Design of UWB Small Loop Antenna with Continuous Tuning Frequency 1–10 MHz

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***Abstract*— This paper presents a novel UWB small loop antenna with continuous tuning frequency 1–10 MHz. A prototype of the design is fabricated and measured to demonstrate the effectiveness of the concept. Accurate frequency tuning is achieved by incorporating tolerances of the electronics, utilizing accurate circuit model, and extrapolating capacitor values through high order polynomial curve fitting.**

Keywords*— *Ultra-wideband; UWB; loop antenna; HF; VHF; frequency tuning;

I. Introduction

Small loop antennas have been widely used as field probes and ground penetration radars (GPR) in HF (3-30 MHz) and VHF (30–300 MHz) bands [1]. In order to have higher sensing capabilities, the major requirements for the antenna include wide frequency tuning range, relatively higher power handling capability, and low loss. To achieve wide frequency range operation, UWB antennas with multiple resonances [3] are often seen being used for 3.1-10.6 GHz with FCC standards; whereas, narrow-bandwidth antennas with large tuning range [4] are more suitable for HF and VHF bands, due to the narrow-bandwidth nature of electrically small antennas. To achieve high power handling capability and low loss feature, electronic components need to be carefully selected and characterized.

In this paper, a UWB small loop antenna with continuous tuning frequency 1–10 MHz is presented. In Section II, the design of small loop at a single frequency is studied. In Section III, a loop antenna that has a continuous frequency tunability over wide bandwidth is designed. A recipe of electronic component values is given through curve fitting. In Section IV, the measured and simulated results are presented.

II. Design of Small Loop At Signle Frequency

The configurations and geometry of an electrically small loop antenna are shown in Fig. 1 for a potential rover application. The proposed structure is a $1\ m \times 1\ m$ square loop antenna, which has a series tuning capacitor C_r, a parallel inductor L_r, and another series capacitor C_m that connects to one end of the input terminal. The three lumped elements essentially constitute a Tee impedance matching network for the loop antenna. The small radiation resistance of an electrically small antenna leads to its high Q-factor. Thus, matching a small loop antenna's input impedance to the 50-Ω port impedance with a single set of C_r, C_m and L_r is only possible within a narrow bandwidth.

For systematic design of the small loop antenna, an accurate circuit model is desired. The analytical input impedance of an electrically small $1m \times 1m$ square loop antenna with rectangular-cross-section copper wire (2cm wide and $30\,\mu m$ thick) can be calculated using classical theories in [1] as follows.

$$\begin{aligned}\text{Input impedance} = Z_{in} &= R_{in} + jX_{in} \\ &= (R_r + R_L) + j(\omega L_A + \omega L_i)\end{aligned} \tag{1}$$

Where R_r is the radiation resistance – $(5120\pi^2/\lambda^4)$, R_L is the ohmic resistance – $\left(4R_p + 1.039 \cdot 10^{-5} \cdot \omega^{1/2}\right)$, L_A is the loop inductance – $(3425.2nH)$, and L_i is the internal inductance of the loop conductor –$\left(1.039 \cdot 10^{-5} \cdot \omega^{-1/2}\right)$. ω is the angular frequency, λ is the wavelength and R_p is the ohmic resistance per unit length due to the proximity effect, which is usually small for small loop antennas. R_p is initially set to be 0.02Ω for preliminary analysis and later optimized by fitting the analytical input impedance to CST full-wave simulation results.

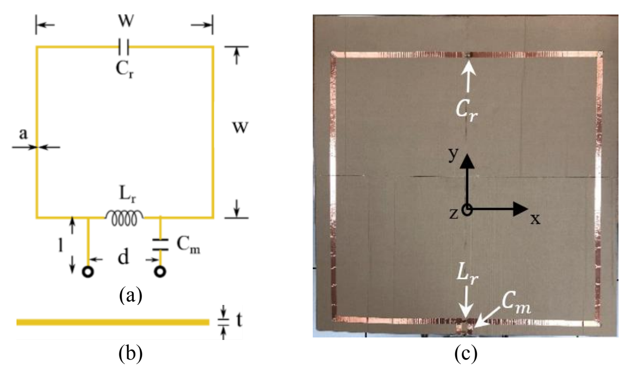


Fig. 1. The proposed small loop antenna that can operate from 1 to 10 MHz by tuning Cr and Cm values (antenna material: copper, $w = 1m, a = 2cm, l = 4cm, d = 2cm, t = 30\mu m$). Not-true-to-scale illustrative view of the geometry, (a) top view, (b) side view. (c) Farbricated prototype.

A circuit model of the proposed small loop antenna, incorporating analytical input impedance of the main loop, is shown in Fig. 2. It is critical that the equivalent series resistance (ESR) of the used inductor is included in the circuit model because the input impedance is very sensitive to the inductor ESR in the structure and as a result ESR has a large impact on the C_r and C_m in impedance matching. Large ESR may increase the loss of the loop antenna and decrease system sensitivity. Inductors with non-magnetic cores is selected to guarantee low ESR at 1–10 MHz. $1\mu H$ inductors and $380nH$ inductors with air core were measured using Agilent 4294A impedance analyzer. The series connected inductors have a total inductance

1282.5 - 1439nH and an ESR 1.7 - 3.9Ω over 0.8–10MHz. It is essential that the frequency-dependent ESR of the inductor components is incorporated in both the circuit model and Computer Simulation Technology (CST) full wave simulation.

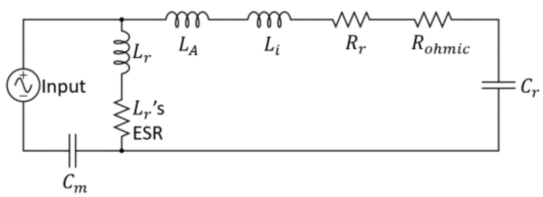


Fig. 2. The circuit model of the small loop antenna including the radiation and ohmic loss resistance (Rr,R_L), the loop and internal inductance (L_A, L_i). The inductor Lr, and capacitors C_r, C_m form a T matching network.

III. Continuous Frequency Tuning Over Wide Frequency Band

Circuit model shown in Fig. 2, with calculated loop antenna parameters and measured inductor and capacitor values, is used as the starting point for the impedance matching and frequency tuning at sampled frequency points from 1 MHz to 10 MHz. 5th order polynomial curve fitting functions in Fig. 3 of the C_r and C_m are used to extrapolate their required values throughout the frequencies and achieve continuous frequency tuning.

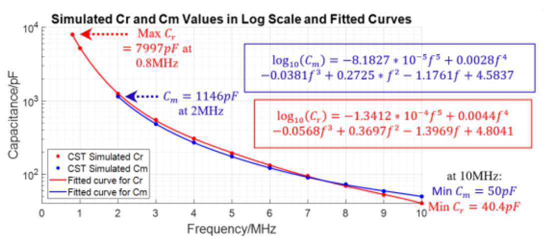


Fig. 3. The required C_r and C_m values at 0.8 to 10 MHz fitted by 5th order polynomial functions. Sampled frequency points at 1–10 MHz are achieved through CST full wave simulation. It is noted that at 0.8 MHz and 1 MHz, C_m is replaced by a piece of copper sheet, so they are not shown in the figure.

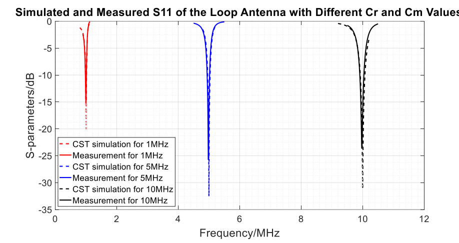
R_p = 0.018 Ω is used in circuit model to achieve the lowest error between calculated and simulated Cr and Cm values. Varactor banks and low loss switches can readily be utilized to tune the resonant frequency continuously over 1–10 MHz.

IV. Measured and Simulated Results

A prototype was built and measured. For construction, 2-cm-wide 30-μm-thick copper foil tapes were used for the loop antenna, and a $1.17\ m \times 1.12\ m$ cardboard was used as support. S_{11} measurements were done for 1 MHz, 5 MHz and 10 MHz, shown in Fig. 4. The simulated and measured S_{11} agree very well. The magnetic field at 6 m away from the loop antenna is plotted using infinitesimal magnetic dipole model and compared with the simulated result. The calculated and simulated results have the same order of magnitude and similar characteristics.

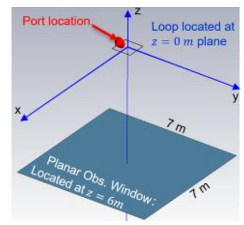
Freq	1 MHz	5 MHz	10 MHz
C_r	$5160pF$	$193.4pF$	$40.4pF$
C_m	$shorted$	$175pF$	$50pF$
$L_r(ESR)$	$1286.9nH(1.7\Omega)$	$1304.4nH(2.3\Omega)$	$1438.8nH(3.9\Omega)$

(a)

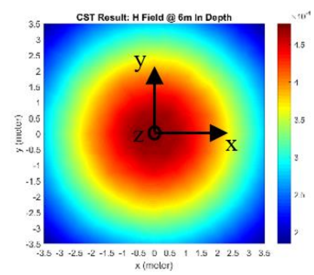


(b)

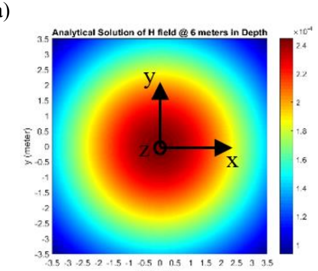
Fig. 4. Simulated and measured S_{11} of the loop antenna with three diferent sets of C_r and C_m. During the measurement, C_r and C_m are tuned for different frequencies, while 11380-nH L_r is fixed, (a) values of the lumped elements, (b) S_{11} comparison.



(a)



(b)



(c)

Fig. 5. Comparison between analytical and simulated magnetic field of the proposed loop antenna at a planar observation window located at 6 m in depth, (a) coordinate system convention, (b) CST simulation, (c) analytical solution.

V. Conclusion

UWB small loop antenna with continuous tuning frequency 1–10 MHz is designed, fabricated and measured to demonstrate the effectiveness of the concept presented in this paper. Excellent S_{11} is achieved throughout the frequencies. Good agreement is observed between calculated and simulated H fields distribution.

VI. Acknowledgement

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