Design of Integrated Inverted F Antennas Made of Asymmetrical Coplanar Striplines

By Ping Hui

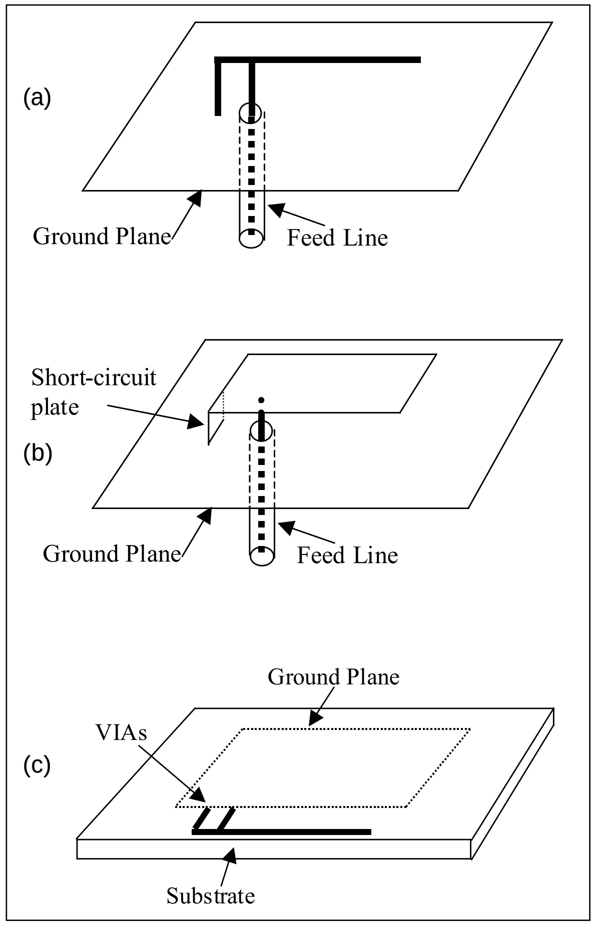
This article presents design curves and formulae for integrated inverted F antennas on FR4 laminates. A design example is shown for the FLEX pager application at a frequency of 930 MHz. Measurements of the resonant frequency and antenna gain are given.

Introduction

Inverted F antennas (IFAs) have a low profile structure, are light in weight and are easy to integrate into personal communication equipment. They can receive both vertically and horizontally polarized waves, resulting in some improvement on the probability of signal cancellation due to multipath fading [1].

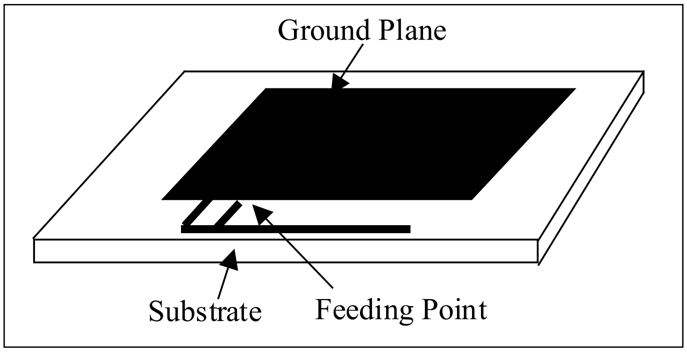
There are three kinds of IFAs: conventional wire element IFAs, planar inverted F antennas (PIFAs) and integrated inverted F antennas (IIFAs), as shown in Figure 1.

The conventional wire element IFAs were originally evolved from the folded L antenna, with the additional freedom to tap the input along the horizontal wire to achieve some control of input impedance [2]. To further reduce the length of the antenna and to increase the bandwidth, the wire elements are stretched to form planar sheets. The design formulas for the resonance frequency of PIFAs can be found from Reference [3]. To make the IFAs more compact, the antenna elements can be printed on the top plane of substrates to form the integrated inverted F antennas. IIFAs have been used in Bluetooth and DECT applications [4, 5].

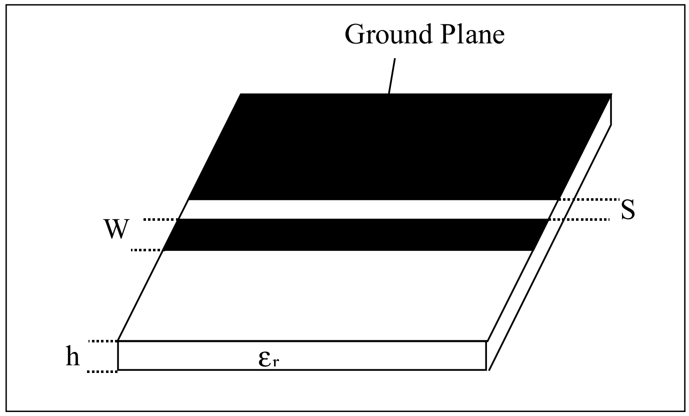


▲ **Figure 1. Three kinds of inverted F antennas (IFAs): (a) Conventional wire element IFA; (b) Planar IFA; and (c) Integrated IFA.**

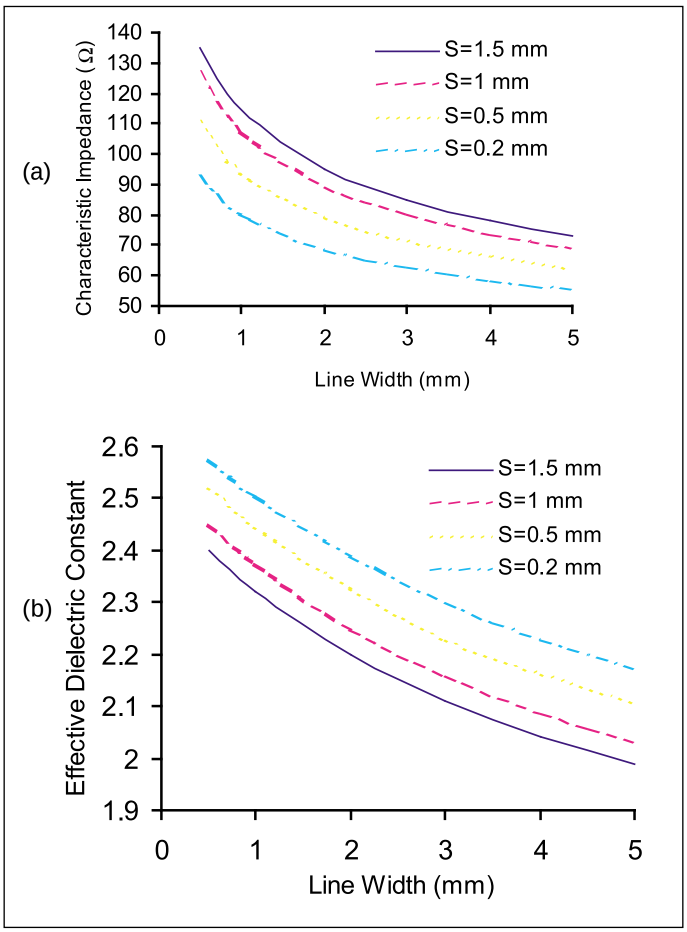
This article discusses an IIFA with the antenna elements printed on the same plane as the ground plane, as shown in Figure 2. This antenna structure can be viewed as being made of an asymmetrical coplanar strip (ACPS) line with a shorted-end and an open-end. A transmission line model has been developed for efficient design of the IIFAs. The design curves for the effective dielectric constant, the characteristic



▲ **Figure 2. Integrated inverted F antenna (IIFA) made of ACPS lines.**



▲ **Figure 3. ACPS line configuration.**



▲ **Figure 4. Characteristic impedance (a) and the effective dielectric constant (b) versus line width on FR4 laminate of 1.57 mm at a frequency of 930 MHz.**

impedance, and the corrections for the shorted- and open-end effects of the ACPS lines on FR4 laminates are obtained using the Method of Moments-Agilent's Momentum. As a demonstration, we have designed an IIFA for the FLEX pager application at a frequency of 930 MHz validated by measurements of the antenna resonant frequency and gain.

Asymmetric coplanar striplines

The ACPS line consists of a ground plane on one side of the transmission line, a separation S and a conductive strip of width W, as illustrated in Figure 3. The substrate has a height h and a dielectric constant ε_r. The characteristic impedance and the effective dielectric constant ε_{re} have been calculated using Agilent's Momentum for the FR4 laminate (ε_r = 4.4) of thickness 1.57 mm at a frequency of 930 MHz.

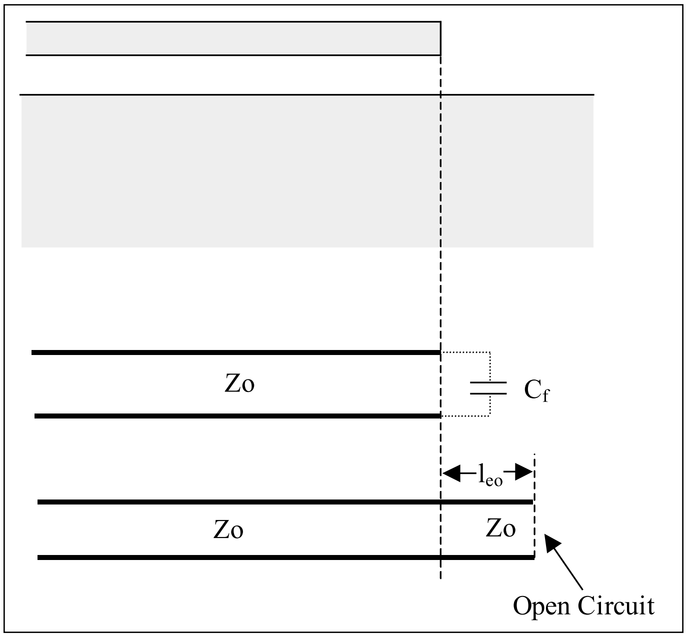
The larger ratio of the space to the line width (S/W) leads to higher characteristic impedance (see Figure 4 (a)). The effective dielectric constant ε_{re} has a range of 2.0 to 2.6 for the FR4 laminate, as seen in Figure 4(b). When S or W increases (holding W or S constant), a large percentage of the electromagnetic fields are present in the air, resulting in reduction of the effective dielectric constants.

The characteristic impedance and the effective dielectric constant are two parameters used to characterize infinitely long transmission lines. In order to design the physical length of the antenna accurately, both open- and shorted-end effects due to the fringing fields must be considered.

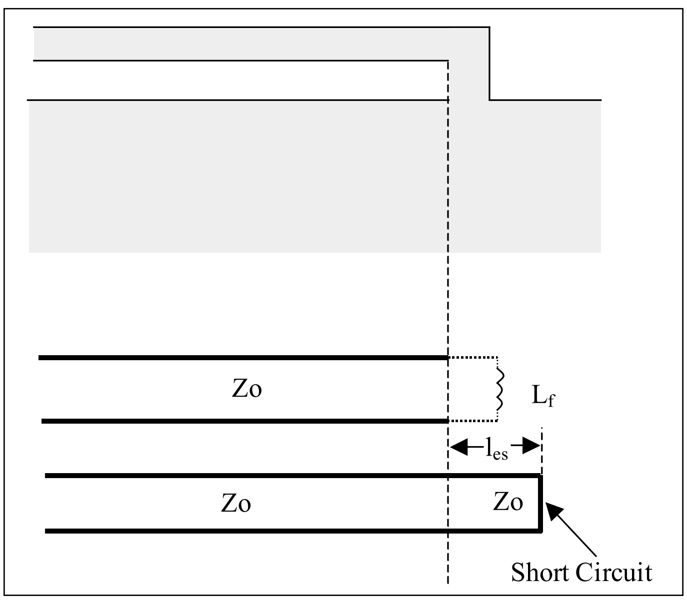
Open-end corrections

At the open-end, there is capacitive energy stored in the form of the fringing electric fields between the end of the strip line and the ground plane. In many aspects of circuit design it is very useful to think of the ACPS line as rather longer than it actually is, to account for such open-end effect. The concept of the equivalent open-end effect length l_{eo} is illustrated in Figure 5.

Using the ABCD matrix [6] and Agilent's Momentum, we have calculated the equivalent open-end effect length l_{eo} for the FR4 laminate of thickness 1.57 mm at frequency 930 MHz, as given in Figure 6. As the width W or the spacing S increases, the fringing electric fields between the end of the strip line and the ground plane increase and yield longer length of the equivalent transmission line.



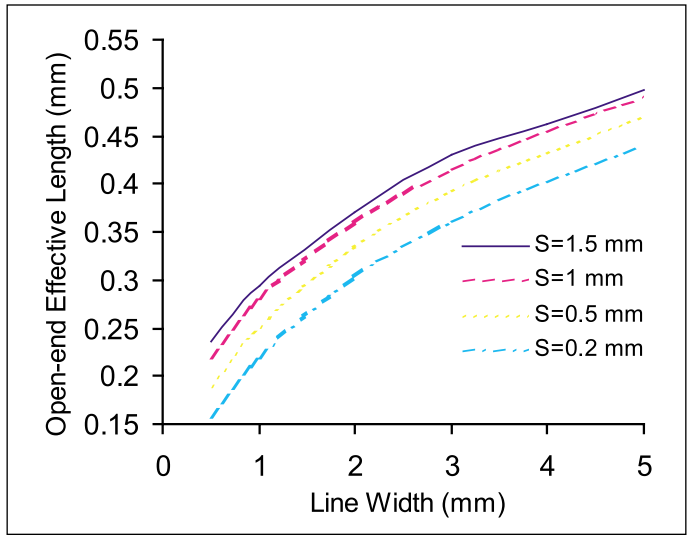
▲ **Figure 5. Development of the equivalent open-end effect length concept.**



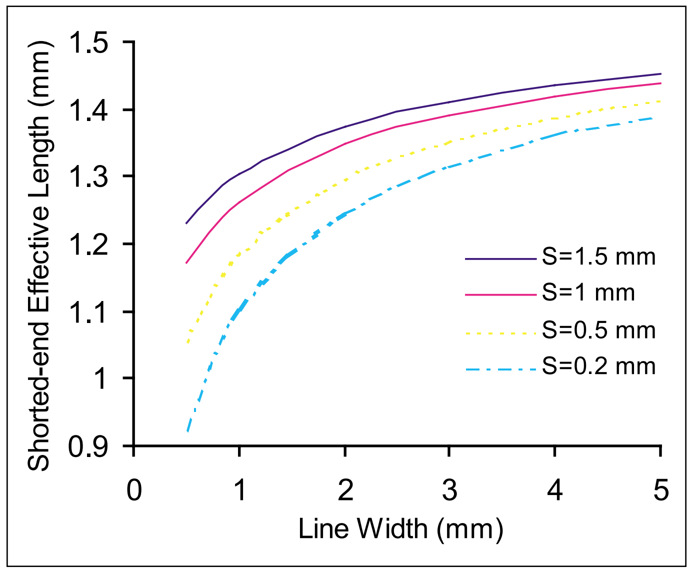
▲ **Figure 7. Development of the equivalent shortened-end effect length concept.**

Shorted-end corrections

Similarly, the shorted-end of ACPS lines stores magnetic energy and the concept of the equivalent shorted-end effect length l_{es} can be used to account for such phenomena, as shown in Figure 7. The calculated values of l_{es} with the short-end width of 3 mm for the FR4 laminate with a thickness of 1.57 mm at a frequency of 930 MHz are given in Figure 8. Again, the equivalent length increases as the space *S* or the width *W* increases (holding *W* or *S* constant). When the width of the shorted-end is doubled to 6 mm, the change in equivalent length is virtually flat.



▲ **Figure 6. Equivalent open-end effect length (mm).**

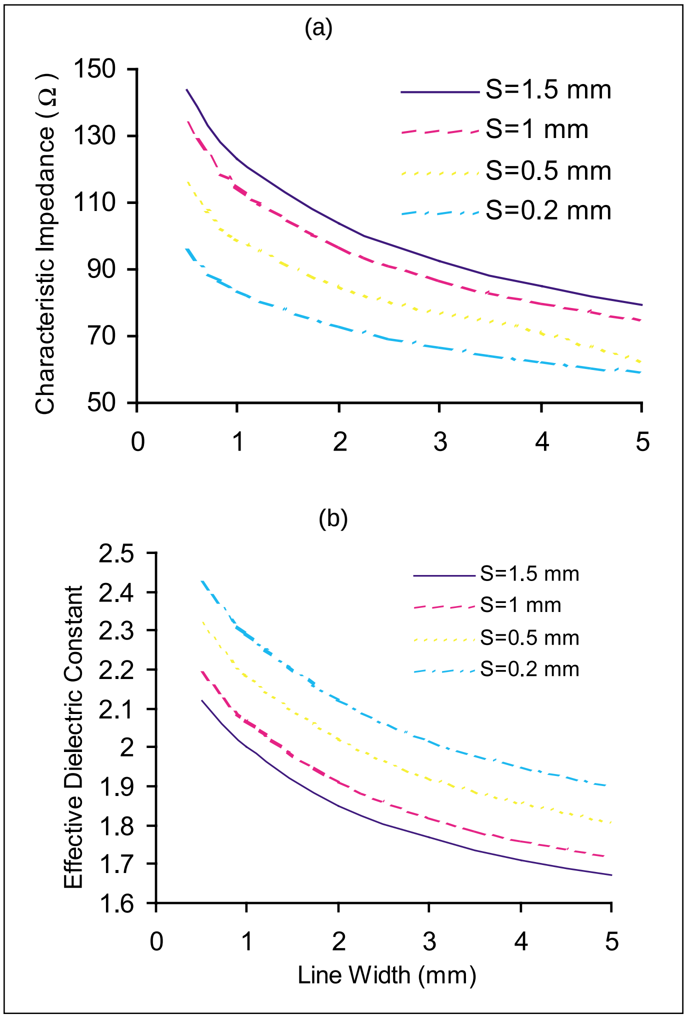


▲ **Figure 8. Equivalent shortened-end effect length.**

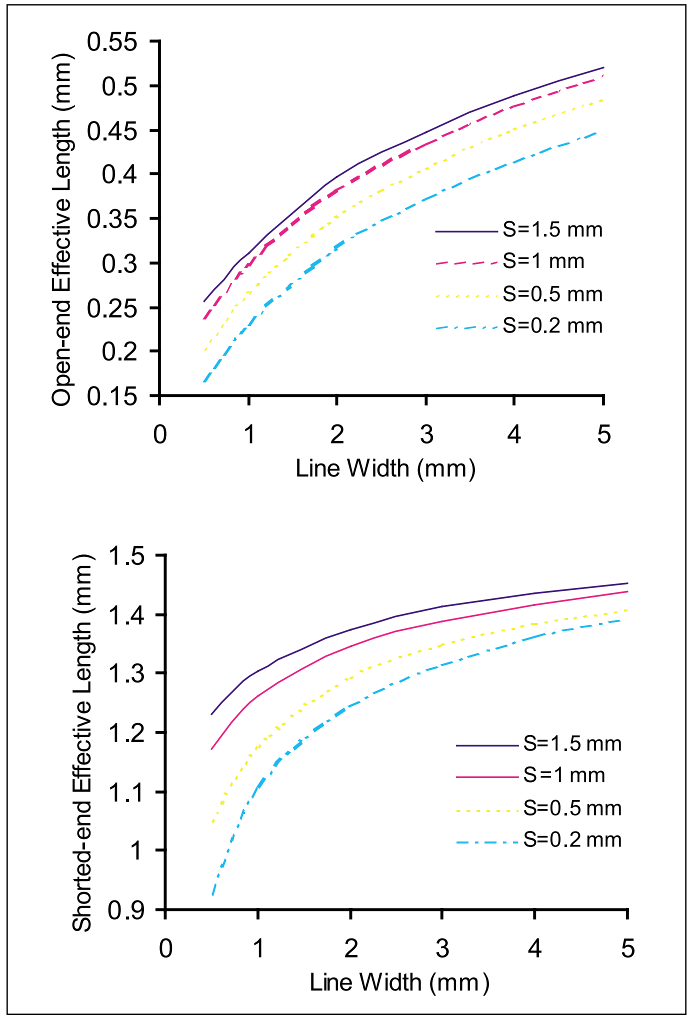
Figure 9 and 10 show the design curves of the characteristic impedance, the effective dielectric constant, and the end corrections for a FR4 laminate (ε_r = 4.4), with a thickness of 0.76 mm. For the same layout geometrical dimensions, the ACPS lines have a higher characteristic impedance and a lower effective dielectric constant on the thinner substrate than on the thicker substrate. However, the end correction lengths are almost the same for both substrates.

Antenna designs

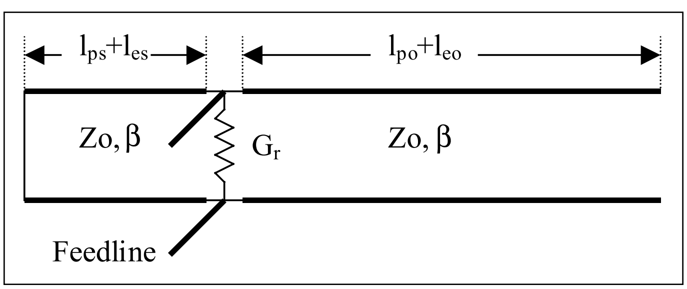
The IIFAs made of the ACPS lines can be viewed at



▲ **Figure 9. Characteristic impedance (a) and the effective dielectric constant (b) on FR4 laminate with a thickness of 0.76 mm at a frequency of 930 MHz.**



▲ **Figure 10. End corrections for FR4 laminate with a thickness of 0.76 mm at a frequency of 930 MHz.**



▲ **Figure 11. Equivalent network for the IIFA.**

the feeding point as the shunt of a shorted-end transmission line and an open-end transmission line. For the purpose of efficient antenna design, an approximate network model as shown in Figure 9 is proposed, where l_{ps} is the physical length of the line from the feeding point to the short-end, l_{es} is the equivalent short-end effect length, l_{po} is the physical length of the line from the feeding point to the open-end, and l_{eo} is the equivalent open-end effect length. A radiation conductance (G_r) is used to account for the radiation loss.

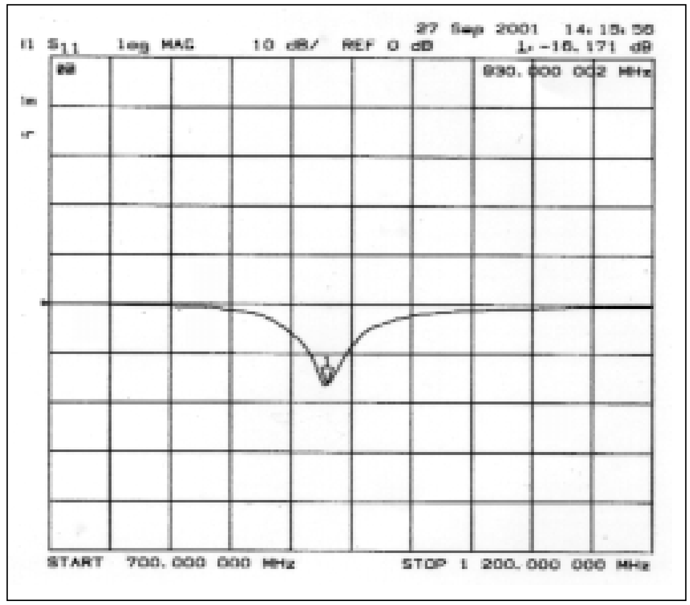
At the resonant frequency, the antenna can be viewed as a quarter-wave resonator, which implies that at the feeding point the inductive reactance looking into the shorted-end transmission line is equal to the capacitive reactance looking into the open-end transmission line. Therefore, we have the design formulae for determining the antenna length and the feeding position as:

$$l_{ps} + l_{es} + l_{po} + l_{eo} = \lambda_g / 4 \quad (1)$$

$$\tan\left[\beta\left(l_{ps} + l_{es}\right)\right]\tan\left[\beta\left(l_{po} + l_{eo}\right)\right] = 1 \quad (2)$$

where λ_g and β are the guided wavelength and the propagation constant of the ACPS line, respectively.

▲ **Figure 12. Experimental layout of an IIFA.**



▲ **Figure 13. Measured return loss of the IIFA.**

To demonstrate the use of the design curves and formulae given above, let us design an antenna for a FLEX pager receiver at the center frequency of 930 MHz. The substrate used is a FR4 laminate with a thickness of 1.57 mm. Choose the line width to be W = 2 mm and the separation to be S = 1.5 mm. From Figure 4 (b), we determine the effective dielectric constant is ε_{re} = 2.2 and thus $\lambda_g/4$ = 54.4 mm. The equivalent open-end effect length is l_{eo} = 0.37 mm from Figure 6 and the equivalent shorted-end effect length is l_{es} = 1.37 mm from Figure 8. Thus, the physical length of the antenna is $l_p = l_{ps} + l_{po}$ = 52.66 mm from Equation (1).

Substituting the effective dielectric constant and the end correction lengths into Equations (1) and (2) yields

$$l_{ps} + l_{po} = 52.66(mm) \tag{3}$$

$$\tan\left[0.0289\left(l_{ps} + 1.37\right)\right]\tan\left[0.0289\left(l_{po} + 0.37\right)\right] = 1 \tag{4}$$

Numerically solving equations (3) and (4) gives the feeding position l_{ps} = 4.2 mm.

Note that the equivalent network model shown in Figure 11 is approximate and for the purpose of efficient antenna design. Once the key geometrical dimensions of the antenna have been determined using the procedures outlined above, it is recommended to run numerical simulations using Agilent's Momentum or other electromagnetic simulators to optimize the antenna dimensions.

Measurement results

The designed antenna was fabricated on a FR4 laminate of thickness 1.57 mm, as shown in Figure 12. The antenna feeding point is accessed through a via hole from a 50-ohm microstrip line on the top plane. The return loss measurement obtained using a HP 5387D vector network analyzer, which agrees with the simulation results, as shown in Figure 13.

It has been shown that a GTEM cell can be utilized to measure gains of small antennas [7, 8]. We used a standard dipole antenna tuned to a center frequency of 930 MHz from EMCO as a reference and measured antenna gain to be –2 dBi.

Conclusion

An equivalent network model for the integrated inverted F antenna made of asymmetrical coplanar strip lines has been developed, and design formulae for determining the physical length of the antenna and the feeding point were given. The design curves for the effective dielectric constant, the characteristic impedance, the length corrections for the shorted- and open-end effect are given to facilitate the design process using FR4 laminates. Finally, a design example is given, validated by measurements of return loss and antenna gain. ■

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