Near-Field Loop Antenna for the UHF RFID Reader

Peng Yang, Yan Li, Li-Jun Jiang, and Feng Yang

Abstract—A loop antenna for near field readers is proposed. Through periodic interdigital capacitors, the phase of the current on the loop is compensated and kept in phase. Hence, a loop with a perimeter of one wavelength at 900 MHz achieves a uniform near magnetic field distribution inside the loop. A novel method is proposed to evaluate the performance of the coplanar waveguide (CPW) to coplanar stripline (CPS) transition, which is used as a balun for the feeding network in this paper. This loop antenna has a 70 MHz operating bandwidth and 12 cm maximum reading range when the output power is 24 dBm, which is suitable for most near field radio frequency identification (RFID) applications.

Index Terms—Loop antenna, near field, reader antenna, radio frequency identification.

1. Introduction

Radio frequency identification (RFID) system has been widely used in many applications such as logistics and supply chain management, warehouse tracking systems, book keeping at libraries, and modern ID cards. The common working spectrum of RFID systems are the LF (low frequency 125 kHz/134 kHz), HF (high frequency 13.56 MHz), UHF (ultra high frequency 860 MHz–960 MHz), and MW (microwave 2.4 GHz–2.45 GHz) [1]. Among them, the LF and HF belong to the near field system. This kind of system is widely used for smart cards (such as ID cards, and transportation cards) and access control systems in libraries, bookstores, or supermarkets. The principle of the near field RFID system is the inductive coupling: the energy is transferred from the reader to the tag through the magnetic field. Hence, the reading range of the near field system is very limited, usually only a few centimeters. Compared with the near field system, the UHF and MW bands are used the far field system because the reader can launch a propagating electromagnetic wave. Hence, far field systems have a longer read distance. The tag can be detected by the reader at a location of several meters away.

Recently, there are big interests in UHF near field systems due to their robust performance, high data transmission rate, and superior read speed. One of the key technologies to this system is the reader antenna design. Usually, we use a loop as the near field antenna. It is well known that at LF and HF bands, the size of the simple inductive loops is far smaller than the operating wavelength. These loops can be regarded as “electrically small” loop. Hence, the current on the loop is almost uniform and the magnetic field distribution is also uniform. However, at the UHF band, the current distribution on the loop departs from the uniform distribution. This causes significant impact on the magnetic distribution when the loop’s circumference is greater than about 0.1λ (where λ is the operating wavelength). Hence, the challenge is on how to design a large loop while keeping the magnetic field distribution uniform (or keeping the current as constant).

One efficient solution to this problem is to divide the antenna into short segments, and add some lumped capacitors between each pair of segments [2]. The lumped capacitors, the distributive inductor of the segment and some resistive loss form a RLC series circuit. By choosing the proper capacitance of the capacitors, the circuit can resonate at desired frequency. However, in [2], a resistor was added to achieve the desired impedance, which would lead to a big loss. On the other hand, using lumped elements will complicate the fabrication and increase the cost. Recently, there are other novel designs using the segmented printed loop or a solid-line loop with stub phase shifters [3],[4]. These designs can achieve a uniform magnetic distribution in a large loop with a circumference about 2λ, but the reading range is very limited, no more than 7 cm.

In this paper, we propose a simple design using interdigital capacitors to provide sufficient capacitance in the loop structure. A strong magnetic field in a loop with a circumference about λ is achieved. The circuit model will be extracted to explain the working principle of this loop antenna. A concise coplanar waveguide (CPW) to coplanar stripline (CPS) transition network is designed to connect the balanced loop antenna with the unbalanced coaxial cables. Simulation and measurement results are provided at the end of this paper to demonstrate the performance of this novel UHF near field reader antenna.

2. Antenna Design

The current distribution on a simple loop antenna can be represented approximately by
\[ I(\phi) = I_0 e^{-j(\alpha + \phi)} \]  

(1)

where \( \alpha \) denotes the loss (including the ohmic loss, dielectric loss and radiation loss) and \( \phi = \beta p \) is the phase delay along the loop (\( \beta \) is the phase constant and \( p \) is the path length). From (1), we can easily find that if the circumference of the loop is equal to \( \lambda \) (the wave length at the working frequency), the current falls to zero and reverses direction about a quarter wave length away both ends of the loop. Hence, the magnetic field in the center of the loop goes to zero. This occurs at a loop with a radius about 5 cm at 900 MHz. Our goal is to design a new kind of loop with a circumference about \( \lambda \) while keeping the current on the loop uniform (in phase).

To achieve this, we can divide the loop into several segments. If the number of the segments \( N \) is large enough, the length of each unit cell \( \Delta d \) will be far smaller than the operating wavelength \( (\Delta d \ll \lambda) \). In this case, the current distribution on each segment seems uniform. The equivalent inductance of each segment can be estimated approximately from that of a loop with a constant current distribution

\[ L = \frac{\mu a}{N} \ln \left( \frac{8a}{0.25w} \right) - 2 \text{ (Henry)} \]  

(2)

where \( a \) is the radius of the loop, \( w \) is the width of the loop strip, and \( \mu \) is the permeability. Note that (2) is not the same as the equation given by [6]. The difference is that the loop in [6] is supposed to be a wire structure but here the loop is printed on the printed circuit board (PCB). The relationship between the electrical equivalent radius \( a_e \) of the wire and the strip for the inductance calculation can be expressed by [5]

\[ a_e = 0.25w. \]  

(3)

It can be seen that if we introduce a proper capacitance \( C \) into each segment, the equivalent series RLC circuit can resonate at the desired operating frequency \( \omega_0 = 1/\sqrt{LC} \), the phase shift through this segment becomes zero [6], and the impedance is equal to distributive loss \( R \). Hence, there is no phase delay in each segment and the current over the full loop becomes uniform and in phase. To provide such a capacitance, we employ an interdigital structure. The value of the planar interdigital capacitance can be determined by [8]

\[ C = \frac{1}{\omega_0^2 L} = \frac{\varepsilon_r K(k)}{18\pi K'(k)}(n-1)l \times 10^{-9} \text{ (Farad)} \]  

(4)

where \( n \) is the number and \( l \) is the length of fingers, respectively. \( K(k) \) and \( K'(k) \) are the complete elliptic integrals of the first kind and its complement, where \( k \) can be calculated by

\[ k = \tan^2 \left( \frac{w\pi}{4(w+s)} \right) \]  

(5)

where \( w \) is the width of the finger and \( s \) is the distance between two fingers. Both of them are in the units of meter. The approximate value of \( K(k)/K'(k) \) can be found in [7]. Fig. 1 shows the geometry of the loop and one unit segment. In Fig. 1, the loop has been divided into 16 segments. Each unit segment has an interdigital capacitance with 7 fingers. It is noted that the equations provided above cannot accurately model the inductance and capacitance values. But they can provide initial values. After fine tuning, the uniform current distribution at the operating frequency can be obtained.

In order to evaluate the performance of the proposed loop antenna, a conventional loop without the capacitance loaded with the same size is used for comparison. Two orthogonal baseline (\( x=0 \) and \( y=0 \)) positions with different heights are chosen to test the field uniformity. The magnitudes of the magnetic field at the resonant frequency along the selected baselines are shown in Fig. 2. It is seen that the proposed antenna can generate much more uniform and stronger magnetic field than the conventional one because of the reason discussed above. Secondly, as the height of the baselines increases from \( z=1 \) mm to \( z=50 \) mm, the magnitude of the magnetic field close to the center of the loop becomes larger than that close to the edge. This is because the former diverges slower than the latter when the height increases. Thirdly, the magnetic field distribution is symmetrical along \( x \)-axis but not along \( y \)-axis due to the ohmic loss, dielectric loss, and some radiation loss.

![Fig. 1. Geometry of the proposed UHF near field loop antenna, where \( a=46 \) mm, \( l=6.3 \) mm, \( s=0.7 \) mm, \( w=1 \) mm, \( N=16 \) and \( n=7 \). Each unit segment can be represented by a series RLC circuit.](image-url)
The loop antenna is a balance structure and needs a balanced feed. However, the subminiature version A (SMA) connector is unbalanced. A CPW to CPS transition was used as a balun for the antenna feeding. To evaluate its performance, the common mode rejection ratio (CMRR) is used as a balun for the antenna feeding. To evaluate its performance, the common mode rejection ratio (CMRR) is defined as:

\[ \text{CMRR} = \frac{S_{cm}}{S_{di}} \]

where \( S_{cm} \) is the common mode transmission coefficient from port 1 to port 2; \( S_{di} \) is the differential mode transmission coefficient from port 1 to port 2.

Fig. 3. Concept of CMRR.

Two categories of CPW to CPS transitions are used in this work as shown in Fig. 4. The first category\(^\text{[9]}\) has a better CMRR but a bigger size and a narrower bandwidth because of the quarter wave length branch line. The second kind\(^\text{[9]}\) has the more compact size and wider bandwidth but its CMRR is not good enough. From our simulation, the CMRR for the first transition is about \(-31 \, \text{dB}\), while it is \(-14.8 \, \text{dB}\) for the second one. It is noticed that the performance of the loop antenna seems insensitive to the balun in our experiments, because the near field reader antenna is working through the inductive coupling rather than propagating wave.

A small loop antenna for some handheld devices using the same idea is also developed. The radius is 25 mm and 7 interdigital capacitors are used. Unlike the large loop, the real part of the input impedance of the small loop is far below 50 \( \Omega \) due to the small perimeter (it is only about 10 \( \Omega \)). Hence, a matching network is needed. If the operation frequency is below 1 GHz, probably the simplest type of the matching network is the “L section”, which uses two reactive elements to match arbitrary impedance\(^\text{[10]}\). As shown in Fig. 5, \( Z_L \) defines the loading, \( X \) and \( B \) are either inductors or capacitors. Compared with the resistor matching method in [1], the L section matching network used in this paper has low loss and higher efficiency. Using the Smith chart, we can tune the value of the inductors and capacitors to make the small loop matched to 50 \( \Omega \). For our design, they are both inductors and the values are 1.5 nH and 5.6 nH, respectively.

Fig. 2. Comparison of magnetic field distribution in the loop along different baselines: (a) \( y=0, \, z=1 \text{ mm} \) (b) \( x=0, \, z=1 \text{ mm} \), (c) \( y=0, \, z=10 \text{ mm} \), (d) \( x=0, \, z=10 \text{ mm} \), (e) \( y=0, \, z=50 \text{ mm} \), and (f) \( x=0, \, z=50 \text{ mm} \).

Fig. 4. Baluns used for the new loop antenna (the dashed lines are bond wires): (a) the first balun and (b) the second balun.

Fig. 5. Matching topology of the small loop antenna.
3. Prototypes and Measurements

Fig. 6 shows the prototypes of the proposed antennas. Both big loop and small loop were designed and fabricated: the bigger one with 15 interdigital capacitors and the smaller one with 7 interdigital capacitors. They were printed on a FR4 substrate with $\varepsilon_r = 4.2$ and $\tan \delta = 0.02$. The thickness of the FR4 is 1.6 mm. The operating frequency is around 900 MHz (note that the resonant frequencies calculated by approximate equations were about 890 MHz for the big loop and 980 MHz for the small loop). The $S_{11}$ of full wave simulations and measurements are plotted in Fig. 7. The bandwidth of the big loop is about 45 MHz (from 885 MHz to 930 MHz) and 12 MHz for the small loop (from 908 MHz to 920 MHz). To test their performances, a commercial loop antenna and two tag antennas designed by Hong Kong LSCM (shown in Fig. 8) were used for the comparison. The maximum reading ranges with different output powers were measured, which are shown in Table 1. From it we found that our designs achieve a good performance compared with the commercial ones.

![Fig. 6. Prototypes of the proposed UHF loop antenna. The balun and the matching network can also be seen in the figure: (a) big loop with 15 interdigital capacitances loaded and (b) small loop with 7 interdigital capacitances loaded.](image)

![Fig. 7. Simulated and measured $S_{11}$ of the proposed UHF loop antennas: (a) big loop and (b) small loop.](image)

![Fig. 8. Commercial loop antenna and tags used for testing and comparison.](image)

4. Conclusions

A near field loop antennas with interdigital capacitors were designed for near field RFID readers. This design guarantees the uniformity of the current on the loop and thereby the uniformity of the near magnetic field on the loop. The balun and the matching network were also designed for this antenna. The CMRR is employed to evaluate the performance of the balun. The proposed loop antennas were fabricated and compared with commercial loop antennas. It is demonstrated that the proposed antenna has better performance.
References


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