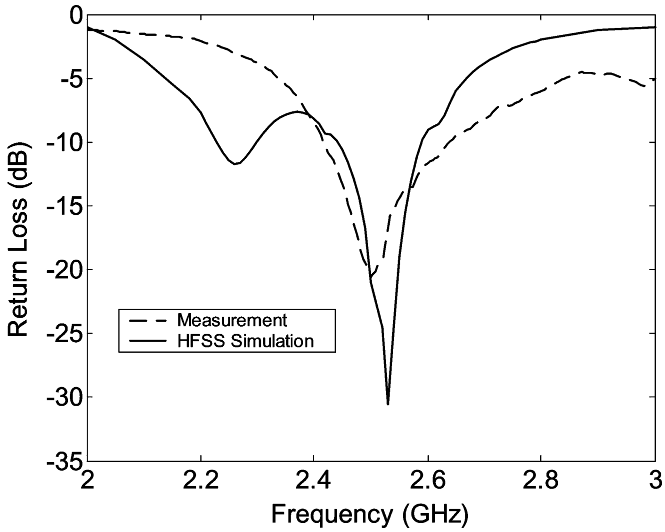

Fig. 5. Measured and simulated return loss versus frequency for the straight F antenna.

14 mm by 6 mm for a 4-layer stack-up FR-4 substrate of 18 mil overall thickness for a 2.4 GHz band operation. The substrate has a truncated ground plane on the second and the bottom layers indicated in the dark area in Fig. 4. Antenna is built on the upper-left corner of the board with 7 mm extension of board beyond the ground plane. The top sandwiched substrate is 5 mil thickness so that 50 ohm line trace is about 10 mil wide. Detailed drawing is also shown in Fig. 4. Return loss measurement is performed with a network analyzer through on-surface probing. Both simulated and measurement results are shown in Fig. 5 with good agreement found. For 2.4 GHz band wireless communications, the required bandwidth is about 80 MHz. The designed antenna has bandwidth of about 200 MHz, sufficient for the required applications. The F antenna can be miniaturized further by reducing the bandwidth. A 9 mm by 8 mm antenna with a bandwidth of 120 MHz was made for a Bluetooth dongle [7].

An additional advantage of the F antenna is that the radiation null can be pushed to the circuit side of the board due to the fact that radiated fields are the vector summation of fields from two linear antenna segments (horizontal and vertical arms) transverse to each other. As an example, the calculated gain pattern for the antenna structure in Fig. 4 is shown in Fig. 6. It is seen that there is a deep null on the right backside of the board, which is usually the nonradiation zone. The gain in the front of the board is about -2 dB and maximum radiation (2 dB gain) is at about 45° from the front. The existence of a null or a low radiation zone is common for a linear antenna due to the nulls of magnetic field. In reality, the diffraction and other vicinity components will smooth out the pattern. The gain versus the elevation angle (not shown here) is found fairly smooth, similar to the figure of eight characteristics of a linear antenna.

IV. Comparison Between Inverted F and Straight F Antennas

In general, the horizontal arm of the inverted F antenna is the radiation arm, while both vertical and horizontal arms of the F antenna are for radiation purpose. It is expected that the inverted F antenna would be longer for the similar bandwidth. A test example is used here to demonstrate this point. An F antenna is designed on 10 mil FR-4 substrate with bandwidth 200 MHz at 2.4 GHz. The vertical and horizontal arms are 11 and 7 mm, respectively. An inverted F is designed by moving the inductor arm out to the left. It is found from HFSS simulations that the inverted F horizontal arm is longer (15 mm) and vertical arm is shorter (9 mm) to obtain similar bandwidth (210 MHz) at 2.4 GHz. The straight F occupies 57% of the area of an inverted F, a significant reduction. The simulation results are shown in Fig. 7 for comparison.

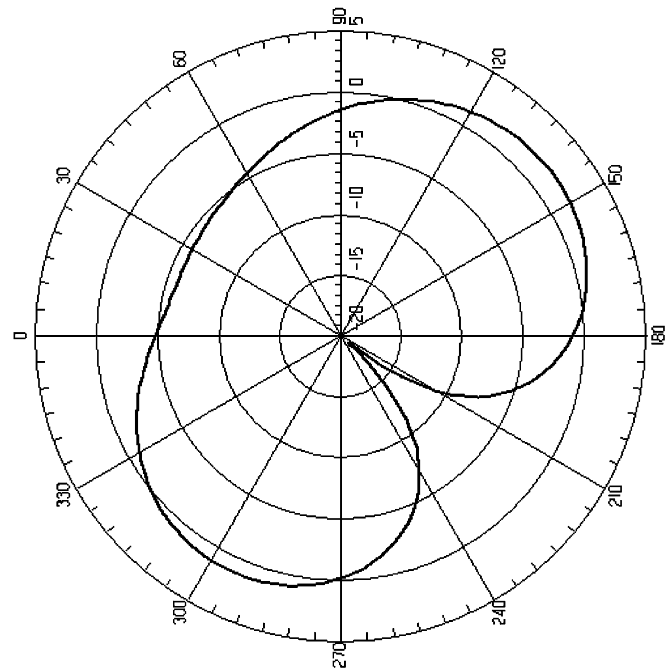

Fig. 6. Computed radiation pattern in the plane of a printed circuit board shown in Fig. 4. Note that the pattern angle is aligned with the antenna layout in Fig. 5.

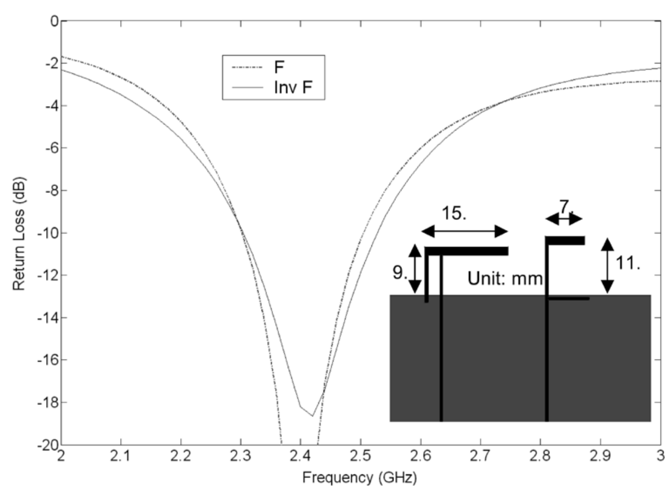

Fig. 7. HFSS return loss simulation of inverted and straight antennas with similar bandwidth (220 MHz). Substrate is FR-4 and 10-mil thick.

V. Conclusion

This letter described the design and characteristics of miniaturized F-shape PCB antennas. It was demonstrated that the antenna area is much reduced as compared to an inverted F by moving the inductive tuning arm into the ground-plane covered area. The main reason is that the both the vertical and horizontal arms are for radiation purpose. In contrast, in an inverted F, most radiation is due to the horizontal arm. The F antenna is most suitable at the corner of a circuit board. The tradeoff between antenna size (vertical and parallel length) and bandwidth was discussed. It was found that for miniaturized antenna designs, the parallel arm reduces and vertical arm enhances the bandwidth. A 2.4-GHz ISM band antenna was designed and tested. The designed F antenna has the performance of 200 MHz bandwidth with an area of 14 mm by 6 mm. The proposed antenna structure should find useful applications in WLAN or Bluetooth where the antenna length and width need to be flexible to fit into a small area.

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