Single-coil dual-band antenna design for wireless capsule endoscopic communication in MHz band

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Abstract: Inductive coupled coil is an antenna structure that can easily realize multiple resonant frequencies with planar structure for MHz band wireless capsule endoscopic (WCE) communication. However, since one resonant frequency is generated by one coil, the antenna size is large when designing multi-band antennas. In this paper, the antenna matching circuit is modified to be a series circuit with an LC tank so that one coil can generate two resonant frequencies. For the receiving antenna, this improvement can reduce half the number of coils and achieve smaller antenna size. For the transmitting antenna that is difficult to use multiple coils due to the strict size constraints of the WCE, this improvement can achieve two resonant frequencies through one coil. In order to evaluate the feasibility and whether this improvement will reduce the antenna transmission performance, a single-coil dual-band antenna operating in the MHz band is designed and manufactured, and the simulated and measured reflection and transmission coefficients are evaluated by a biological tissue equivalent phantom. By comparing with the previously proposed antenna results, it can be known that the transmission performance is not deteriorated, indicating that the improvement is feasible for the WCE transmitting and receiving coil antennas.

Keywords: wireless capsule endoscopic communication, low frequency communication, multi-band communication, coil antenna, matching circuit

Classification: Antennas and Propagation

References


1 Introduction

Wireless Capsule Endoscope (WCE) is a device that can conduct gastrointestinal (GI) tract inspection without the use of cables [1]. Images can be transmitted wirelessly through a transmitting antenna inside WCE and a receiving antenna on the surface of the patient’s body [2]. The Medical Implant Communication System (MICS) is widely used for medical communication (core band: 402–405 MHz), but narrow bandwidth limits the transmission rate of the device [3]. On the other hand, according to Japanese law, the 10–60 MHz band is license-free, and wide frequency band offers the possibility of high-speed medical communication [4].

In [5], Wang, et al. designed and manufactured a transceiver for 10–60 MHz band human body communication. Impulse radio (IR) signal is adopted to decrease the size of the transceiver. The transceiver output power is shown in Fig. 1. It can be seen that the transceiver contains five signal peaks (19.3, 28.9, 38.5, 48.2 and 57.6 MHz) in the 10–60 MHz band. In order to obtain the strongest signal, the antenna resonant frequencies are usually designed to match the signal peaks of the transceiver. In [6], the corresponding WCE transmitting and receiving antennas are designed with the resonant frequency of approximately 30 MHz. Both antennas are
capsule-shaped, which achieves a total data rate of 1.25 Mbps through the transceiver in [5]. However, the receiving antenna is not suitable for design in a capsule shape as it is difficult to be mounted on the surface of the patient’s body during the inspection. In addition, the two antennas can only resonate at one signal peak of the transceiver, which fails to fully utilize signal energy of the transceiver.

As another antenna structure used for power and signal transmission in the MHz band, the inductive coupling coil can easily realize the planar antenna structure and multiple resonant frequencies [7, 8, 9, 10]. In our previous study [9, 10], the authors designed and fabricated planar-structured dual-band and tri-band coil receiving antennas for WCE signal reception in the 10–60 MHz band, and a single-band transmitting antenna for communication performance evaluation. However, since one coil generates only one resonant frequency, the use of multiple coils results in a relatively large size of the receiving antenna. In addition, due to the strict size limitations of the capsule, it is difficult for the transmitting antenna to use multiple coils, therefore only one resonant frequency can be generated.

In this paper, by using a series circuit with an LC tank in the antenna matching circuit, the authors attempt to reduce the total number of coils while maintaining the same number of resonant frequencies. In order to evaluate the feasibility and whether this improvement will reduce the antenna transmission performance, a single-coil dual-band antenna is designed and fabricated for WCE communication in the 10–60 MHz. By comparing with the previously proposed antenna results [6], it is possible to evaluate the transmission performance difference and the feasibility of the improvement.

2 Antenna structure with simulated and measured results

Instead of using a series and parallel circuit, the improved antenna uses a series circuit with an LC tank so that two resonant frequencies can be realized by one coil. When the coil operating frequency is lower or higher than LC tank resonant frequency, the LC tank can be equivalent to an inductor or a capacitor, and two resonant frequencies can be obtained by connecting the inductive or capacitive LC tank with the series circuit. Detailed principle and the resonant frequency calculation formula can be obtained in [11].

In Fig. 2(a), the structure and dimensions of the proposed antenna are shown, which is optimized by Computer Simulation Technology Microwave Studio 2018.
Photographs of the fabricated antenna top and bottom side are shown in Fig. 2(b). The antenna is made of a 1.6 mm thick FR-4 substrate ($\varepsilon_r = 4.3$; $\tan \delta = 0.035$), a coil (width: 0.5 mm; pitch: 1 mm; copper thickness: 0.017 mm), two metal vias (diameter: 0.5 mm), with a matching circuit and GND.
the bottom of antenna. Inductance and capacitance values of the matching circuit for the simulation are: $C_1 = 3.4 \text{ pF}$, $C_2 = 4.7 \text{ pF}$, $L_1 = 1 \mu\text{H}$, and $L_2 = 0.95 \mu\text{H}$, respectively. Inductance and capacitance values of the matching circuit for the measurement are: $C_1 = 3 \text{ pF}$, $C_2 = 4.7 \text{ pF}$, $L_1 = 1 \mu\text{H}$, and $L_2 = 0.82 \mu\text{H}$, respectively. By re-adjusting the antenna inductance and capacitance values after fabrication to ensure that the antenna can resonate at the peak of the transceiver.

A biological-equivalent phantom is used for antenna simulation and measurement, as shown in Fig. 2(c). Since the authors only designed the receiving antenna, two identical proposed antennas are used to evaluate the antenna transmission performance, with 1 mm gap from the phantom and 50 mm distance of two antennas. In the measurement, the distance between the antenna and the phantom can be adjusted by covering the phantom with a plastic wrap, and the electrical properties of the plastic wrap are negligible. The measured relative permittivity and conductivity of the phantom are 72.9 and 1.21 S/m at 50 MHz, with small change in the 35–65 MHz frequency range. To simplify antenna simulation, the measured electrical properties are used for antenna simulation in the entire frequency range.

The simulated and measured antenna reflection and transmission coefficients are shown in Figs. 3(a) and 3(b). Two resonant frequencies that match the signal peak of the transceiver can be observed at 38.5 and 57.6 MHz, with 50-mm transmission coefficients of $-18.6$ and $-26.9 \text{ dB}$ for the simulated results, and $-14.1$ and $-25.8 \text{ dB}$ for the measured results, respectively. Since there is a weak coupling between the coaxial cables at low frequencies, the measured transmission coefficient is slightly higher than the simulated result [9]. The measured reflection coefficient is lower than the simulated result as measurement errors occur when plastic wrap is used to adjust the distance between the antenna and the phantom.

Fig. 3. (a) Simulated antenna reflection and transmission coefficient. (b) Measured antenna reflection and transmission coefficient. (c) Simulated reflection coefficient of different $C_2$. (d) Simulated reflection coefficient of different $L_2$. 
As a comparison in [6], two resonant frequencies that match the signal peak of the transceiver can be observed at 48.2 and 57.6 MHz, with 50-mm transmission coefficients of −19 and −37.9 dB for the simulated results, and −14.3 and −32.7 dB for the measured results, respectively. It can be seen that the transmission performance at the signal peak of the transceiver is not deteriorated, indicating that the improvement is feasible for the WCE transmitting and receiving coil antennas.

In order to clarify whether different capacitance and inductance values of the LC tank can influence the antenna resonant frequency, the authors simulated the antenna transmission coefficient with different inductance and capacitance values of the LC tank, and results are shown in Figs. 3(c) and 3(d). It can be seen that as the capacitance and inductance values increase, the higher resonant frequency of the antenna (57.6 MHz) decreases, while the lower resonant frequency of the antenna (38.5 MHz) hardly changes. The simulated results show that different capacitance and inductance values of the LC tank will influence the resonant frequency of the antenna, and the degree of two resonant frequencies is different. This is good news for antenna frequency adjustment and can be used to better guide future antenna designs.

3 Conclusion

In this paper, the authors improved the antenna matching circuit by using a series circuit with an LC tank to reduce the total number of coils while maintaining the same number of resonant frequencies. A single-coil dual-band antenna is designed and fabricated to evaluate the feasibility of the improvement. The simulated and measured results show that two resonant frequencies can be realized by one coil and the antenna transmission performance at the signal peak of the transceiver is not deteriorated, indicating that this improvement can be used to design WCE transmitting and receiving antennas.

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