Compact Coplanar Waveguide Spiral Antenna With Circular Polarization for Wideband Applications

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***Abstract*—This letter presents a compact, uniplanar, circularly polarized, coplanar waveguide (CPW) spiral antenna for wideband applications. The antenna is directly fed by a 50-Ω CPW from the outside edge of the spiral, thus a balun for matching is not required. This feed provides the capability to have an entire uniplanar array of spirals. It is found that a thick substrate of high dielectric constant absorbs most of the radiated power and results in a unidirectional radiation pattern, which is desirable in many applications. Therefore, this antenna structure is fabricated on a substrate of high dielectric constant, resulting in miniaturization and capability for integrated system applications. It is experimentally verified that the proposed spiral antenna has stable radiation pattern, and its axial ratio is less than 3 dB over the frequency range of 11.4–17.5 GHz.**

***Index Terms*—Bandwidth, circular polarization, coplanar waveguide (CPW), spiral antennas.**

I. Introduction

DECREASING size and weight of wireless communication systems has been a driving force for research in this field. The antenna is one of the biggest and critical parts of radar and communication systems. Designing antennas on substrates with high dielectric constant is an effective solution to reduce the size of the antenna because it shortens the wavelength. In fact, most of the materials used for fabricating integrated circuits present relatively high dielectric constants, which provide the capability of designing antennas for integrated system applications.

Spiral antennas [1] have numerous applications due to their wide bandwidth and circular polarization. Unfortunately, unless integrated with differential circuits, they generally suffer from two main disadvantages. First of all, their input impedance is not 50 Ω, and thus a wideband balun for impedance matching is required. Second, the central feeding leads to a thickness that incurs high fabrication cost, especially at high frequencies. Also, the central feeding makes planar array design more of a challenge.

Although different microstrip spiral antennas were studied, as frequency increases, microstrip-based configuration suffers from serious losses especially in millimeter-wave bands [2]. Coplanar waveguide (CPW) is desirable due to its high efficiency at millimeter-wave frequencies and also its unbalanced and uniplanar structure. Therefore, different structures of CPW-fed spiral antennas with external feed have been reported [3]–[5]. Although these structures provide a wide impedance bandwidth, they present circular polarization over a relatively narrow bandwidth. An externally fed three-arm spiral antenna was proposed in [6]. This antenna has a circular polarization over the frequency range of 2.3–3.7 GHz. Increasing the dielectric constant of the substrate decreases the dimension of the antenna, but unfortunately also increases the axial ratio. For a substrate with dielectric constant of 6.15, the axial ratio is more than 3 dB for circular polarization. To obtain a unidirectional radiation pattern, that spiral antenna must be mounted a quarter-wavelength above the ground plane, thus introducing frequency dependence [6].

Therefore, this work presents a compact externally fed CPW spiral antenna that is designed on an Alumina substrate of dielectric constant 9.8. Miniature hybrid microwave integrated circuit (MHMIC) technology is used to fabricate the spiral antenna with good processing precision. The effect of radiation absorption of thick substrates with high dielectric constant [7], [8] is used to obtain a unidirectional radiation pattern. (Note that in [7], the high dielectric constant is foremost a consequence of integration with the CMOS fabrication process.) This simple method results in a thinner antenna compared to the technique that consists of mounting the circuit a quarter-wavelength above the ground plane. The proposed method also provides a stable radiation pattern for wideband applications because it is no longer dependent on wavelength. A CPW feed is desirable due to its uniplanar structure, and it does not require a balun for impedance matching. Moreover, it has a high efficiency at millimeter-wave frequencies. Feeding from the outside edge of the antenna provides the design capability of a uniplanar antenna array and reduces the cost of fabrication, especially at millimeter-wave frequencies. Experimental results show that the antenna is circularly polarized and has a stable radiation pattern over a wide portion of the Ku-band for various radar and communications applications.

II. Antenna Design

The proposed antenna structure consists of a CPW line that curls up three times. This 50-Ω CPW line is tapered linearly to

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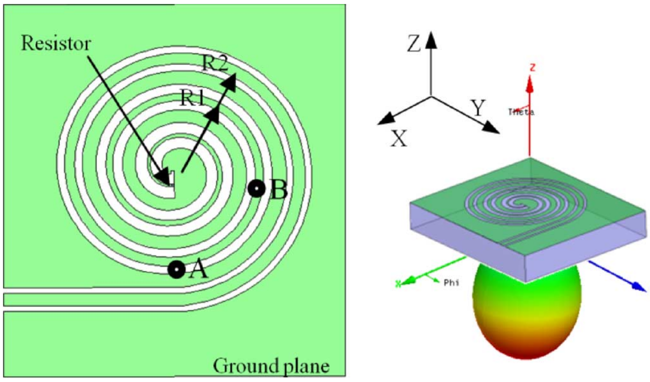

Fig. 1. Geometry and 3-D view (including radiation pattern) of the CPW-fed spiral antenna.

its 100-Ω counterpart at the center of the antenna and is terminated by connecting a 100-Ω resistor. Top and 3-D views of the spiral antenna are shown in Fig. 1.

The maximum radiation occurs when currents in neighboring CPW lines are in phase. To achieve the in-phase condition with respect to neighboring lines, the length of one turn must be equal to one wavelength. This means that as frequency increases, the proposed antenna will become more intensively radiating at the part more contiguous to the center. If the length of one turn is equal to one wavelength, circularly polarized radiation will also take place because the radiated electric field from points A (E_y) and B (E_x), see Fig. 1, will be 90° out of phase. This can easily be expressed mathematically by using the following equation:

$$\lambda = \frac{c_0}{f\sqrt{\varepsilon_{\text{eff}}}} = \pi(R_1 + R_2) \tag{1}$$

where R_1 and R_2 are, respectively, the small and large radius of the curved CPW line, and ε_{eff} is the effective dielectric constant. This expression suggests that the size of the antenna has an inverse relationship with $\sqrt{\varepsilon_{\text{eff}}}$.

To increase the radiation efficiency and decrease the power level reaching the center of the antenna, the impedance of the CPW line is increased from 50 Ω at the outside of the spiral to 100 Ω at its center. Increasing the line impedance decreases the ground plane width and puts two CPW lines closer together. This would potentially generate higher-order modes. However, our simulation results suggest that their effects are in fact negligible. These simulation results are beyond the scope of this letter and thus are not shown here.

Fig. 2 illustrates the effect of the high dielectric constant (9.8) substrate thickness (T) on the front-to-back radiation ratio of the Ku-band CPW spiral antenna, as analyzed by Ansoft HFSS. Fig. 2 suggests that by increasing the thickness of the substrate to 1.75 mm, most of the radiated energy is concentrated inside the dielectric, and a unidirectional radiation pattern is thus obtained. The effect of radiation absorption of thick substrates with high dielectric constants is illustrated in detail in [7]. Alumina is of interest for this antenna design due to its high dielectric constant (9.8) and low dielectric losses ($\tan\delta = 0.0001$).

Fig. 3 illustrates how the axial ratio of the antenna is dependent on the thickness of the substrate and loading at the end of the CPW line. We consider four cases: with and without resistor at $T = 1.75$ mm, and with resistor at $T = 1$ and 0.25 mm. As

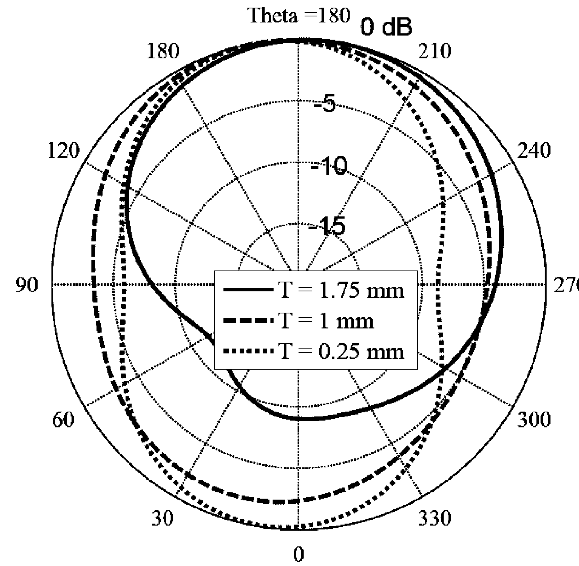

Fig. 2. Impact of the high dielectric constant (9.8) substrate thickness (T) on the front-to-back radiation ratio of the compact CPW spiral antenna at 14.5 GHz.

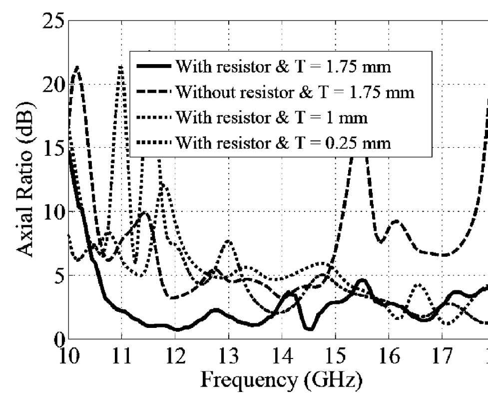

Fig. 3. Effect of CPW line termination and thickness of the substrate (T) on the axial ratio of the compact CPW spiral antenna.

shown in Fig. 3, the thickness of the substrate with high dielectric constant has significant effect on the axial ratio of the spiral antenna. The best axial ratio of the antenna (1 dB at 12 GHz) is obtained by utilizing the 1.75-mm-thick substrate.

Consequently, using a thick substrate with high dielectric constant decreases the axial ratio and the dimensions of the antenna; it also provides a unidirectional radiation pattern which is suitable for many applications.

Fig. 3 also shows the effect of loading the end of the CPW line with a 100-Ω resistor. Without this termination, the reflected waves increase axial ratio because they radiate in the opposite circular polarization. The 100-Ω termination limits the reflection of waves at the end of the CPW. Terminating the CPW line has a significant effect on reducing the axial ratio, although it also decreases the radiation efficiency of the antenna. The effect of loading on the radiation efficiency at different frequencies is dependent on the portion of the wave that reaches the end of the CPW line. Fig. 4 illustrates this effect. The simulated efficiency of the loaded spiral antenna is more than 72% within the operating frequency of the antenna. Note that all dielectric, metallic, and mismatch losses have been considered in the simulations.

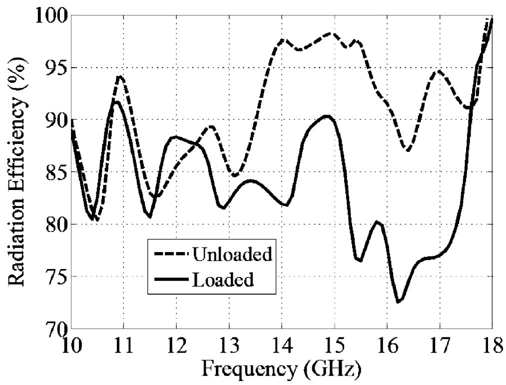

Fig. 4. Effect of CPW line termination on the radiation efficiency of the compact CPW spiral antenna.

When designing antennas on high dielectric constant substrates, the excitation of surface waves might decrease the efficiency of the antenna and also cause sidelobes. However, a comparison of the radiation efficiency of the proposed compact spiral antenna in Fig. 4 with the efficiencies of similar spiral antennas on low-dielectric-constant substrate shows that the efficiencies are similar and that sidelobes are absent in the simulated radiation patterns.

The width of the CPW signal line at the outside edge of the antenna is 0.3 mm, which is tapered linearly to a 0.05-mm width at the center of the antenna in order to increase the impedance of the CPW line from 50 to 100 Ω. The results show that the proposed structure can be used as a circularly polarized compact spiral antenna for wideband application in millimeter-wave frequency bands. To verify the antenna structure, a Ku-band spiral antenna was designed, simulated, and measured, as shown in Section III.

III. Fabrication and Measurement Results

MHMIC technology, an emerging technology for small-scale production, is used to fabricate the proposed spiral antenna on 20-mil (0.508 mm) thick Alumina substrate. The dielectric loss tangent of this Alumina substrate is 0.0001 (at 10 GHz). A 9×7.5 mm^2 rectangular Rogers/duroid 6010 substrate of 50 mil (1.270 mm) thickness with a dielectric constant of 10.2 is attached to the 20-mil Alumina substrate to increase the thickness of the substrate to 70 mil (1.8 mm). Note that the effect of adhesive between the layers is included in the simulation results. The spiral antenna is fabricated from a 1-μm-thick gold film on the ceramic substrate (Fig. 5).

The 100-Ω resistor is fabricated from a thin film of Ti. Its location is shown in the inset of Fig. 5(a). The dimensions of the resistor are 150×150 μm^2 and 20 nm in thickness. A microphotograph top view of the fabricated spiral antenna, the surface resistor, and a 3-D view are shown in Fig. 5. Measured and simulated impedance ($|S11|$ [dB]) of the compact spiral antenna are plotted in Fig. 6 over the 10–20-GHz frequency range. The impedance was measured using an Anritsu 3739C vector network analyzer. The discrepancy between the simulated and measured results is attributed to the proximity of the test fixture (Anritsu 36801 K right angle) to the antenna, although the test fixture was covered with a thin absorber [see Fig. 5(b)].

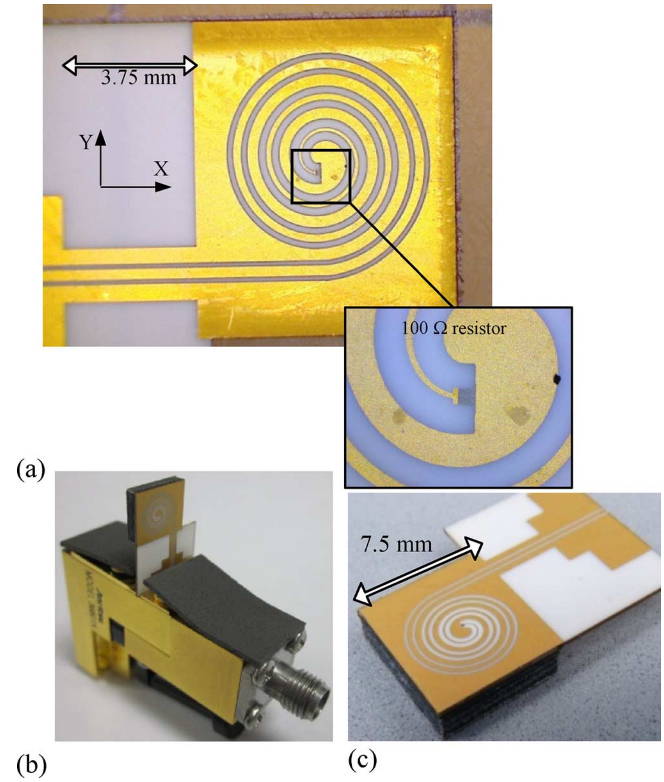

Fig. 5. Microphotograph of the fabricated compact spiral antenna using MHMIC technology: (a) top view, (b) 3-D view with test fixture, and (c) 3-D view.

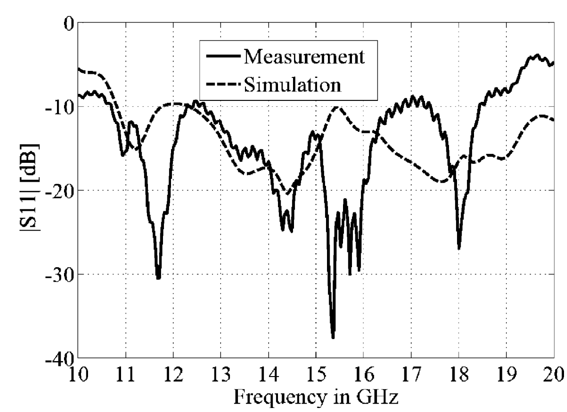

Fig. 6. Measured and simulated impedance of the compact spiral antenna.

Fig. 7 shows simulated and measured gains of the compact spiral antenna over the frequency range of 11–18 GHz. In the gain measurement setup, the frequency step is 0.2 GHz. The reference plane is the yz plane (cf. Fig. 1) for both simulations and measurements. Note that dielectric and metallic losses are included in the simulated gain of the antenna. The measured gain is determined at an elevation angle of $\theta = 180°$. As the gain measurements suggest, the use of a high dielectric constant thick substrate allows a relatively constant gain within a wide bandwidth from 11.5–17.5 GHz. This frequency range is used for numerous applications in radars and communications.

Measured and simulated axial ratios of the compact spiral antenna are shown in Fig. 8. The magnitude at two orthogonal states is used to calculate the axial ratio of the antenna. The

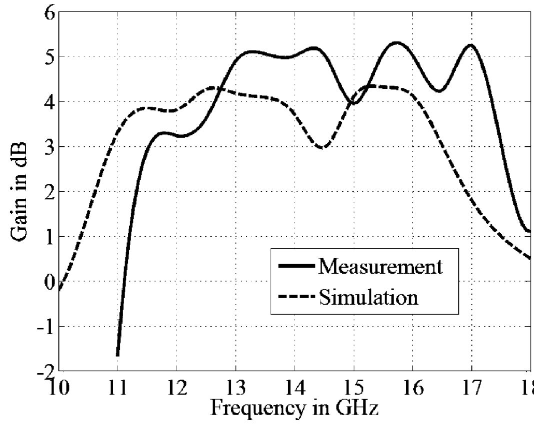

Fig. 7. Measured and simulated gains of the compact spiral antenna.

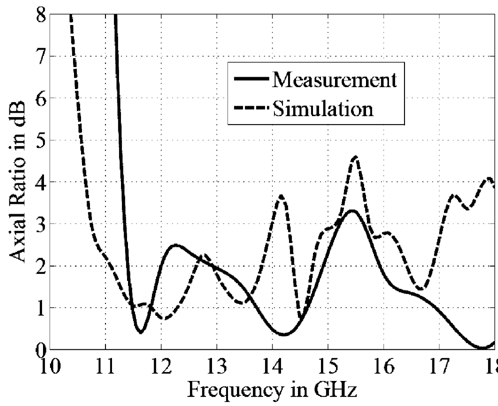

Fig. 8. Measured and simulated axial ratios of the compact spiral antenna.

measured axial ratio of the antenna is less than 3.3 dB over the frequency range of 11.4–18 GHz. The discrepancy between the simulation and measurement is attributed to the effect of the test fixture that has been used to feed the antenna in our anechoic chamber.

Measured (in yz plane) and simulated (in both yz and xz planes) radiation patterns, E-Theta, of the compact spiral antenna are shown in Fig. 9. The measured radiation pattern of the antenna has around 10 dB front-to-back ratio. This suggests that most of the power is concentrated within the substrate due to the high dielectric constant, and a stable unidirectional radiation pattern is obtained over a wide bandwidth. The test fixture that has been used to feed the antenna in the anechoic chamber has an effect on the radiation pattern. This is because the size of the antenna is small and the antenna is too close to the test fixture, which inevitably has effects on the radiation.

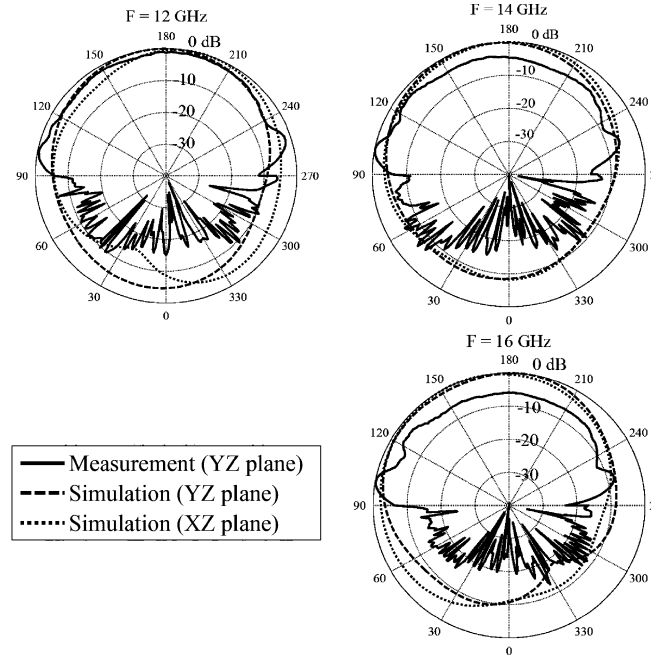

Fig. 9. Measured (in yz plane) and simulated (in both yz and xz planes) radiation patterns, E-Theta, of the compact spiral antenna at frequencies of 12, 14, and 16 GHz.

IV. CONCLUSION

A new compact spiral antenna was designed and validated both theoretically and experimentally. A CPW feed from the external edge of the antenna has been used to excite the antenna. The proposed topology is desirable due to its uniplanar structure, which offers easy fabrication at millimeter-wave frequencies. The second advantage of using CPW is low radiation losses at high frequency compared to microstrip lines. This spiral antenna does not require a balun due to the unbalanced CPW feed. The use of a substrate with high dielectric constant has effectively reduced the antenna size. It is shown that using a thick substrate and terminating the CPW at the center of the spiral antenna decrease the axial ratio. Nearly constant unidirectional radiation patterns over a wide bandwidth are obtained with a thick substrate of high dielectric constant.

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