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# Characterisation and optimisation of a coplanar waveguide fed logarithmic spiral antenna

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## Abstract

A cavity backed coplanar waveguide (CPW) to coplanar strip (CPS) - fed logarithmic uniplanar spiral antenna, which covers a 9 to 1 bandwidth with a return loss better than 10 dB from 0.4 to 3.8 GHz is presented.

A wideband balun is used to accomplish the transition from the unbalanced CPW transmission line to the balanced CPS transmission line. The balun exhibits an insertion loss of less than 3 dB in a frequency band from sub 100 kHz and up to a frequency of 3.85 GHz.

The numerical results presented are based on simulations using the IE3D Version 6.03 for Windows 98 on an INTEL Celeron 338 MHz computer. The obtained numerical results are in good agreement with experimental data.

The spiral antenna is designed and prototyped for the FR-4 substrate. By placing the antenna on the FR-4 substrate it yields a low cost solution, which indeed is an advantage. Simulations have shown that the input impedance remains essentially constant over a bandwidth, which is larger than 11 to 1. The simulated as well as the measured input impedance for the spiral antenna is 80  $\Omega$ .

Measurements in an anechoic chamber have been made in order to measure the radiation pattern and the directivity of the antenna. The cavity backed spiral antenna exhibits a unidirectional radiation pattern, due to the absorbing material. It is noted that only half of the input power is transformed into radiated power due to the presence of the absorber.

The simulated performance of the spiral antenna is very promising. The simulations indicated that the antenna has a radiation efficiency of more than 70 % and an axial ratio and a return loss better than 3.5 dB and 10 dB, respectively, in the frequency band from 0.4 to 3.8 GHz, i.e., a 9 to 1 bandwidth.

**Keywords:** Logarithmic uniplanar spiral antenna, Coplanar waveguide, Wideband antenna, Balun.

## Introduction

Antennas whose characteristics remain virtually unchanged over an exceptionally large bandwidth

have a multitude of uses. The class of frequency independent antennas is made up of antennas whose radiation pattern, impedance, and polarization remain virtually unchanged over a large bandwidth [1]. Frequency independent antennas are distinguished by the trait that their electrical dimensions scale with frequency. Ideally the electrical size of such antennas would remain constant over the entire electromagnetic spectrum. This though requires infinite physical dimensions. The practical frequency independent structure is truncated, which limits the antenna's upper and lower frequency limit [2], [3].

To aid the antenna design, the Electromagnetic Simulation Program, IE3D – a method of moment computer program – developed by Zeland Software [4], was used to predict the performance of the spiral antenna in terms of radiation pattern and input impedance. Furthermore the IE3D was used to predict the performance of the balun structure. The measured results of the constructed antenna and the balun structure were compared to the simulated results obtained from IE3D.

The FR-4 substrate is used for the antenna, which is commonly used for printed circuits. The FR-4 board is much less expensive than commonly used microwave substrates such as, e.g., Duroid. This feature, combined with the advantages of the uniplanar circuit, makes this configuration suitable as a low-cost wideband antenna, which indeed is an advantage.

## Balun and antenna configurations

The logarithmic spiral antenna configuration is shown in Figure 1. A wideband CPW-to-CPS balun was designed and used to transform the unbalanced coplanar waveguide (CPW) feed line to a balanced CPS feed line for the logarithmic spiral antenna. The CPW-to-CPS balun is a slightly modified version from that of Li's [5]. A four section Chebyshev impedance transformer was designed in order to change the impedance from 50  $\Omega$  to 80  $\Omega$ . The input impedance of the spiral antenna is found to be around 80  $\Omega$ . The wideband transition from CPW-to-CPS is accomplished by using a slotted, radial patch. This patch represents a very wideband open circuit, which forces the field to be mainly between the two conduc-

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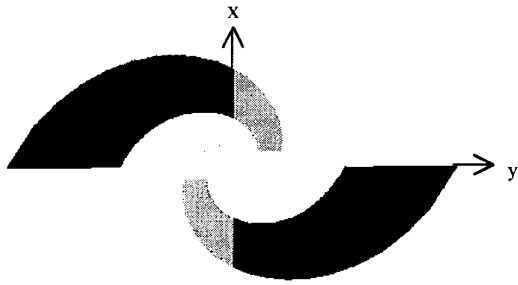


Figure 1. Illustration of how the spiral is broken up into smaller parts, to reduce the simulation time.

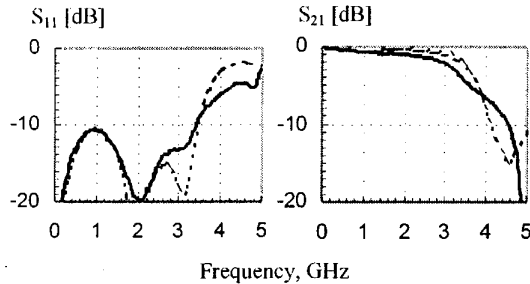


Figure 2. Measured (solid) and simulated (dashed) S-parameters of two baluns mounted back-to-back.

tors of the coplanar transmission line. The two bond wires near the plane of the discontinuity ensure that the potential on the two ground planes is equal. The balun structure was fabricated on an RT/Duroid substrate with a thickness of 0.785 mm and a relative dielectric constant  $\epsilon_r$  of 10.8.

The logarithmic spiral antenna was designed using the equations,  $r_1 = r_0 e^{a\theta}$  and  $r_2 = r_0 e^{a(\theta - \theta_0)}$ , where  $r_1$  and  $r_2$  are the outer and inner radii of the spirals, respectively;  $r_0$  and  $r_0 e^{-a\theta_0}$  are the initial outer and inner radii, respectively;  $a$  is the growth rate, and  $\theta$  is the angular position.

To obtain the most frequency independent radiation pattern, and at the same time the most constant input impedance the dimensions are found to be  $r_0 = 2.1$  mm,  $a = 0.5 \text{ rad}^{-1}$ , and  $\theta_0 = 1.3 \text{ rad} = 75^\circ$  [2], [6]. The spiral antenna is shown in Figure 1. The largest diameter of the spiral antenna determines the lowest operation frequency. A diameter of 0.47 m was used to obtain a lower operating frequency of 0.32 GHz. The antenna is designed to meet conditions where circular polarisation is required, thus the minimum frequency is where the arm length correspond to one wavelength. With an arm length of 0.5 m the lower frequency limit is 0.5 GHz [6]. The spiral antenna is fabricated on a FR-4 substrate with a thickness of 1.5 mm and a relative dielectric constant  $\epsilon_r$  of 4.4.

### Numerical and experimental results

Two back-to-back CPW-to-CPS transitions were simulated and optimised using IE3D from Zeland

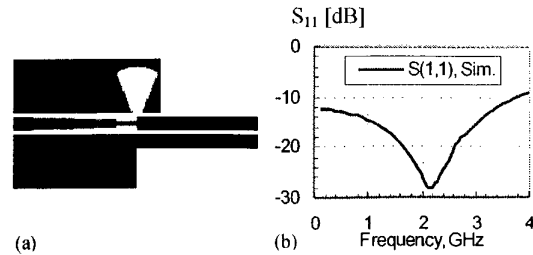


Figure 3. The coplanar waveguide (CPW) to coplanar strip (CPS) balun (a). Simulated  $S_{11}$ -parameter for one balun with the CPS terminated by an ideal  $81\Omega$  resistor.

Software. The size of this prototype is  $17 \times 46$  mm. The structure was fabricated to verify the performance. The numerical and the experimental result are shown in Figure 2. The results for  $S_{11}$  seem to agree well. For the insertion loss, i.e.,  $S_{21}$ -parameter the numerical and the experimental result look alike. Good agreements are obtained between the simulated and measured up to a frequency of 3.4 GHz.

The structure was tested on an HP 8720D and an HP 8752A network analyser to determine the return loss and the insertion loss of the balun. The two back-to-back CPW-to-CPS transitions provide an insertion loss of less than 2 dB from below 300 kHz to 3.4 GHz with a return loss better than 10 dB. The lower limit of the frequency bandwidth is believed to be practically DC although the balun characteristics are measured starting from 300 kHz because of the available equipment's limitations.

Simulations on the balun using IE3D, are performed by substituting the antenna with an ideal  $80 \Omega$  resistor. The balun is shown in Figure 3 (a). Simulations were carried out, and the results are shown in Figure 3 (b). In the frequency range from 100 kHz to 3.85 GHz the simulated return loss is better than 10 dB. For the balun loaded with an ideal  $80 \Omega$  resistor the simulated bandwidth within which the return loss is better than 10 dB is higher than the bandwidth obtained for the back-to-back balun. The main reason for this is believed to be due to interaction between the two baluns.

Simulations on the entire spiral antenna structure is not possible to within a reasonably amount of time due to the limited computer capacity. To solve this problem the spiral antenna is broken up into smaller parts, as illustrated by the different shadings in Figure 1. The electrical size of the spiral increases as the frequency increases. The entire structure is first simulated in the frequency range from 0.1 to 1.4 GHz. Then the fractions of the two arms, which correspond to the darkest, parts shown in Figure 1, are removed. Then the simulations are performed in a frequency range that is shifted upwards. The size of the substrate used for the spiral antenna is  $280 \times 430$  mm.

The numerical and experimental results are shown in Figure 4 for the CPW-fed spiral antenna. The mea-

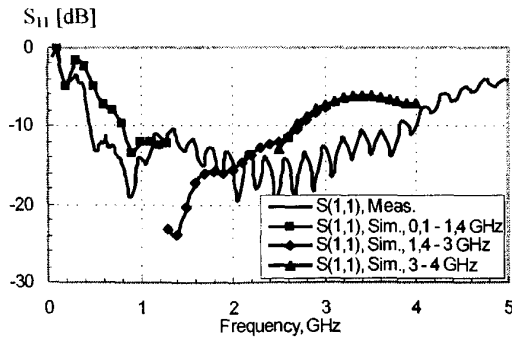


Figure 4. The measured and the simulated  $S_{11}$ -parameter for the CPW-fed spiral antenna placed on FR-4 substrate material. Notice that the simulated result is made up of three simulations.

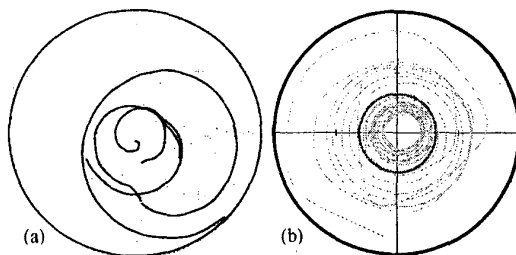


Figure 5. Simulated (a) and measured (b) impedances for the CPW-fed spiral antenna. The measured results shows several loops in the Smith chart, which is due to a 0.4 m RG316U coaxial cable that is connected to the CPW on the balun. The circle shown in (b) indicates that every point inside that circle has an impedance match better than -10 dB.

measured bandwidth, for a return loss better than 10 dB, is slightly larger than the simulated one. The measured and the simulated bandwidth is from 0.4 to 3.8 GHz and from 0.8 to 2.7 GHz, respectively. The observed ripple on the measured reflection coefficient is due to a 0.4 m RG316U flexible coaxial cable that is connected to the CPW on the balun.

When the electrical size of the structure becomes too large the benefits of using the IE3D is reduced. If the spiral arms are truncated, inaccuracies can occur when the currents on the arms are not negligible.

To reduce the simulation time the spiral antenna is broken up into smaller parts. This method is unfortunately not well documented in the literature. Another way to solve this problem is to use a faster computer, thought it can only solve it to a certain extent.

The measured and the simulated impedances for the spiral antenna including the CPW-to-CPS feed network are shown in the Smith chart in Figure 5. Due to the electrical length of the 0.4 m RG316U coaxial cable the measured impedance is mapped into the Smith chart as a spiral located around the centre of the Smith chart. This indicates that the spiral antenna

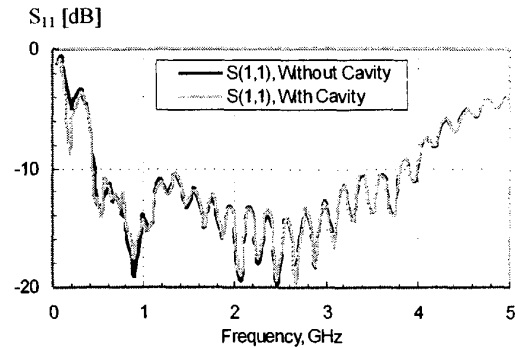


Figure 6. Measured  $S_{11}$ -parameter for the spiral antenna with and without a cavity.

including the feed structure is close to being matched to 50  $\Omega$ .

The constructed cavity is backed by an absorbing material and PS foam that have a thickness of 150 mm and 50 mm, respectively [7]. Measurements on the cavity backed spiral antenna are carried out in order to verify the simulated performance. Due to the available computer capacity it is too time consuming to simulate the absorbing material using IE3D. In Figure 6 the measured  $S_{11}$ -parameter for the cavity backed spiral antenna can be compared to the measured  $S_{11}$ -parameter for the spiral antenna without a cavity. Hardly any difference is observed in the  $S_{11}$ -parameter for the spiral antenna with or without a cavity. This result indicates that there is good reason to believe that the radiation in the main direction remains unchanged in the presence of the cavity.

Anechoic chamber measurements in the Spherical Nearfield Antenna Test Facility (SNATF) at the Technical University of Denmark (TUD) are made in order to measure the far-field radiation pattern and the polarisation. Two  $\theta$ -cuts are measured at four different frequencies in the frequency range from 0.8 GHz to 2.6 GHz. The far-field criterion is fulfilled thus the measured data can be used directly, without the need of a near-field-to-far-field transformation.

The spiral antenna has a broad bi-directional radiation pattern with the two maxima perpendicular to the plane on which the spiral antenna is located, i.e., the xy-plane as shown in Figure 1. The simulations and the measurements have verified this. The measured radiation patterns are shown in Figure 7. A small tilt of the main lobe can be observed at all four frequencies. This is believed to be attributed to asymmetry in the CPS. The radiation in the  $\theta = 180^\circ$  direction is 5 dB lower due to the absorbing material.

The measured half-power beamwidth ( $HPBW$ ) in the xz-plane remains nearly constant between  $79^\circ$  and  $86^\circ$  independent of the frequency. Whereas the  $HPBW$  in the yz-plane the measured  $HPBW$  are spanning from  $53^\circ$  to  $132^\circ$ . The directivity is estimated to 6.6 dB and 2.7 dB at 0.8 GHz and 2.6 GHz, respectively, by using the measured  $HPBW$ .

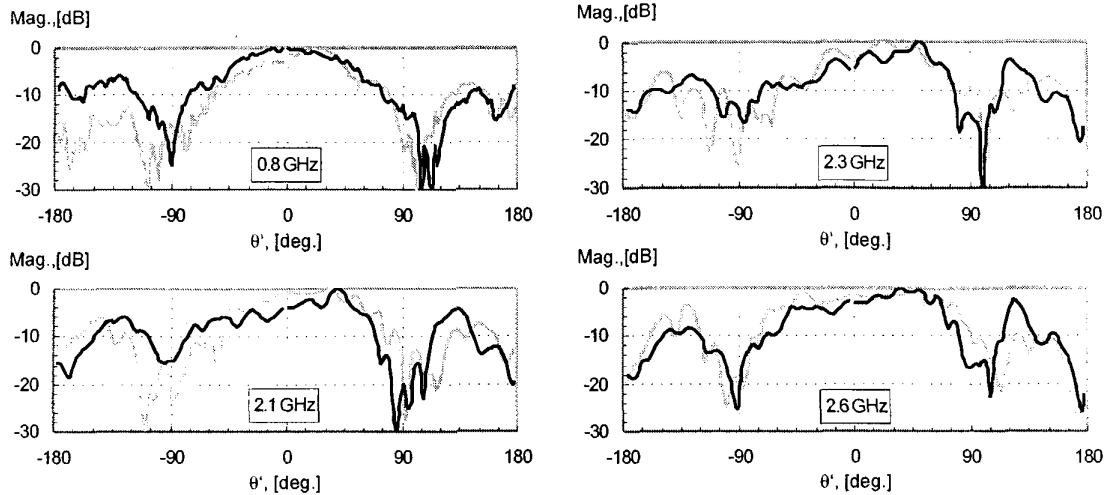


Figure 7. Measured  $\theta$ -cuts for  $\phi = 0^\circ$  (solid) and for  $\phi = 90^\circ$  (grey). Positive values of  $\theta'$  corresponds to  $\phi = \phi_0$ ,  $\theta = \theta'$  and negative value of  $\theta'$  corresponds to  $\phi = \phi_0 + 180^\circ$ ,  $\theta = -\theta'$ , with respect to the polar orientation of the spiral antenna at frequencies of 0.8, 2.1, 2.3, and 2.6 GHz.

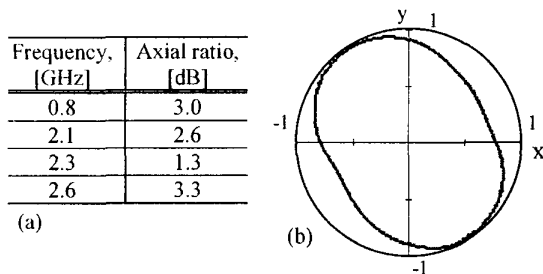


Figure 8. Measured Axial Ratio vs. frequency (a) and the measured polarization ellipse at a frequency of 2.6 GHz (b).

The polarisation ellipse is measured in order to calculate the axial ratio ( $AR$ ). The polarisation ellipse is somewhat elliptical at a frequency of 2.6 GHz as can be seen in Figure 8 (b). The axial ratio is less than 3.3 dB in the frequency range from 0.8 GHz to 2.6 GHz.

The antenna is designed to meet conditions where circular polarisation is required. A commonly used criterion is that the axial ratio should be less than 6 dB [6]. The presented spiral antenna satisfies this criterion.

### Conclusions

A spiral antenna is designed and prototyped for the FR-4 substrate. A balun is designed and prototyped for the Duriod substrate. The electromagnetic simulation program, IE3D, has been used to simulate the performance of a spiral antenna and a balun.

Good agreement between the numerical results and the measured results obtained using a network analyser in the frequency range from 300 kHz to 5 GHz. The measured return loss for the fabricated spiral antenna shows a slightly better performance than the simulated results, which is mainly due to computer capacity limitations. The measured return

loss is better than 10 dB over a 9 to 1 bandwidth from 0.4 to 3.8 GHz

The simulations and the measurements of the spiral antenna show that the radiation pattern and the input impedance are essentially constant over a bandwidth larger than 11 to 1.

Measurements in an anechoic chamber from 0.8 GHz to 2.6 GHz are made showing an axial ratio of less than 3.3 dB and a directivity in the range between 2.7 and 6.6 dB.

The constructed uniplanar spiral antenna and the balun is very well suited to be used in a stepped frequency ground penetrating radar (GPR) for humanitarian demining due to the very wide bandwidth, circular polarisation, relative small size, and being uniplanar.

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