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Self-Resonant Electrically Small Loop Antennas for Hearing-Aids Application

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***Abstract*—Two novel self-resonant electrically small antennas are proposed in this paper, which are designed for hearing aids applications. They are miniaturized by using the capacitive and inductive coupling mechanism between two loops, and the antenna impedance can be matched to a specific value without using any additional matching network and lumped components. The dimension of the proposed antenna is $0.10\lambda_0 \times 0.03\lambda_0$, and it is designed to be resonant at 900 MHz. Both the analytical model and numerical simulations are discussed and explained. The antenna is also fabricated and measured in an anechoic chamber. The measurement methods for electrically small antennas are reported.**

I. Introduction

Hearing-aids already constitute an advanced technology, and wireless communication integrated in hearing-aids will open for a range of completely new functionalities. For this application, there are several requirements that should be satisfied as follows. First, since the power that can be provided by hearing-aids battery is in the μW range, low frequency would be preferred, and thus in this paper the antenna is designed at 900 MHz. Second, the communication distance from hearing-aids to external devices is set to 10 meters and the according link budget must be fulfilled. Third, the demand for compact systems with stringent specifications makes the antenna size reduction a significant challenge. Therefore antenna miniaturization should be one of the key technologies in designing successful wireless hearing-aids. Hence, the above requirements lead us to the area of compact antenna designs for ultra low power and short range wireless communications. This paper aims at designing the miniaturized antennas for hearing-aids application at 900 MHz, by designing the self-resonant small loop antennas, in which the antennas are not only geometrically small but also electrically small.

Electrically small loop antennas are popularly used in short range wireless communications. However, the small loop antenna itself is inefficient and badly matched, and additional matching network is required to make the antenna resonant, in which lumped components may be included. The tolerance and aging of lumped components can result in the change of antenna properties. Recently, a metamaterial-inspired small loop antenna was proposed in [1], where a small loop is covered by a simple mu-negative (MNG) shell.

In this paper, a differential-fed self-resonant electrically small loop antenna is proposed and developed, and the geometry and design variables of this antenna are illustrated in Fig. 1. The working mechanism is based on the coupling between two loops. In this antenna, there are two loops, the small one and the large one, which are connected together and shown in Fig. 1 in different colors. The large loop is effectively closed by the capacitive loading formed by two closely spaced wires. The small loop is covered by the large loop and is excited by a differential feed. The antenna impedance is matched to 50 ohm without any additional matching network and lumped components. The analytical model will be explained in Section. II.

Moreover, if the dimension of two loops are comparable as illustrated in Fig. 2, the antenna represents a single split ring component. The same analytical model can still be applied by considering the capacitive coupling together with the inductive coupling between loops, and thus by proper tuning an ultra small split ring itself can behave as a small resonant antenna, the radiation efficiency of which can be improved.

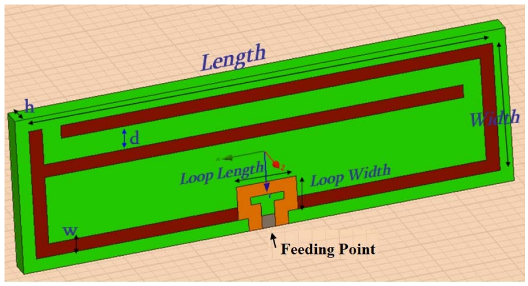

Fig. 1. Geometry of design variables of the self-resonant electrically small loop antenna. (Antenna design 1 for 900 MHz, the dimension is $35mm \times 10mm \times 1.5mm$)

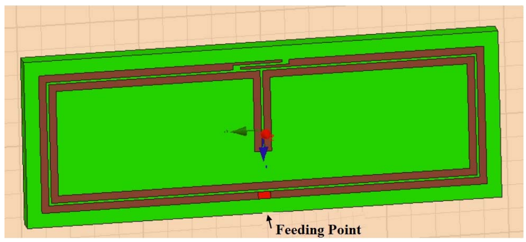

Fig. 2. Geometry of design variables of the self-resonant electrically small split ring antenna. (Antenna design 2 for 900 MHz, the dimension is $36.6mm \times 11.6mm \times 1.5mm$)

II. Antenna Design and Analysis

The antenna working mechanism and the physical model will be explained in this section. For antenna design 1 which is presented in Fig. 1, the antenna system is fed on the small loop. The large loop is coupled to the small loop by the magnetic flux linkage, and the magnetic flux due to the large loop can be approximated by the flux due to two infinitely long wires that carry currents with equal amplitudes and opposite directions. The antenna impedance can be matched to a specific value without using any additional matching network and lumped components by tuning the antenna as follows. First, the imaginary part of the antenna impedance can be tuned to zero since the inductance is compensated by the capacitance involved in the large loop. Second, the real part of the antenna impedance, resistance, can be matched to 50 ohm by tuning the dimension of the small loop.

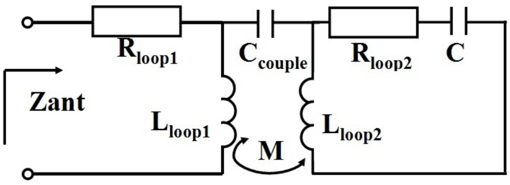

Fig. 3. Analytical Model of Self-Resonant Electrically Small Loop Antenna.

The two loops contained in the antenna can be located on the same layer or opposite layers depending on the specific designs. On the same layer, the small loop can also be placed inside and outside of the large loop, as shown in Fig. 4-5. The mutual inductance is quite different in these two cases, which plays an import role in impedance matching, and the analytical formulas will be derived to illustrate the design rules. Additionally, the antenna shape also has its influence. The hearing-aids application requires the shape of the large loop to be rectangular. While for the small loop, the influence of the shape on impedance matching will be analyzed in the following subsections, which are the rectangular and circular shape respectively .

The analytical model used to explain the working mechanism is illustrated in Fig. 3, and the details of the antenna configuration are presented in Fig. 4-5. The dimension of small loop is L_1 and W_1, and those of the large loop are L_2 and W_2. The smallest distance between the two loops is d. The antenna system is fed on the small loop. R_{loop1} and L_{loop1} are the resistance and inductance of the small loop, and R_{loop2} and L_{loop2} are the resistance and inductance of the large loop respectively. R_{loop2} can be further expressed to be the sum of antenna radiation resistance R_{rad} and ohmic loss resistance R_{loss}, that is $R_{loop2} = R_{rad} + R_{loss}$. C is the capacitive loading existing in the large loop. C_{couple} and M are the mutual capacitance and mutual inductance between two loops. C_{couple} can be influenced by the relative size of two loops. For the antenna design shown in Fig.1, the size of small loop is much less than the large loop, and therefore C_{couple} can be approximated to be negligibly small and only the mutual inductance M contributes to the working mechanism. While for the antenna design 2, illustrated in Fig. 2, the size of the small loop is comparable to the large loop, and both the mutual capacitance C_{couple} and mutual inductance M must be taken into account.

In the circuit model illustrated in Fig. 3, the resistance and reactance of the antenna input impedance Z_{ant} of the antenna can be determined from

$$R_{ant} = R_{loop1} + (\omega M)^2 \frac{R_{loop2}}{R_{loop2}^2 + (\omega L_{loop2} - \frac{1}{\omega C})^2} \quad (1)$$

$$X_{ant} = j\omega L_{loop1} - j\frac{(\omega L_{loop2} - \frac{1}{\omega C})}{R_{loop2}^2 + (\omega L_{loop2} - \frac{1}{\omega C})^2}. \quad (2)$$

Near the resonance condition where $\omega L_{loop2} = \frac{1}{\omega C}$, the resistance and reactance becomes

$$R_{ant} = R_{loop1} + (\omega M)^2 \frac{1}{R_{loop2}} \quad (3)$$

$$X_{ant} = j\omega L_{loop1} \simeq 0 \quad (4)$$

A. Mutual Inductance and Antenna Resistance when the Small Loop is Rectangular

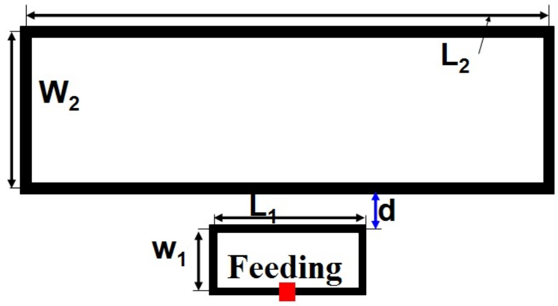

Fig. 4. Rectangular Small Loop Feeding (Small Loop is Outside).

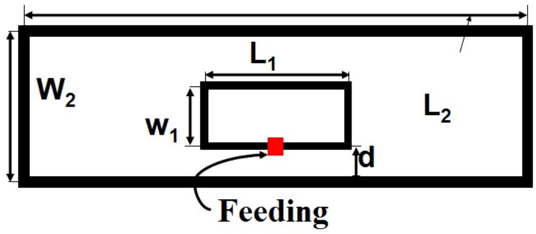

Fig. 5. Rectangular Small Loop Feeding (Small Loop is Inside).

The small rectangular loop can be placed inside or outside the large loop. For the case where the small loop is located outside the large one, as shown in Fig. 4, the magnetic flux due to the big loop is approximated by that due to two infinitely long wires that carry currents with equal amplitudes and opposite directions. Hence the magnetic flux due to two infinitely long wires are opposite, and the mutual inductance M can be determined from

$$M = \frac{\mu_0}{2\pi} L_1 ln \frac{(W_2+d)(W_1+d)}{d(W_1+W_2+d)}, \qquad (5)$$

and the antenna input resistance R_{ant} at resonance is

$$R_{ant} = \frac{1}{R_{loop2}} \{2\pi f \frac{\mu_0}{2\pi} L_1 ln \frac{(W_1+d)(W_2+d)}{d(W_1+W_2+d)}\}^2 \qquad (6)$$

When the small loop is placed inside the large one, as shown in Fig. 5, again the magnetic flux due to the big loop can be approximated by that due to two infinitely long wires that carry currents with equal amplitudes and opposite directions. But the small loop is in between these two wires, the magnetic flux contributions from two infinitely long wires are the same, and thus the mutual inductance is much stronger than that when the small loop is placed outside. The mutual inductance can be determined from

$$M = \frac{\mu_0}{2\pi} L_1 ln \frac{(W_1+d)(W_2-d)}{d(W_2-W_1-d)}, \qquad (7)$$

and the antenna input resistance at resonance is

$$R_{ant} = \frac{1}{R_{loop2}} \{2\pi f \frac{\mu_0}{2\pi} L_1 ln \frac{(W_1+d)(W_2-d)}{d(W_2-W_1-d)}\}^2 \qquad (8)$$

B. Mutual Inductance and Antenna Resistance when the Small Loop is Circular

As shown in Fig. 6-7, the small circular loop can be placed inside and outside the large loop. The dimension of the large loop are L_2 and W_2, and the small loop radius is r. The distance between the two loops is d. Again the magnetic flux due to the big loop can be approximated by that due to two infinitely long wires that carry currents with equal amplitudes and opposite directions. When the small loop is outside the large one, the mutual inductance can be determined from

$$M = \mu_0[\sqrt{(W_2+d+2r)(W_2+d)} - \sqrt{(d+2r)d} - W_2] \qquad (9)$$

and the antenna input resistance at resonance is

$$R_{ant} = \frac{1}{R_{loop2}} \{2\pi f \mu_0[\sqrt{(W_2+d+2r)(W_2+d)} - \sqrt{(d+2r)d} - W_2]\}^2 \qquad (10)$$

When the small loop is inside the large one, the mutual inductance can be determined from

$$M = \mu_0\{W_2 - \sqrt{(d+2r)d} - \sqrt{(W_2-d)(W_2-2r-d)}\}. \qquad (11)$$

and the antenna input resistance at resonance is

$$R_{ant} = \frac{1}{R_{loop2}} \{2\pi f \mu_0[W_2 - \sqrt{(d+2r)d} - \qquad (12)$$

$$\sqrt{(W_2-d)(W_2-2r-d)}]\}^2 \qquad (13)$$

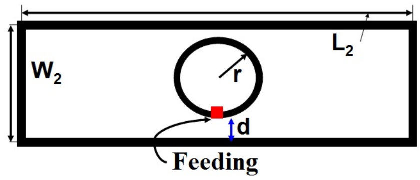

Fig. 6. Circular Small Loop Feeding (Small Loop is Inside).

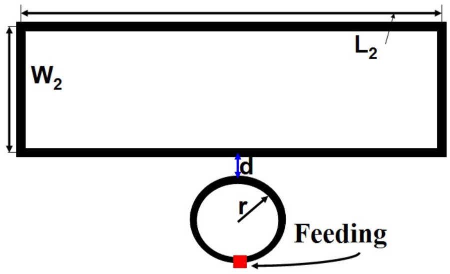

Fig. 7. Circular Small Loop Feeding (Small Loop is Outside).

C. Model Extension to Self-Resonant Split Ring Antennas

The split ring antenna has been recently used in antenna miniaturizations, in which it behaves as the ultra electrically small antenna. However, it has to be excited by an extra small dipole or loop element that contributes to the loss mechanism. In this paper, it was shown by applying this model and tuning properly, a split ring itself can behave as the small resonant antenna, as shown in Fig. 8-9. Therefore the radiation efficiency can be improved.

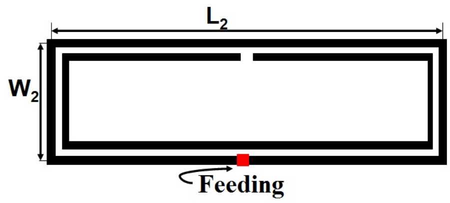

Fig. 8. Self Resonant Split Ring Antenna.

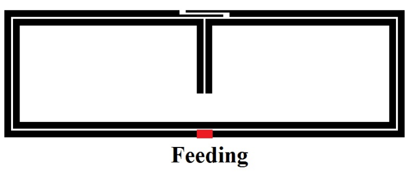

Fig. 9. Self Resonant Split Ring Antenna at 900 MHz.

In our previous analysis, the capacitance between two loops is viewed to be negligibly small, and only the magnetic coupling is considered. While for this self resonance split ring antenna design, both the capacitive and magnetic coupling should be taken into account in the antenna tuning. A design example will be shown in Section. III.

TABLE I
DIMENSION OF SELF RESONANT ELECTRICALLY SMALL ANTENNA DESIGNS (FREQUENCY: AROUND 900MHZ).

	Antenna Dimension	Resonance Frequency	Bandwidth @-10 dB	Bandwidth @-15 dB	Efficiency %	Directivity [dBi]	Gain [dBi]
Design1 Electrically Small Loop Antenna	$Length = 35mm = 0.105\lambda_0$ $Width = 10mm = 0.03\lambda_0$ $LoopLength = 4.5mm, LoopWidth = 1.5mm$ $W = 1mm$, $d = 1.8mm$ Substrate: Rogers 5870 (thickness=1.5mm)	906 MHz	3.3 MHz	1.75 MHz	17%	1.74 dBi	-5.9
Design2 Electrically Small Split Ring Antenna	$L_{loop2} = 36.6mm = 0.109\lambda_0$ $W_{loop2} = 11.6mm = 0.03\lambda_0$ $d_1 = d_2 = d_3 = d_4 = d_5 = 0.2mm$ $L = 6.2mm$, $W = 0.6mm$ $L_1 = 4.6mm$,$L_2 = L_3 = 0.6mm$ Substrate: Rogers 6002 (thickness=1.5mm)	903.2 MHZ	4.5 MHz	2.5MHz	35 %	1.64 dBi	-2.89dBi

III. ANTENNA DESIGNS AND SIMULATIONS

Two electrically small antennas will be presented in this section, based on the designs of Fig. 1-2.

A. *Self Resonant Electrically Small Loop Antenna 1*

For our application, we are aiming at designing antennas around 900 MHz. The dimension of the big loop is fixed to be $35mm \times 10mm$ from which the resistance and inductance of the large loop can be determined first, which are R_{loop2} and L_{loop2}. Then by using equation (8) in the circuit model, the dimension of small loop can be calculated accordingly. Based on this starting point, the antenna is designed and simulated using the commercial software package HFSS [2]. The antenna dimensions are illustrated in Tab. I. The simulated resonance frequency is 906 MHz, and the bandwidth at -10 dB is 3.3 MHz. The radiation efficiency is found to be 17 %. The antenna reflection coefficient and antenna input impedance are given in Fig. 10-11.

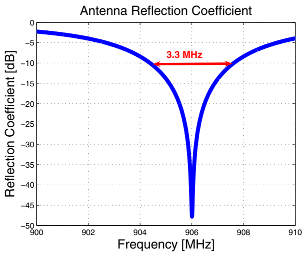

Fig. 10. Antenna Reflection Coefficient.

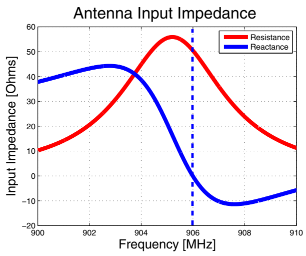

Fig. 11. Antenna Input Impedance.

B. *Self Resonant Electrically Small Loop Antenna 2*

The geometry and design variables of the self-resonant electrically small split ring antenna is illustrated in Fig. 12 and its dimension are given in Tab.1. The simulated resonance frequency is 903.2 MHz, and the bandwidth at -10 dB is 4.5 MHz. The radiation efficiency is found to be 35 %. The antenna reflection coefficient and antenna input impedance are given in Fig. 13-14.

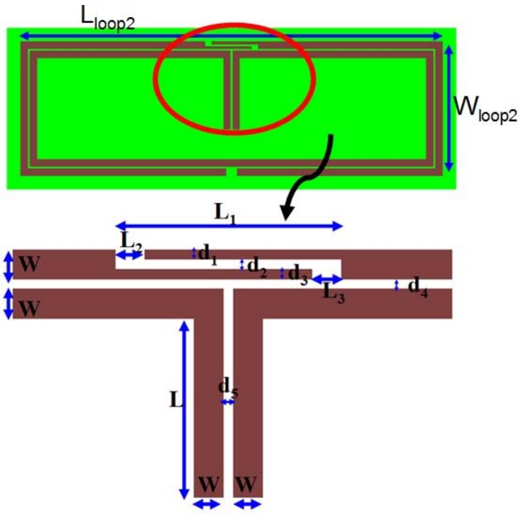

Fig. 12. Geometry of design variables of the self-resonant electrically small split ring antenna.

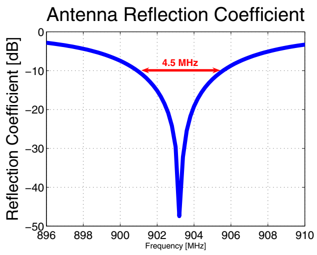

Fig. 13. Antenna Reflection Coefficient.

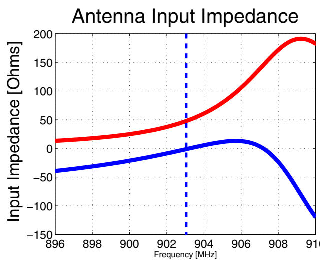

Fig. 14. Antenna Input Impedance.

IV. MEASUREMENT RESULTS

The small loop antenna from design 1 was fabricated on a piece of dielectric substrate, Rogers 5870, with the dielectric constant 2.33 and loss tangent 0.0012. The overall antenna dimension is $35mm \times 10mm \times 1.5mm$, and the electrical size of the antenna length is ka = 0.33, which is shown in Fig. 15.

The S_{11} parameter was measured first by using the network analyzer HP 8753 with an absorber placed in front of the antenna, and a tunable quarter-wave sleeve balun is added to avoid the leak current along the cable. The sleeve balun used in our measurement is illustrated in Fig. 16, and since an ordinary balun is a narrow band device, a tunable balun is designed, which allows us to choose the optimal parameters for the balun. First, in order to suppress the leaking current efficiently, the diameter of the sleeve balun should be fairly large compared to that of the coaxial cable [3]. Based on HFSS simulation results, a diameter of 11 mm is chosen. Second, due to the fringing field effect, a gap is suggested between the antenna and the open end of balun. Moreover, a conductive glue is necessary to provide a perfect shorting wall. Then the simulated and measured S_{11} of this small loop antenna are compared in Fig. 17. While the simulated resonance frequency is 906 MHz, the measured resonance frequency is 911 MHz, and the deviation is 5 MHz, that is 0.6 %. The simulated and measured -10dB bandwidth are 3.3 MHz and 4.9 MHz respectively, and the difference is thus 1.6 MHz. The difference in resonance frequency is due to the sensitivity in the capacitance loading in the large loop as well as the fabrication accuracy.

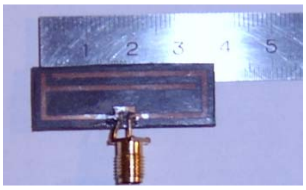

Fig. 15. The fabricated electrically small loop antenna, operated at 906 MHz

Fig. 16. Illustration of the sleeve balun and the conductive glue.

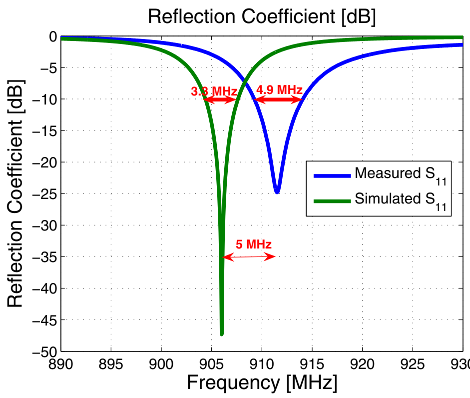

Fig. 17. The simulated and measured S11 values for electrically small loop antenna, which is designed to operate at 906 MHz.

The radiation efficiency measurement is of a great challenge. The small antenna is a balanced device, and using unbalanced coaxial feed line to feed antenna can results in the leak current along the cable, which gives significant change in radiation efficiency. For this measurement, the antenna is measured using two different methods, and in both of them the quarter-wave balun should be added. First, the antenna is measured by using the Wheeler's Cap method, and the radiation efficiency is found to be 21 %, which is reasonably

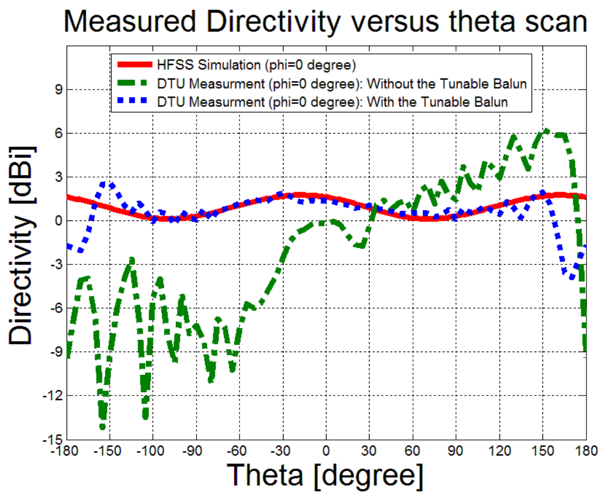

Fig. 18. The simulated and measured directivity versus theta for electrically small loop antenna, which is designed to operate at 906 MHz.

close to the simulated efficiency 17 %. The gain is acceptable for the antenna of such small dimension. The difference in efficiency can be explained that the loss in dielectric material may be not exactly the same as the value in simulations. Second, the antenna was also measured in the DTU-ESA Spherical Near Field Antenna Test Facility. The simulated and measured directivity versus theta scan are compared, and a good agreement can be found when the balun is used, as shown in Fig. 18. The efficiency of the antenna was measured by using the substitution method, and found to be 20 %, which agrees very well with the measured result in the Wheeler's cap.

V. Conclusions

In this paper, two differential-fed self-resonant electrically small loop antennas are proposed. They are miniaturized by using the coupling mechanism between two loops, without using additional matching circuit and lumped components. An analytical model is also proposed to explain the working mechanism and illustrate the design rules. Moreover, one of two antenna designs is simulated, fabricated, and measured. The dimension of this antenna is ka = 0.33, and the measured radiation efficiency is 21 %. The simulated and measured radiation pattern are also compared and presented, and a good agreement is found.

Acknowledgment

Dr. S. Pivnenko is acknowledged for doing the antenna measurement in Anechoic Chamber.

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