World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:11, No:1, 2017

An Electrically Small Silver Ink Printed FR4 Antenna for RF Transceiver Chip CC1101

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***Abstract*—**An electrically small meander line antenna is designed for impedance matching with RF transceiver chip CC1101. The design provides the flexibility of tuning the reactance of the antenna over a wide range of values: highly capacitive to highly inductive. The antenna was printed with silver ink on FR4 substrate using the screen printing design process. The antenna impedance was perfectly matched to CC1101 at 433 MHz. The measured radiation efficiency of the antenna was 81.3% at resonance. The 3 dB and 10 dB fractional bandwidth of the antenna was 14.5% and 4.78%, respectively. The read range of the antenna was compared with a copper wire monopole antenna over a distance of five meters. The antenna, with a perfect impedance match with RF transceiver chip CC1101, shows improvement in the read range compared to a monopole antenna over the specified distance.

***Keywords*—**Meander line antenna, RFID, Silver ink printing, Impedance matching.

I. INTRODUCTION

A significant amount of research is focused on electrically small antennas (ESAs) in the last few years. ESAs can be enclosed in a sphere of radius *r* such that: $kr \leq 1$, where *k* is the wave number at the operating frequency [1]. Small antennas are known for low radiation efficiency and narrow bandwidth because of their small resistance and large reactance, resulting in poor impedance match to commonly used transmission lines [2].

Radio frequency identification (RFID) is the wireless use of electromagnetic fields to transfer the data, for the purposes of automatically identifying and tracking the objects with the use of antennas [3]. These RFID applications demand ESAs with large resistance and capacitive/inductive reactance at the frequency of interest. Son et al. provided a design solution for RFID antennas using inductively coupled loop feed [4]. Marrocco [5] provided the survey of various size reduction and impedance matching techniques for ultra-high frequency (UHF) RFID antenna design. These techniques include T-match, inductively coupled loop and nested slots. It was concluded that T-match leads to inductive reactance for half wave dipoles, for all the geometric ratios of original dipole and T-match. For ESAs, T-match leads to capacitive reactance but with a very large real part of impedance, which in some cases is undesirable. Inductively coupled loop and nested slots can also be used to make the inductive antennas due to energy storing capability of these structures.

Bandwidth is an important parameter of the antennas designed for RFID applications. The fractional matched voltage standing wave ratio (VSWR) bandwidth of the antenna was defined as [6]:

$$FBW(f_0) = \frac{f_+ - f_-}{f_0} \tag{1}$$

where, f_+ and f_- are the frequencies on either side of resonant frequency (f_0) for a fixed value of VSWR. Equation (1) can be used to measure the 3 dB or 10 dB fractional bandwidth of any tuned antenna with a sufficient condition that first order derivatives of real and imaginary part of antenna impedance do not change significantly over the bandwidth.

Loo et al. [7] verified that the agreement between simulated and measured scattering parameter (S_{11}) of the antenna for RFID chips would be better if the variable chip impedance over the entire frequency range was taken into account. The reflection coefficient (Γ) for matching complex antenna impedance to the complex chip impedance is given in (2):

$$\Gamma = \left(\frac{Z_a(f) - Z_c(f)}{Z_a(f) + Z_c(f)}\right) \tag{2}$$

$Z_a(f) = R_a(f) + jX_a(f)$ and $Z_c(f) = R_c(f) + jX_c(f)$ are the antenna and chip impedance, respectively, varying over the entire frequency range. For maximum power transfer between antenna and chip, $Z_a(f)$ and $Z_c(f)$ should be complex conjugate of each other at the resonant frequency (f_0).

Circuits in plastic (CiP) technology of embedded electronic components [8] is a technique of manufacturing completely waterproof circuits inside their enclosure in one thermal process step. Silver ink can be used as a conductor instead of copper to reduce the environmental impacts of the manufacturing process. The impact of reduced conductivity on antenna performance was investigated in [9]. The ant colony algorithm was used to optimize small meander line antennas in a fixed area to find the highest and lowest resonant frequency structures for the fixed grid size [10]-[12].

The radiation efficiency of the antenna is an important parameter in RFID applications. It can be measured by various methods [13]-[15], however, the Wheeler cap method is considered to be the most accurate method [13]. The antenna is inserted in a sealed metallic container and efficiency is found from the difference of the reflected waves (S_{11}), for the antenna inside the cap and in free space. Shahpari et al. [16] reported

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various antenna designs optimized for highest radiation efficiency and lowest resonant frequency for a fixed grid size.

CC1101 is a low-cost UHF transceiver chip designed for very low-power wireless applications. The data sheet of CC1101 provides the chip impedance at three discrete frequencies i.e. 315, 433 and 868 MHz, respectively. The values are provided in Table I. The antenna for impedance match to CC1101 at 433 MHz requires a very large resistive part i.e. R_a=116 and capacitive reactance $X_a = -41$ to conjugate match for the complex chip impedance.

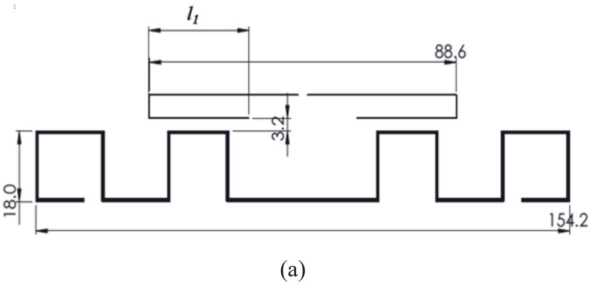
TABLE I
COMPLEX IMPEDANCE OF CC1101 AS A FUNCTION OF FREQUENCY FROM DATA SHEET

Frequency (MHz)	Differential load impedance (Ω)
315	122+j31
433	116+j41
868	86.5+j43

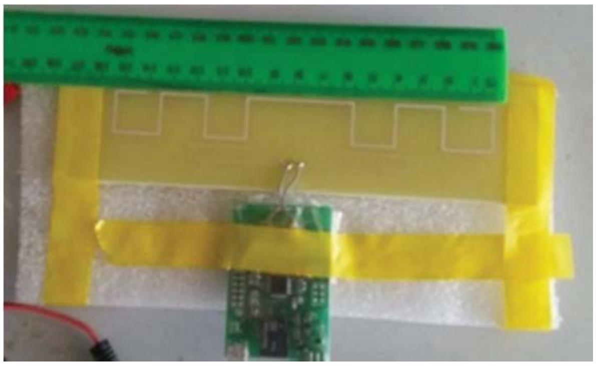
This article reports design and measurement results of a meander line dipole optimized for impedance match with a CC1101 transceiver chip for 433 MHz applications. The C-match structure was introduced to the original meander line antenna [16] to meet the impedance matching requirements of a RF transceiver chip CC1101 at the desired frequency. The scattering parameter, fractional bandwidth, radiation efficiency and read range of the antenna are reported.

II. ANTENNA DESIGN

A meander line antenna design was optimized using 3 mm FR4 substrate (permittivity 4.3, loss tangent 0.025). The silver ink was chosen as a conductor with conductivity 4.3 x 10^6 S/m (see "Electrodag 479SS technical data sheet") used in simulations [17]. The simulated design and dimensions of the antenna are included in Fig. 1 (a). The largest dimension of the antenna was 154.2 mm, being 0.22 fraction of the free space wavelength λ_0. The design was fabricated with silver ink using the CiP technique [8] with a screen having a mesh count of 90 threads per square centimeter. The printed design was cured at elevated temperatures (93 ^{0}C) for 15 minutes. Conductive epoxy was used for solderless electronic connections. Fig. 1 (b) shows the silver ink printed FR4 antenna connected with a beacon containing CC1101. Two standard straight copper wire monopole antennas (operating at 433 MHz) of length l = 17.3cm were also fabricated to compare the read range of meander line antenna design.



(a)



(b)

Fig. 1 (a) Simulated silver ink FR4 design with dimensions (in mm), (b). Fabricated silver ink FR4 antenna connected to beacon with CC1101

The aim of the meander line antenna design was to provide the impedance match with an RF transceiver chip CC1101 to improve the read range. A C-shaped matching structure (track width w_1 = 0.2 mm) was included in the meander line antenna (track width w_2 = 0.8 mm) design optimized for highest radiation efficiency [16]. The C-match structure provides more freedom to the designer to provide the impedance matching solution for RFID applications, as compared with the previously defined impedance matching techniques (T-match, loop and nested slots). The open terminals of the C-match can be tuned even after the fabrication of the antenna to obtain the desired operating frequency, which was not the case for previously described techniques [4], [5].

III. RESULTS AND DISCUSSION

The complex impedance of CC1101 was interpolated over the frequency range 350-500 MHz using data of Table I (see Fig. 2). This variable chip impedance was used as reference in simulations [17].

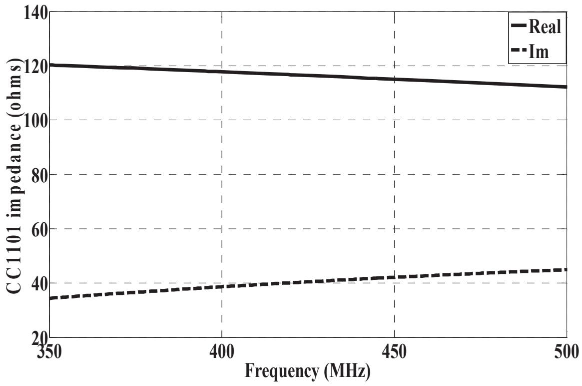


Fig. 2 The interpolated impedance of RF transceiver chip CC1101 over the frequency range 350-500 MHz

The impedance of silver ink printed FR4 design was simulated (see Fig. 3) for three different variations of length l_1 (mentioned in Fig. 1 (a)) to show the significance of the design. While the spacing between antenna structure and C-match helps in tuning the reactance of the antenna, the ratio of track widths (w_2 / w_1) help in adjusting the resistance of the antenna as in case of loop [4], the variation of l_1 gives one more degree of freedom to the designer to vary the impedance of the antenna over a wide range. It helps the designer to make the antenna inductive or capacitive at the frequency of interest. Three different cases are shown in Fig. 3. The results indicate that the real part of the impedance (R_a) increases when l_1 is varied from 9 mm to 29 mm. On further increase of length l_1 i.e. 44 mm, R_a decreases again. The reactance of the antenna increases with the increase of l_1. It becomes highly inductive along with a low real part (R_a), when the C-match becomes a closed loop for l_1 = 45.5 mm (not shown here). The l_1 = 29 mm was suitable for impedance match with CC1101 at 433 MHz in simulations [17]. However, the fabricated antenna was tuned by increasing the length l_1 by 1 mm to make the antenna resonant at $f_0 = 433$ MHz with a desired $Z_a(f_0)$=116 – j41.

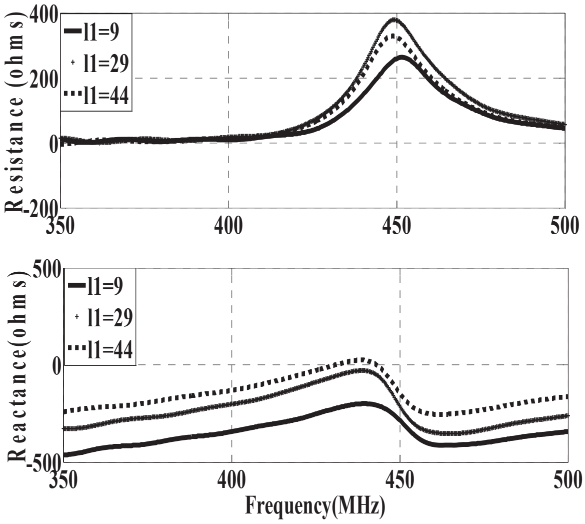


Fig. 3 Impedance (ohms) of silver ink printed FR4 meander line antenna design for three different variation of l_1 over the frequency range 350-500MHz

The simulated and measured scattering parameter S_{11}(dB) of the antenna calculated using (2) is shown in Fig. 4. The fabricated antenna is perfectly matched to the chip at 433 MHz. The measured S_{11}(dB) result was found to be in good agreement with the simulation. The measured 3 dB and 10 dB fractional bandwidth of the antenna (calculated using (1) was 14.5% and 4.78%, respectively.

The radiation efficiency (η_r) of the antenna was measured using Wheeler cap method [13]. A cylindrical container with 8.8 cm diameter and 16 cm height was used as Wheeler cap, which led to an η_r of 81.3% at resonance (see Fig. 5). The result was in good agreement with the simulated radiation efficiency at 433 MHz.

The experimental setup for the read range measurement of silver ink printed FR4 antenna over a distance of five meters is shown in Fig. 6. Fig. 6 (a) shows arrangements for read range measurement between monopole to monopole and (b) shows communication between monopole and meander line antenna. The antennas were at the sufficient height from the ground to reduce the effect of reflections from the earth's surface. All the fabricated antennas were connected to CC1101 transceiver chip for measurement of read range at 433 MHz.

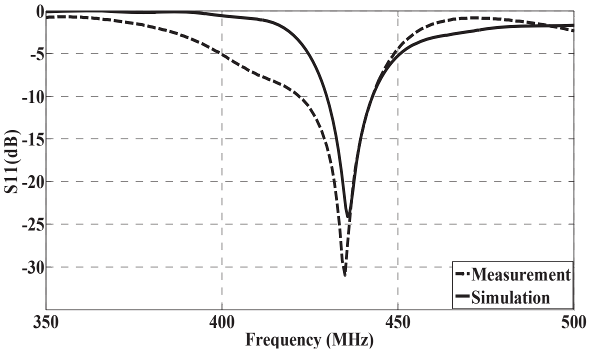


Fig. 4 S_{11} (dB) of meander line antenna (simulation vs measurement) over the frequency range 350-500MHz

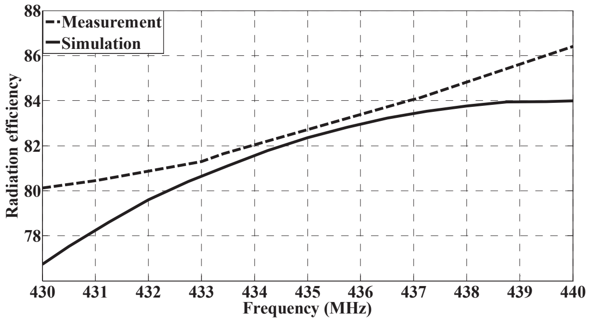


Fig. 5 Radiation efficiency (η_r) of meander line antenna (simulation vs measurement) at resonance (433 MHz)

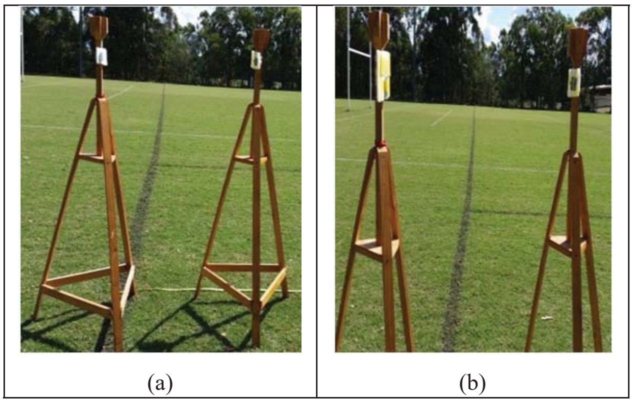

(a)
(b)

Fig. 6 The experimental setup for read range measurement of the FR4 meander line antenna over a distance of 1-5 meters (a) monopole to monopole (b) monopole to meander line antenna

A comparison of the read range of the two mentioned scenarios (Figs. 6 (a) and (b)) is shown in Fig. 7. The results provide a comparison of logarithmic power log (P) received by meander line antenna matched to CC1101 and a standard wire monopole antenna over the logarithmic variation of distance log (d) for 1<d<5 meters. The transmitter antenna was standard wire monopole antenna in both the cases. The meander line antenna matched to CC1101 (with largest dimension: l = 15.4cm) receives more power than a standard wire monopole antenna (l = 17.3cm) over the specified distance showing an increase in the read range. The equations of fitted straight lines on the measured data for both cases are also included in the figure.

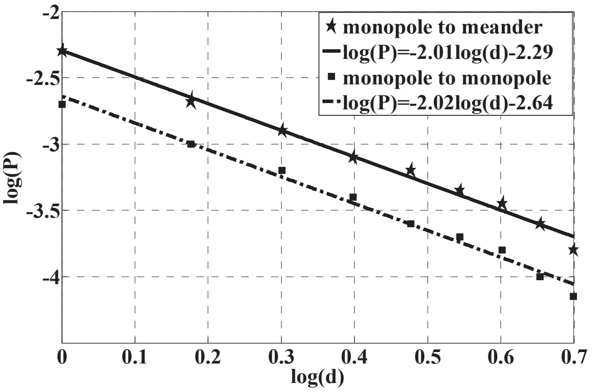


Fig. 7 The logarithmic power log (P) received between monopole to monopole (dotted line) and monopole to meander line (solid line) antennas over logarithmic distance log (d)

IV. CONCLUSION

An electrically small silver ink printed FR4 antenna was designed for impedance match with an RF transceiver chip CC1101. The C-shaped impedance matching structure offers flexibility to the designer to match the antenna impedance with a wide range of RFID chips. The design is tunable after fabrication because of open ended C-match structure. The meander line antenna matched with CC1101, with a radiation efficiency of 81.3%, which shows larger read range than a copper wire monopole antenna of standard size operating at 433 MHz. The CiP technology was used for fabrication process to replace the traditional printed circuit board (PCB) designs. The design is recyclable and environment friendly, as it eradicates the need of copper which is a major pollutant in the environment.

ACKNOWLEDGMENT

Farhat Majeed is highly thankful to Griffith University for an HDR scholarship. The project was supported financially by ARC DP130102098 from the Australian Research Council.

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