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Analysis and Design of the LC Resonant Circuit Security Tags

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The design theory was revealed by theoretical analysis of the tag's properties in the measuring apparatus, and was confirmed experimentally. Higher quality tags having new circuit designs were proposed by the revealed theory, and by using a novel insulating film, a small-sized tag was developped. The measuring apparatus equivalent to main portions of the security system was produced to estimate the properties of the LC resonant circuit security tags quantitatively.

1. Introduction

There are passive tags comprised only of the LC resonant circuit and active tags comprised of such circuit and IC etc.[1]. They are attached to articles to prevent theft. The magnetic tags also exist[2]. But we have been investigating only the passive tags using aluminium foils, considering giving the foils higher added-value such as electrical performance and application.

Recently, the store using this kind of tags have been increasing. To conceal their usage, to apply to more kinds of articles and to hold the beautiful appearance of articles, the tags are wanted to have higher quality and smaller size. To achieve them, it is very necessary to reveal the design theory of the tag's quality and the way to estimate the properties of tags quantitatively. However, they have not been clear enough previously[3]. In this paper, the design theory is revealed by the theoretical analysis and is confirmed experimentally. From this theory, we present higher quality tags and a small-sized tag having new circuit designs to achieve lower prices. The produced measuring apparatus can estimate the properties of the tags quantitatively.

2. Security system and tags

Figure 1 shows (a) the illustration and (b) the conceptual shape of the received signal of the security system. The system consists of a transmitter, a transmitting loop antenna (1.5 m×0.5 m), a receiver and a receiving loop antenna (1.5 m×0.5 m). These antennas are arranged parallel with each other (~1 m distance).

The transmitter generates the frequency-modulated signal centering on 8.2 MHz within ±10% (7.4−9.0 MHz) in a period of 10 msec. When no tag exists between the two antennas, the received signal has constant intensity. The size and the arrangement distance of these antennas are smaller enough than the wavelength of the radiating electric wave. Because these antennas are loops, they are thought to be magnetically coupled with each other. The tag includes a coil, and is also smaller enough than the

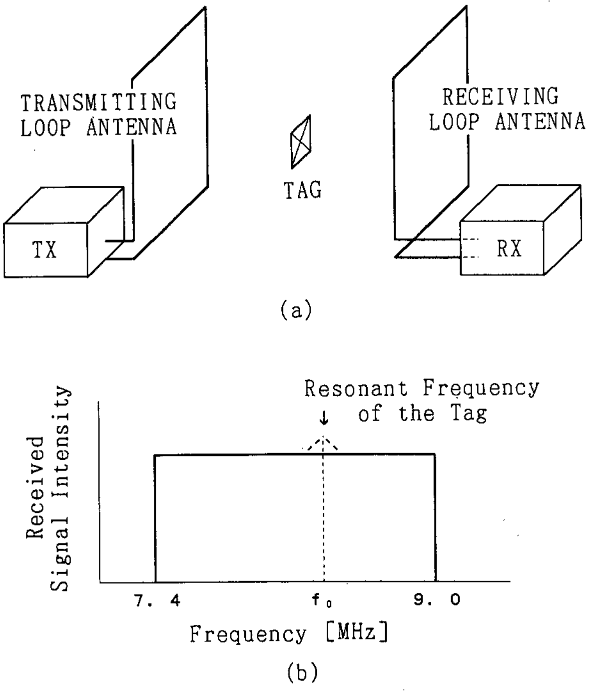

Fig. 1 Security system.
(a) Illustration. (b) Conceptual shape of received signal.

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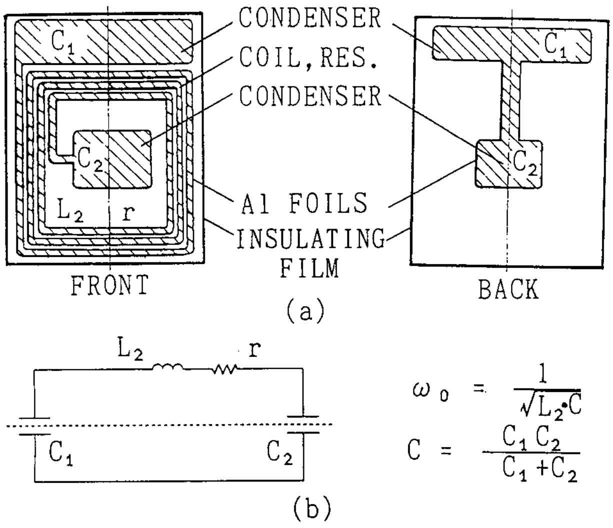


Fig. 2 Proposed tag.
(a) Constitution. (b) Equivalent Circuit. ω_0: Resonant angular frequency. C: Composed capacitance.

wavelength. Therefore, when the tag exists between the two antennas, it is also thought to be magnetically coupled with these.

In General, the two antennas are set at the exit (or the entrance) of a store. When the tag attached to articles passes between these antennas, the received signal intensity varies at and near the resonant frequency of the tag, as shown in Fig. 1 (b). Then, the receiver detects the signal varying. The security system recognizes the unauthorized removal of the article and denote this with alarm activation[4].

Figure 2 shows (a) the constitution and (b) the equivalent circuit of the proposed tag (40×40 mm^2 or 35×35 mm^2) having new circuit designs. The tag consists of a insulating film and Al foils bonded on respective opposite surfaces of the film. The front Al foil has 50 μm thickness. It is shaped into two condenser plates and one spiral coil (resistnace). The back Al foil has 10 μm thickness. It is shaped into two-condenser plates. In the 40×40 mm^2 proposed tag, cast polypropylene (CPP) of 20 μm thickness is used as the insulating film. In the 35×35 mm^2 tag, novel polyphenylene sulfide (PPS) of 9 μm thickness is used. L_2 and r are the inductance and the resistance of the spiral coil. C_1 and C_2 are capacitance of two condensers containing the insulating film, respectively. This tag is comprised of a closed LC resonant circuit.

The conventional tag has about 40×40 mm^2 size and uses the CPP film of 20 μm thickness. Both sides of the Al foils are interconnected at the place equivalent to the condenser C_1 (small area), and the circuit is composed of a condenser and a coil[5]. Sometimes, the interconnecting process causes the contact resistance in the circuit. The design theory described later shows that the resistance makes the Q factor decrease and the quality of tag poorer.

The proposed tags are produced without this complicated process and achieves lower prices and their quality improvements. The small-sized tag of 35×35 mm^2 size is fabricated with the PPS film of 9 μm thickness. By using this film, the area of C_2 and the reduction of the Q factor can be much decreased. Thus, the small-sized tag achieves about the same quality as the conventional tag.

3. Theoretical analysis and experiments

3.1 Signal Strength V_m

To estimate the properties of the tags applied to the security system quantitatively, the measuring apparatus equivalent to main portions of the system was produced. Figure 3 shows (a) the block diagram and (b) the circuits of the measuring apparatus including the tag. The radiating coil (L_1) and the receiving coil (L_3) are very weakly magnetically coupled with each other in order to measure the induced current of the tag only. Therefore, no voltage appears on the receiving coil (L_3) without the tag. The tag is fixed at the center of the two coils coaxially. The area of the cross sections of these two coils is same, and it is about as same as that of the tag's coil. By varying the output frequency of the signal generator, the appearing voltage ($\dot{V}_m$) on the receiving coil (L_3) is measured by the voltmeter.

When the directions of the currents are determined as shown in the Fig. 3 (b), equations of the circuits are expressed by

$$\begin{aligned} j\omega L_1 \cdot \dot{I}_1 + j\omega M_{12} \cdot \dot{I}_2 \quad + j\omega M_{31} \cdot \dot{I}_3 &= \dot{V}_1 \\ j\omega M_{12} \cdot \dot{I}_1 \quad + Z \cdot \dot{I}_2 \quad + j\omega M_{23} \cdot \dot{I}_3 &= 0 \\ j\omega M_{31} \cdot \dot{I}_1 + j\omega M_{23} \cdot \dot{I}_2 + (R + j\omega L_3) \cdot \dot{I}_3 &= 0, \end{aligned} \tag{1}$$

Where M_{12}, M_{23} and M_{31} are the mutual inductance between the radiating coil, the tag's coil and the receiving coil, respectively[6]. L_1, L_2 and L_3 are their inductance. $\dot{V}_1$ is the output voltage of the signal generator. R is the input impedance of the voltmeter. Z is the impedance ot the tag. From these Eqs., the current $\dot{I}_3$ is derived as

$$\dot{I}_3 = -\Delta^{-1} \cdot (\omega^2 M_{12} M_{23} + j\omega M_{31} \cdot Z) \cdot \dot{V}_1, \tag{2}$$

where $\Delta = j\omega L_1 \cdot Z \cdot (R + j\omega L_3) + j\omega L_1 \cdot \omega^2 M_{23}{}^2 + Z \cdot \omega^2 M_{31}{}^2 + (R + j\omega L_3)\omega^2 M_{12}{}^2 - 2\,j\omega^3 M_{12} M_{23} M_{31}$. (3)

Since $M_{31} \fallingdotseq 0$ and $R + j\omega L_3 \fallingdotseq R$, $\dot{I}_3$ is described by

$$\dot{I}_3 = \frac{-\omega^2 M_{12} M_{23} \dot{V}_1}{j\omega L_1 R \cdot (Z + \omega^2 M_{23}{}^2/R + \omega^2 M_{12}{}^2/j\omega L_1)}\,. \tag{4}$$

And since $\omega^2 M_{23}{}^2 \ll R$ and $\omega^2 M_{12}{}^2 \ll \omega L_1$, $\dot{I}_3$ is given by

$$\dot{I}_3 = \frac{-\omega^2 M_{12} M_{23} \dot{V}_1}{j\omega L_1 R Z}\,. \tag{5}$$

Finally, the measured voltage $\dot{V}_m$ is given by

$$\dot{V}_m = \dot{I}_3 R = \frac{j\omega M_{12} M_{23} \dot{V}_1}{L_1 Z}\,. \tag{6}$$

The absolute value of $\dot{V}_m$ is the signal strength V_m of the tag.

Meaning of Eq. (6) is shown in Fig. 4 as the equivalent circuit. $\dot{V}_m$ corresponds to the appearing voltage on the coil of the inductance M_{23} by $\dot{I}$, where M_{23} is smaller enough than L_2. In general, properties of the LC resonant circuit are determined by the characteristics of the voltage appearing on the coil (or the condenser) against the frequency. The current $\dot{I}$ $(=\dot{E}/Z)$ is not given by the above Eqs., but it is the induced current $\dot{I}_2$ in the tag. Thereby, it is understood that the measuring apparatus can estimate the properties of the tags directly. Because this apparatus is essentially equivalent to the system, it can measure these properties applied to the system quantitatively.

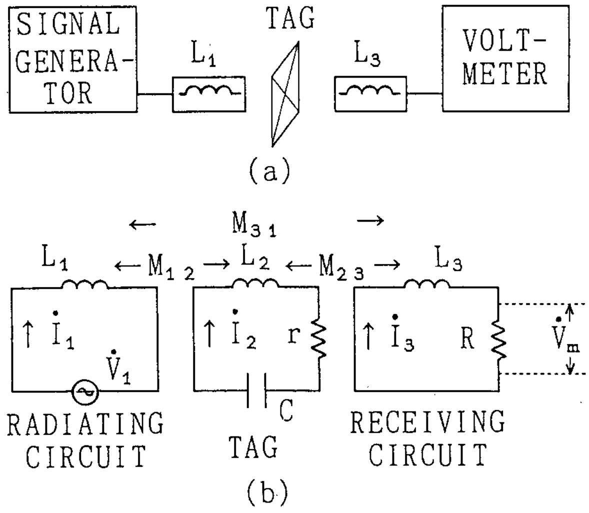
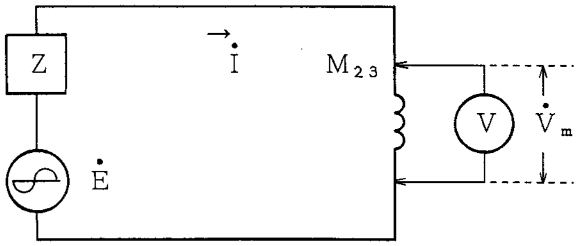


Fig. 3 Measuring apparatus.
(a) Block diagram. (b) Circuits.



$$Z = r + j\omega L_2 + \frac{1}{j\omega C}$$

$$\dot{E} = \frac{M_{12}}{L_1} \cdot \dot{V}_1\,, \quad M_{23} << L_2$$

Fig. 4 Equivalent circuit of measuring apparatus.

3.2 Peak Signal Strength V_{mp}

The security system detects the presence of the tag by varying the magnitude of the received signal at the resonant frequency of the tag. Therefore, the peak signal strength V_{mp}(V_m at the resonant frequency) represents the properties of the tags as quality. From Eq. (6), $\dot{V}_{mp}$ is given by

$$\dot{V}_{mp} = \frac{j\omega_0 M_{12} M_{23} \cdot \dot{V}_1}{L_1 \cdot r}\,, \tag{7}$$

where $\omega_0 (= 1/\sqrt{L_2 C})$ is the resonant angular frequency.

We discuss about Eq. (7) by the analogy of solenoids.

When three solenoids 1, 2 and 3 are comparatively strongly coupled, and when the area of cross sections of the solenoids 1 and 3, S_1 and S_3, are larger than that of solenoid 2, S_2, the mutual inductance M_{12} is expressed by

$$M_{12} = \mu_0 n_1 n_2 l_2 S_2. \tag{8}$$

The inductance L_1 and L_2 of the solenoids 1 and 2 are described by

$$L_1 = \mu_0 n_1{}^2 l_1 S_1, \tag{9}$$

$$L_2 = \mu_0 n_2{}^2 l_2 S_2, \tag{10}$$

respectively, where μ_0 is the permeability of the vacuum (air). n_1 and n_2 are the number of turns per unit length of solenoids 1 and 2. l_1 and l_2 are their length. When μ_0, n_1 and n_2 are eliminated from Eqs. (8), (9) and (10), M_{12} is given by

$$M_{12} = \frac{\sqrt{l_2 L_1}}{\sqrt{l_1 S_1}} \cdot \sqrt{S_2 L_2}. \tag{11}$$

Similarly, M_{23} is given by

$$M_{23} = \frac{\sqrt{l_2 L_3}}{\sqrt{l_3 S_3}} \cdot \sqrt{S_2 L_2}, \tag{12}$$

where L_3 and l_3 are the inductance and the length of the solenoid 3[7].

When the radiating coil, the tag's coil and the receiving coil are regarded as the solenoids 1, 2 and 3, respectively, Eqs. (11) and (12) are substituted into Eq. (7).

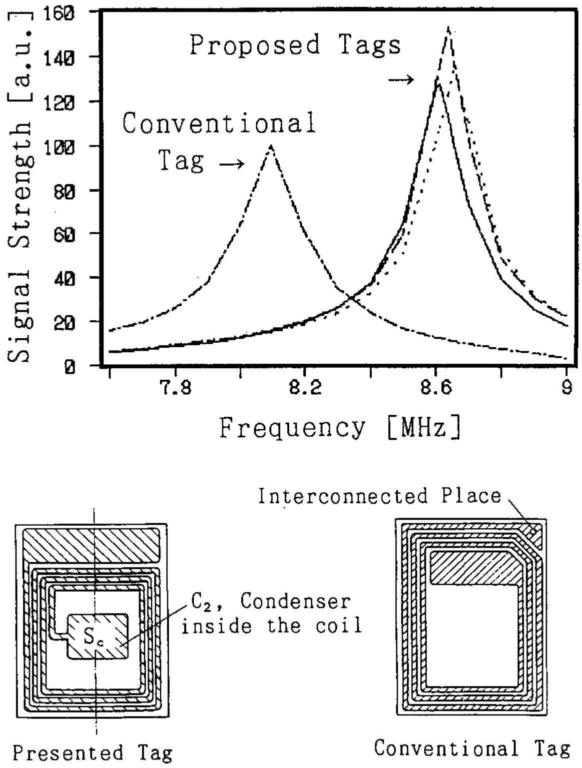


Fig. 5 Signal strength (V_m)-frequency characteristics. Proposed Tags: (—) S_c=0.96 cm², (···) S_c=0.82 cm², (- - -) S_c=0 cm² Conventional tag: (-·-·-)

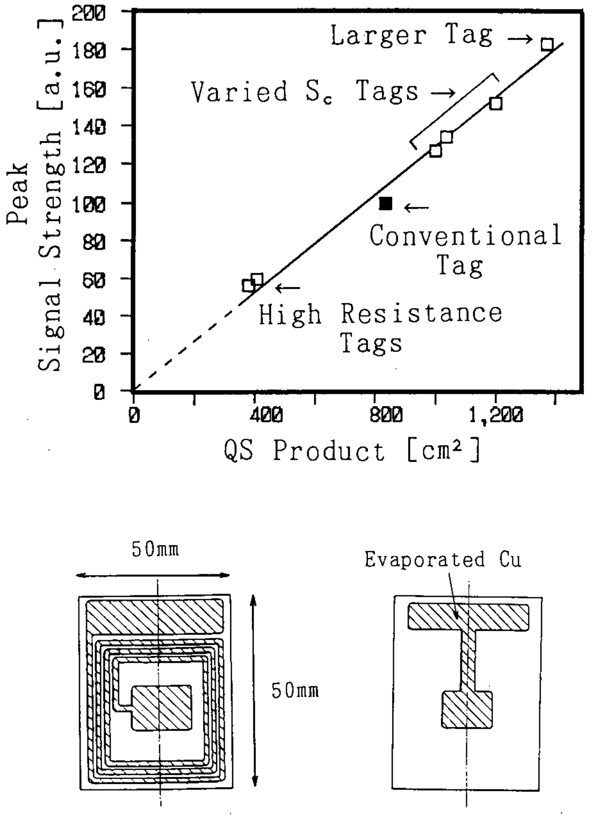


Fig. 6 Peak signal strength (V_{mp})-QS product (product of the Q factor and the effective area S of the tag) characteristics

Thus, V_{mp} is expressed by

$$V_{mp}=K_{12}K_{23}\cdot\frac{V_1}{L_1}\cdot\frac{\omega_0L_2}{r}\cdot S_2, \tag{13}$$

where $K_{12}=\sqrt{l_2L_1/l_1S_1}$ and $K_{23}=\sqrt{l_2L_3/l_3S_3}$. l_2 is the length of the tag's coil (thickness). l_1 and l_3 are the length of the radiating coil and the receiving coil. L_1, L_3 and S_1, S_3 are their inductance and their area of cross sections, respectively. Therefore, K_{12} and K_{23} are constants. V_1 and L_1 are also constants.

Since (ω_0L_2/r) and S_2 are the Q factor Q and the effective area S of the tag, respectively, V_{mp} is finally given by

$$V_{mp}=K\cdot Q\cdot S, \tag{14}$$

where K is a constant $(=K_{12}K_{23}\cdot V_1/L_1)$. $S=S_t-S_c$, where S_t and S_c are the total area of the tag and the area of condenser inside the coil, respectively, since the condenser inside the coil prevents the magnetic flux passing through the coil. Equation (14) shows that V_{mp} is proportional to the product of Q and S (the QS product). This is the basic concept of the design theory of the tag's quality.

3.3 Experimental Results and discussion

Figure 5 shows the signal stregth (V_m)-frequency characteristics of the proposed tags and the conventional tag. V_m is the relative value when V_{mp} of conventional tag is defined to be 100. It is shown that the properties of the tags are estimated quantitatively. Each tag has about 40×40 mm² size. V_{mp} of the conventional tag and the typical proposed tag is 100 and 134. Their Q is 50 and 69, respectively. The ratio of their V_{mp}(134/100=1.34) is nearly equal to that of their Q (69/50=1.38), since they have about the same size.

S_c is varied as 0.96 cm², 0.82 cm² and 0 cm². The tag having S_c=0 cm² is fabricated to investigate the influence of S_c on the properties of the tag by bending back the condenser C_2 upon the condenser C_1. V_{mp} of each tag is 127, 134 and 152. Each Q is 67, 69 and 75, respectively. Ratios of their V_{mp}(134/127=1.06 and 152/127=1.20) are slightly larger than that of their Q (69/67=1.03 and 75/67=1.12), respectively. Each tag has precisely the same size. Therefore, it is understood that S increases by the decrease of S_c ($S=S_t-S_c$).

The ratios of S_c to S_t of the first tag and second one are 6% (0.96 cm²/16 cm²) and 5% (0.82 cm²/16 cm²), respectively. While these ratios decrease within 1% only, their Q increases rapidly within 3% (69/67=1.03). Similarly, while the ratios of the first tag and the third

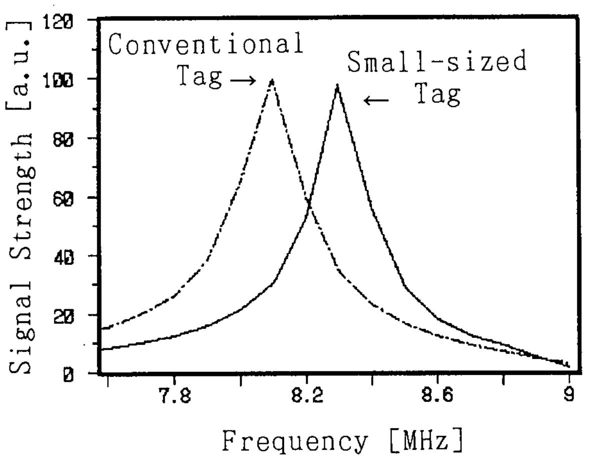


Fig. 7 Signal strength (V_m)-frequency characteristics. (—) Developed small-sized tag, (- · · · -)Conventional tag.

one decrease within 6% only (0.96 cm²/16 cm²→0 cm²/16 cm²), their Q increases rapidly within 12% (75/67 = 1.12).

Figure 6 shows the peak signal strength (V_{mp}) against the QS product. The conventional tag and the varied S_c tags are compared. The larger tag has 50 × 50 mm² size (S_t). High resistance tags are fabricated with the evaporated Cu (~1300 Å) as the back side plates of condensers. They have precisely 40 × 40 mm² size (S_t). Hereby, we can understand that the V_{mp} varies directly as the QS product, and that Eq. (14) is reasonable.

Figure 7 shows the signal strength (V_m)-frequency characteristics of the developed small-sized tag and the conventional tag. It is shown that the small-sized tag has about the same quality (V_{mp}) as the conventional one. The small-sized tag is fabricated with the 9 μm thickness PPS film. When the tag was designed as to be smaller than 40 × 40 mm² size (S_t) with the CPP film of 20 μm thickness, S_c much increases. Thus, from the above results and the design theory, it is estimated that V_{mp} rapidly decreases by the remarkably reduction of Q and the reduction of S itself. Because the PPS film can have thinner thickness and have a higher dielectric constant ε than those of CPP film (PPS: $\varepsilon_r = 3.0$, CPP: $\varepsilon_r = 2.1$), S_c and the reduction of Q can be much decreased. Actually, Q of the small-sized tag (63) is about 9% smaller only than that of the typical proposed tag (69). However, S of the small-sized tag (11.90 cm²) is about 22% smaller than that of the typical tag (15.18 cm²).

Hereby, the QS product of the small-sized tag (738 cm²) becomes smaller about 30% than that of the typical tag (1047 cm², $V_{mp} = 134$). This explains that V_{mp} (the quality) of the small-sized tag (~100) corresponds to that of the conventional tag (= 100).

4. Conclusion

The design theory was provided through the theoretical analysis considering the properties of the tag in the measuring apparatus equivalent to main portions of the security system, and was confirmed experimentally. The peak signal strength V_{mp} (the quality) representing the properties of the tag is proportional to the QS product. The effective area of the tag (S) is fixed by reducing the total area of the tag (S_t) by the area of the condenser inside the coil (S_c). Q increases rapidly by the decrease of S_c. The tags having new circuit designs were proposed to achieve higher quality and lower prices. By using a novel insulating film, the small-sized tag having about the same quality as the conventional tag was developed. The produced measuring apparatus can estimate the properties of the tags quantitatively.

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