

Design of the Equiangular Spiral Antenna on a Dielectric Substrate

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J. D. Dyson's development of the equiangular spiral antenna introduced a circularly polarized antenna with performance that is essentially independent of frequency over an arbitrarily wide bandwidth [1]. The limitations of the frequency independence come from the truncations of the spiral. The truncation at the outer radius creates a limit on the ability of the antenna to radiate low frequencies. The truncation at the center limits the upper frequency of operation. The operating band of the antenna is the region of frequencies between these limits.

The widespread availability of cheap photoetching fabrication has made it common for the spiral to be printed on a dielectric substrate. Previous work has primarily focused on the operation of the antenna in free-space [1,2]. More recently the effect of the dielectric on the impedance was modeled with a transmission line analogy [3]. This paper extends the work with an accurate full-wave simulation to examine the effects of the dielectric on the spiral's impedance and upper frequency of operation. A finite-difference time-domain (FDTD) model of the spiral was constructed and verified with impedance and gain measurements.

As a time-domain method, FDTD allows a wide range of frequencies to be simulated simultaneously by choosing an appropriate excitation. This makes it an excellent choice for modeling a broad-band antenna. It is possible to minimize the amount of simulation space in the dimension normal to the spiral plane (the z axis in Fig. 1) by placing the perfectly matched layer (PML) very close to the antenna. The convolutional PML proposed by Gedney was used because it matches evanescent waves better than the uniaxial PML [4]. It was noted that the antenna could be placed as close as four cells from the PML without introducing a noticeable error into the simulated impedance.

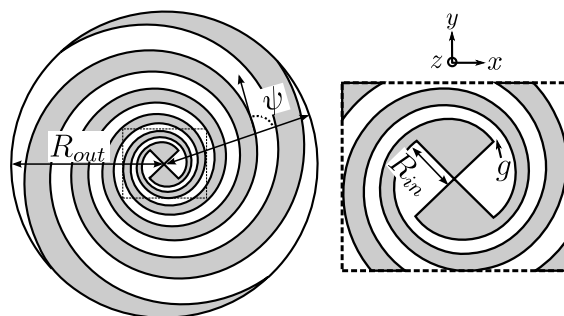


Figure 1: Geometry of a truncated two-arm equiangular spiral antenna

The geometry of the spiral antenna is depicted in Fig. 1. The parameter ψ is the angle between the tangential and radial vector of the spiral curve. Two spirals with

design parameters $\psi = 79^\circ$, $R_{in} = 3$ mm and $R_{out} = 0.1143$ m were fabricated for measurements to demonstrate the validity of the simulated data. The first was made on Arlon Foamclad R/F 100 with a thickness of approximately 1 mm. Foamclad is a composite dielectric with a thin layer of polyester film, $\epsilon_r = 3.2$, on top of a foam layer. For the second, Rogers RO3006 substrate with a thickness of 1.27 mm and $\epsilon_r = 6.15 \pm .15$ was used. The two spirals were also simulated using FDTD. The polyester film layer on the Foamclad spiral was modeled with a thickness of 0.1 mm. Comparisons are shown in Fig. 2.

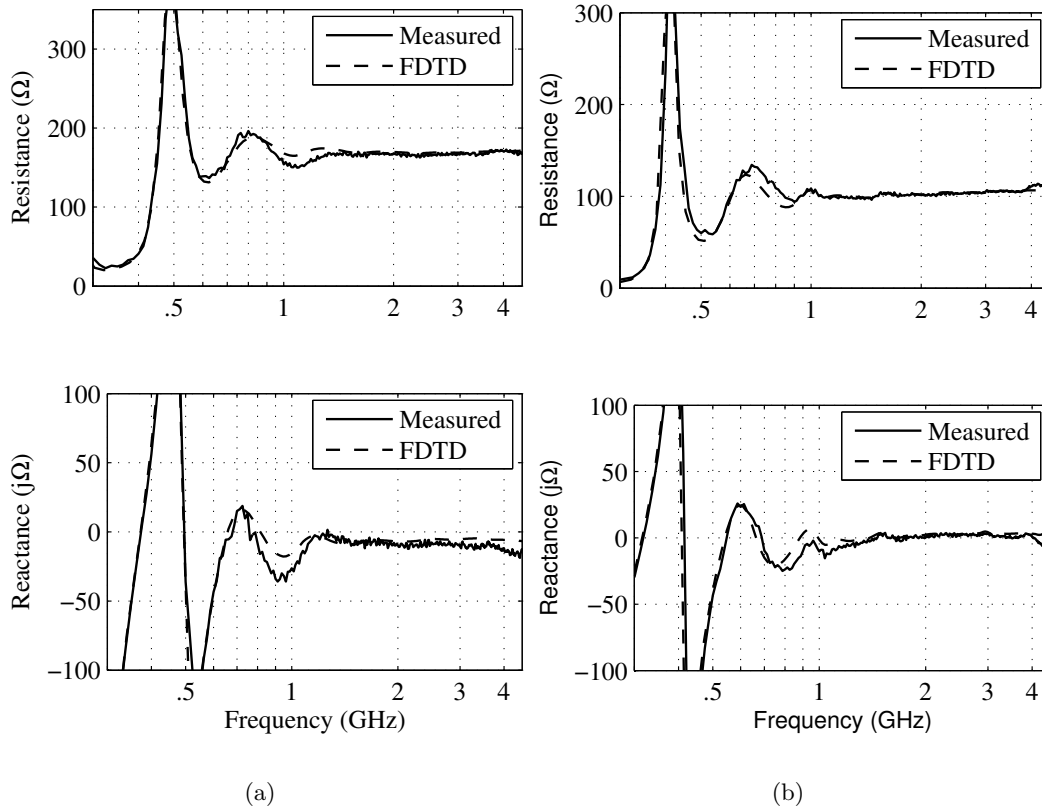


Figure 2: Comparison of measured and FDTD impedance for Foamclad dielectric (a) and Rogers RO3006 dielectric (b).

The experimental and simulated data agree well. It should be noted that the impedance of both spirals is essentially constant at the upper frequency region of each plot. This is the beginning of the operating band of the antenna. Bore-sight gain measurements were also taken for the two spirals using the two-antenna method. The measured and simulated curves for the bore-sight gain of the two spirals are shown in Fig. 3. These also show a reasonably good agreement.

Graphs of the impedance as a function of the spiral geometry were constructed. Fig. 4a is a contour plot of the average value of the resistance, $Re(Z)$, in the operating band. The axes of the plot are the dielectric constant, ϵ_r , and the ratio of g , the gap width of the spiral arms at the feed point shown in Fig. 1, to h , the substrate thickness. For small values of g/h , the real part of the impedance converges to the expected value of a self-complementary structure in a half-space of dielectric. This

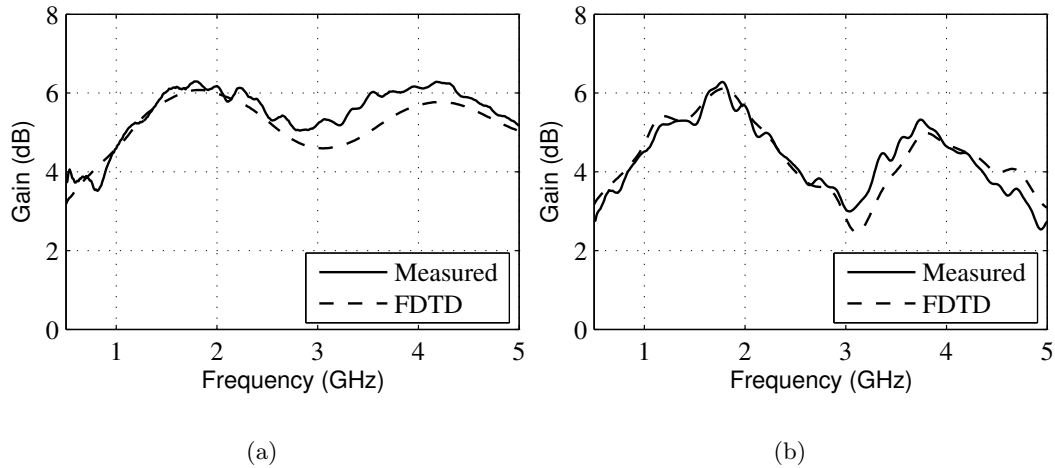


Figure 3: Comparison of measured and FDTD gain for Foamclad dielectric (a) and Rogers RO3006 dielectric (b).

half-space yields an effective dielectric ϵ_{EFF} with a value:

$$\epsilon_{\text{EFF}} = (\epsilon_r + 1)/2. \quad (1)$$

Using Booker's relation one obtains [3]:

$$Z = \eta_0 / (2\sqrt{\epsilon_{\text{EFF}}}) \quad (2)$$

where η_0 is the impedance of free-space. The value of the impedance as a function of ϵ_r is shown in Fig. 4b with the solid line being (2).

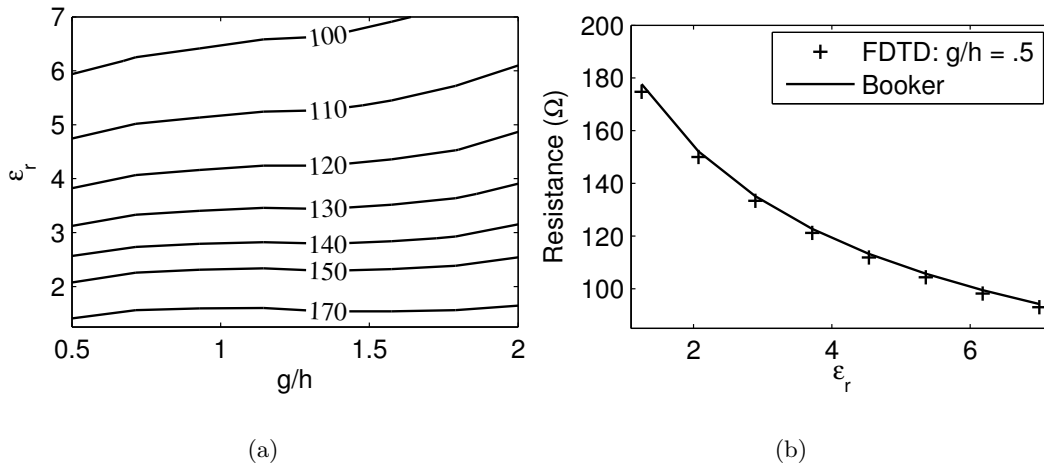


Figure 4: (a) Real part of the impedance as a function of g/h and ϵ_r with $\psi = 79^\circ$. (b) Booker's relation in a half-space is compared to experimental data for $g/h = .5$.

The FDTD model may be used to calculate the operating band of the antenna. As an example, the upper frequency cut-off of the antenna is calculated in this section. The spiral has a near unity axial ratio (AR) over the operating band. Because of this, the upper frequency cut-off of the spiral may be defined as the point where the axial ratio first crosses above $AR = 1.5$. The cut-off frequency of the spiral can

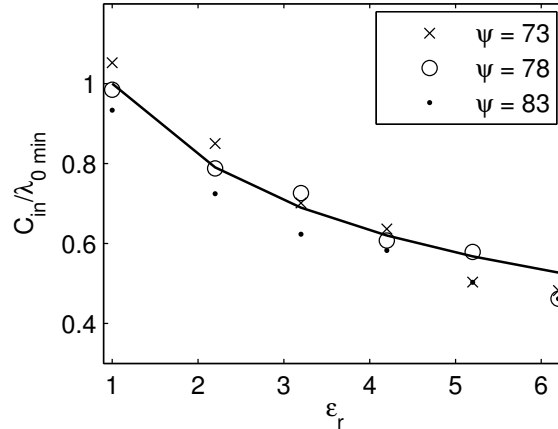


Figure 5: Maximum circumference in wavelengths allowed to keep the axial ratio below the value 1.5 at the upper frequency limit over a range of ϵ_r and three ψ values. The curve shown is the expected value $1/\sqrt{(\epsilon_r + 1)/2}$.

be related to the circumference of the inner truncation, $C_{in} = 2\pi R_{in}$, because the cut-off should occur when the inner circumference is one wavelength long. Fig. 5 shows the maximum C_{in} as expressed in free-space wavelengths allowable to still radiate a given frequency component with circular polarization. Three values of ψ are shown.

These parameters are taken from a spiral with $R_{in} = 3$ mm, $R_{out} = 0.1143$ m, and $h = 1.27$ mm. Since the free-space spiral requires an inner circumference greater than one wavelength to radiate a frequency component, one would expect that this result would generalize to the spiral on dielectric if the relationship between λ and f were known (the value of the phase velocity, v_p). Here it is assumed that at the feed point the phase velocity is approximately what one would expect to see in a half-space of dielectric ϵ_r . Making this approximation:

$$C_{in}/\lambda_{0 \min} \approx \lambda/\lambda_0 = v_p/c \approx 1/\sqrt{(\epsilon_r + 1)/2} \quad (3)$$

which is shown as the solid curve in Fig. 5.

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