UHF RFID Tag With Slot Antenna Integrated Into Blister Medicine Package

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***Abstract*—Passive UHF radio frequency identification (RFID) tag is proposed for integration into aluminum blister medicine package. To fit the very limited space left on aluminum foil and inevitable errors in hot-press fabrication, an antenna of multiple-fold slot is optimized in terms of normalized tag performance index and Latin hypercube sampling model of fabrication errors in hot-press. It is shown that the antenna of one-fold slot provides the largest read range, while the antenna of zero-fold slot (single rectangular slot) provides the best tolerance to fabrication errors. Prototypes of UHF tag with zero-fold and one-fold slot antenna are fabricated and tested, respectively. For 50 tags with zero-fold slot antenna, an average maximum read range of approximately 1.18 m is measured by using a UHF reader of 4 W EIRP at 915 MHz. For 50 tags with one-fold slot antenna, an average maximum read range of 3.19 m is measured.**

***Index Terms*—Antenna, blister medicine package, impedance matching, Latin hypercube sampling, radio frequency identification (RFID), slot antenna.**

I. Introduction

RADIO frequency identification (RFID) technology is expected to play a more important role in medicine management and drug safety [1]. Nowadays, some RFID-based medical applications, including drug delivery tracking [2]; distribution of pharmaceutical drugs [3]; blood collection, processing, distribution, and transfusion [4]; and animal oral drug experiment control [5], have been reported.

Many kinds of commercial RFID tags can be considered for medicine identification if the RFID tag is attached to medicine paper package [1]. To attach an RFID tag directly to aluminum blister medicine package, anti-metal RFID tag can be considered. Unfortunately, it is hard for these anti-metal tags to fit the medicine blister package due to either the relatively large tag size or complex tag structures for mounting [6]–[10].

RFID tags with slot antenna carved on aluminum foil seem quite suitable for medicine blister package. However, the slot should be specially designed for hot-pressed aluminum blister. In addition to the very limited space left on medicine blister for carving the slot antenna, there is another major design challenge, i.e., effects of fabrication errors in hot-press fabrication of medicine aluminum blister should be included at the design stage. Otherwise, a well-designed high performance of slot antenna for RFID tag cannot be maintained in hot-press fabrication.

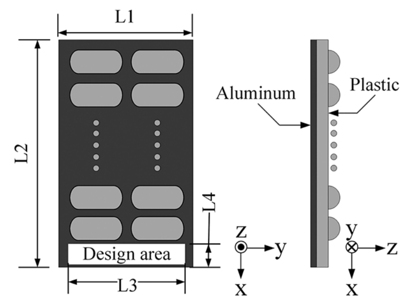

Fig. 1. Design area on blister package.

To include errors of hot-press fabrication in antenna slot design, a comprehensive factor must be defined for tag performance evaluation. Statistical methods can be applied to building a model for fabrication errors analysis. Latin hypercube sampling [11] is a statistical method for generating a sample of plausible collections of parameter values from a multidimensional distribution. For design of slot antenna with quite a lot of geometry parameters, the Latin hypercube sampling method can be very helpful.

In this letter, we report the design of passive UHF RFID tags with slot antenna of enough tolerance to hot-press fabrication errors that is suitable for integration into aluminum blister medicine package. In Section II, geometry and deployment of tag antenna of multiple-fold slot are proposed. In Section III, analysis flow of fabrication errors is introduced to finding the satisfactory fold number for maximum read range and best tolerance to fabrication errors among slots of different folds. In Section IV, prototype tags with zero-fold slot and one-fold slot are fabricated and tested by using an Alien ALR 9900 reader (of 4 W EIRP) to verify the design.

II. Tag Deployment and Slot Structure

Although different blister medicine packages may have different dimensions, there is always a space left for incused production date and other information, as shown by the design area in Fig. 1. General dimensions of the incused space are L4 = 8 mm. We will restrict our RFID slot antenna within this space. The RFID chip may be installed across the slot on aluminum foil blister package.

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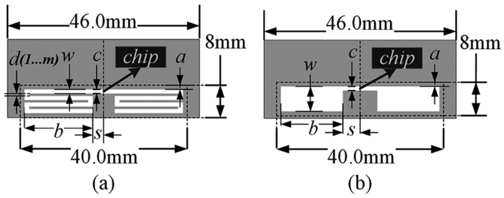

Fig. 2. Antenna with (a) symmetrical multifold slot and (b) zero-fold slot.

A. Multifold Meander Slot Antenna

With no loss of generality, a relatively small dimension of $\mathrm{L1}\times\mathrm{L2} = 46\times 92\ \mathrm{mm}^2$ and $\mathrm{L3} = 40$ mm can be considered for demonstration. Hence, a design space of $\mathrm{L3}\times\mathrm{L4} = 40\times 8\ \mathrm{mm}^2$ is left for slot antenna on aluminum foil blister.

For such a restricted design space, meander slot antenna [12] is a good candidate. An m-fold slot is shown in Fig. 2(a). In addition to slot parameters defined in Fig. 2(a), fold number m is also a major indicator.

For the m-fold slot in Fig. 2(a), a characterizes position of slot antenna, b defines length of the folded slot, s defines half-interval between the two symmetrical slot arms, w defines width of slot, d defines width of metal strip between two neighboring slots, and c defines width of gap for chip mounting. To simplify the antenna structure, all d parameters are set to be the same, and c is set to be 1 mm, which is suitable for mounting RFID chip such as Impinj Monza-4 chip. It should be noted that zero-fold slot antenna has two symmetrical rectangular slots, which means $d = 0$, as shown in Fig. 2(b).

B. Tag Performance Analysis

For a passive UHF RFID tag of chip impedance $Z_c = R_c + jX_c$ and antenna input impedance $Z_a = R_a + jX_a$, the read range can be evaluated by [13]

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_{\mathrm{t}}G_{\mathrm{t}}G_{\mathrm{r}}\tau}{P_{\mathrm{th}}}} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{\mathrm{t}}G_{\mathrm{t}}}{P_{\mathrm{th}}}}\sqrt{G_{\mathrm{r}}\tau} \equiv r_0\sqrt{G_{\mathrm{r}}\tau} \quad (1)$$

where λ is the wavelength, P_{t} is the power transmitted by RFID reader, G_{t} is the gain of RFID reader antenna, G_{r} is the gain of passive tag antenna, P_{th} is the minimum threshold power to activate the RFID tag chip, and τ is the power transmission coefficient between the RFID chip and the tag antenna, which is given by

$$\tau = \frac{4R_cR_a}{|Z_c + Z_a|^2}. \quad (2)$$

In (1), r_0 is determined by the minimum threshold power of the RFID chip and the RFID reader, and $\sqrt{G_{\mathrm{r}}\tau}$ is a comprehensive index characterizing the overall tag performance. A larger value of $\sqrt{G_r\tau}$ indicates a larger RFID read range.

C. Fabrication Errors Analysis

For hot-pressed RFID slot antenna on aluminum blister, effects of fabrication errors should be considered in optimization design of slot antenna.

To model fabrication errors of the hot-press process for aluminum blister, statistical sampling method can be applied. In hot-press process, errors are majorly due to slot dimension errors, which can be considered to conform to Gaussian distribution with a standard deviation of σ. Deviation of $\sigma = 0.2$ mm [14] ensures dimension errors within ± 0.6 mm based on three-sigma rule or empirical rule [11], which is reasonable for practical hot-press of aluminum blister. Since there are five key parameters, viz., a, d, w, b, and s, defining an m-fold slot and different parameters have different effects on RFID tag performance, a comprehensive factor must be defined to include errors from all the key geometry parameters.

Latin hypercube sampling [11] is a compromise procedure that may incorporate many of the desirable features of random sampling and stratified sampling, and may produce more stable analysis outcomes than random sampling. To include all random errors of five key parameters defining an m-fold slot antenna, Latin hypercube sampling is an ideal technique to form a comprehensive factor to characterize hot-press fabrication errors.

With Latin hypercube sampling, a comprehensive factor to evaluate influence of random fabrication errors can be defined by normalized root mean square error (NRMSE) as [15]

$$NRMSE = \frac{\sqrt{\frac{\sum_{t=1}^{n}(\tilde{y}_t - y)^2}{n}}}{y_{t\_\max} - y_{t\_\min}} \times 100\% \quad (3)$$

where $\tilde{y}_t$ is the value sequence of $\sqrt{G_{\mathrm{r}}\tau}$ at Latin hypercube sampling points in vector space $\vec{x} = (a, d, w, b, s)$ defining an antenna, y is the $\sqrt{G_{\mathrm{r}}\tau}$ value for an optimum $\vec{x}$, n is the number of samples to be evaluated, $y_{t\_\max}$ and $y_{t\_\min}$ are the maximum and minimum values of $\sqrt{G_{\mathrm{r}}\tau}$ among $\tilde{y}_t$, respectively. A smaller $NRMSE$ value indicates a better tolerance of m-fold slot antenna to fabrication errors.

III. Tag Design and Fabrication Errors Analysis

A. Antenna Parameters Optimization

In the design simulation, thickness of the aluminum foil is set to be 0.025 mm, and thickness of the plastic substrate of blister is 0.5 mm. Typical blister plastic is polyvinyl chloride, which has a dielectric constant of $\varepsilon_{\mathrm{r}} = 3.19$ and dielectric loss of $\tan\delta = 0.0096$.

For demonstration, we consider Impinj Monza-4 chip for the RFID tag, which has an input impedance of $Z_C = 11 - 143j(\Omega)$ at UHF 915 MHz [16].

For an m-fold slot antenna structure defined in restricted design space $\mathrm{L3} \times \mathrm{L4} = 40 \times 8\ \mathrm{mm}^2$ on aluminum foil of dimensions $\mathrm{L1} \times \mathrm{L2} = 46 \times 92\ \mathrm{mm}^2$, we may optimize its structure parameters by numerical simulation design. All the simulations were performed with the whole blister package, viz., a 46×92-mm^2 aluminum foil attached to a plastic sheet with air-filled slot in the aluminum foil as antenna. In the optimization, sequential nonlinear programming method [17] is applied. Maximum normalized tag performance index in (1) is used as a prior optimization objective, and small as possible $NRMSE$ value serves as another design objective.

Table I lists the optimized structure parameters for $\sqrt{G_{\mathrm{r}}\tau}$ and $NRMSE$ for slots of different fold numbers. From Table I, we find that the RFID tag with one-fold slot antenna provides the largest $\sqrt{G_{\mathrm{r}}\tau}$ value, while the tag with zero-fold slot antenna has the smallest $NRMSE$ value. Slot antennas of more than

TABLE I
ANTENNA PARAMETERS FOR TAG PERFORMANCE INDEX $\sqrt{G_r\tau}$ AND $NRMSE$

fold number	a	d	w	b	s	$\sqrt{G_r\tau}$	$NRMSE$
m=0	2.0	0	5.0	16.0	6.0	0.2010	0.1780
m=1	1.0	3.8	1.2	21.0	1.0	1.0685	0.4312
m=2	0	0.5	1.7	21.0	0.9	0.9582	0.4707
m=3	0	0.2	1.4	20.9	1.2	0.9264	0.6844

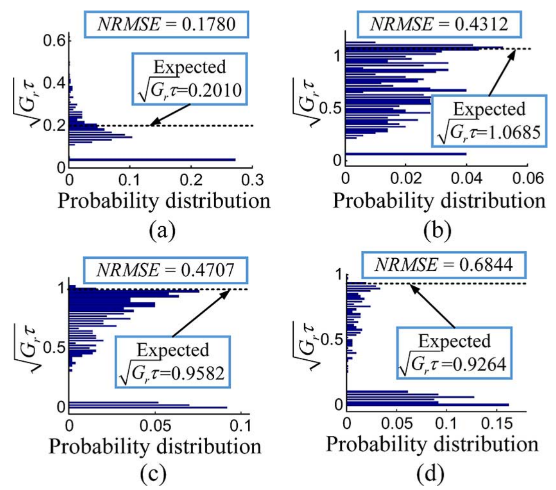

Fig. 3. Probability distribution of $\sqrt{G_r\tau}$ value based on Latin hypercube sampling. (a) $m = 0$. (b) $m = 1$. (c) $m = 2$. (d) $m = 3$.

two folds (viz., $m \geq 2$) have even larger $NRMSE$ values but similar $\sqrt{G_r\tau}$ values, so that they do not provide considerable merit.

Both the slot antennas for $m = 0$ and 1 have dipole-like radiation patterns. Tag with zero-fold slot antenna has a gain of around 0 dBi, and tag with one-fold slot antenna has a gain of 0.8372 dBi.

B. Effects of Fabrication Errors

For the designed tag antennas given in Table I, we may analyze the effects of fabrication errors for verification by taking 500 Latin hypercube sampling points to simulate the fabrication process. Probability distributions of $\sqrt{G_r\tau}$ value based on Latin hypercube sampling are presented in Fig. 3.

In Fig. 3, the dotted lines indicate expected $\sqrt{G_r\tau}$ value obtained from optimized parameters shown in Table I. The range of the $\sqrt{G_r\tau}$ values of all the 500 sampling points is divided into 50 intervals, and the probability of them appearing in a certain interval can be read from the x-axis. Values of $NRMSE$ in (3) of the 500 sampling points for tag of slot antenna of $m = 0$, $m = 1$, $m = 2$, and $m = 3$ are 17.80%, 43.12%, 47.07%, and 68.44%, respectively.

From the probability distributions in Fig. 3(a), it is found that 67.6% of the samples for $m = 0$ have $\sqrt{G_r\tau}$ values within a dynamic range of 0.2010 ± 0.1, which leads to the smallest $NRMSE$ value. Therefore, the zero-fold slot antenna suffers less from the fabrication errors than any other slot antennas.

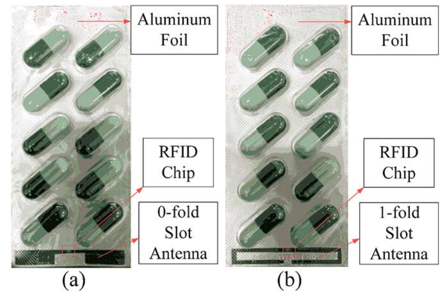

Fig. 4. Prototype medicine blister with UHF RFID tags integrated into aluminum foil. (a) Zero-fold slot. (b) One-fold slot.

Although tags for $m = 1$, 2, and 3 have satisfactory $\sqrt{G_r\tau}$ values, they have large $NRMSE$ so that suffer more from the fabrication errors. From the probability distributions in Fig. 3(b), (c) and (d), it is found that 4.0% of the samples for $m = 1$ have $\sqrt{G_r\tau}$ values less than 0.1, while 21.4% of the samples for $m = 2$ and 62.4% of the samples for $m = 3$ have $\sqrt{G_r\tau}$ values less than 0.1. Therefore, tags for $m \geq 2$ are not practical because of the hazard of tag performance degradation.

Comparison between Fig. 3(a) and (b) indicates that roughly 96% of samples for $m = 1$ have $\sqrt{G_r\tau}$ values larger than the expected $\sqrt{G_r\tau} = 0.2010$ for samples of zero-fold slot, although tags with one-fold slot may suffer more from the fabrication errors than tags with zero-fold slot.

Therefore, judging from both the tag performance and tolerance to fabrication errors, RFID tag with one-fold slot is highly recommended for medicine blister package although RFID tag with zero-fold slot has a more stable performance.

IV. EXPERIMENT TEST

For demonstration, tags with the designed zero-fold and one-fold slot antenna are fabricated and tested in the laboratory.

Fig. 4 shows two prototypes of medicine blister package with RFID tag integrated into aluminum foil with zero-fold and one-fold slot antenna, respectively. The aluminum foil has a plastic substrate of thickness of 0.5 mm. Both the prototypes are made with fabrication errors at the general level of hot-press for aluminum blister medicine packaging.

The prototypes have been tested by using an Alien ALR-9900 RFID reader, which has an EIRP of 4 W. Figs. 5 and 6 show the typical normalized patterns in measured read range for prototype tags with zero-fold antenna and one-fold antenna, respectively. For comparison, the calculated read range patterns obtained from the $\sqrt{G_r\tau}$ value shown in Table I are also presented. We have the observation that the measured and calculated patterns are in good agreement.

The statistics of measured maximum read range of 50 sample tags with zero-fold slot and one-fold slot are shown in Fig. 7(a) and (b), respectively. Fig. 7 is presented by scaling the maximum read range with step of 0.5 m and recording the number of sample tags that can be interrogated at different read ranges. It is observed that distributions of maximum read range in Fig. 7(a) and (b) agree well with the analytical probability distributions shown in Fig. 3(a) and (b), respectively.

The statistics indicate an average maximum read range of 1.18 m for tags with zero-fold slot and 3.19 m for tags with

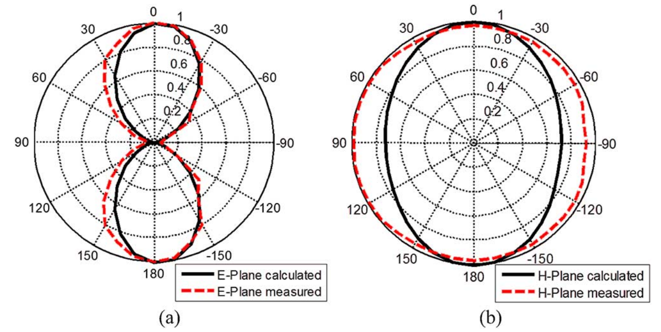

Fig. 5. Normalized read-range pattern of the zero-fold UHF tag on aluminum foil. (a) Pattern in E-plane. (b) Pattern in H-plane.

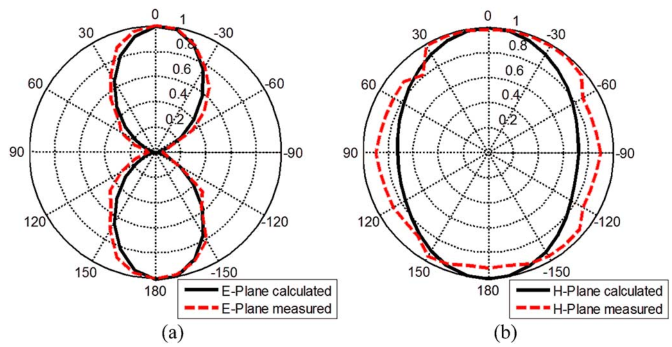

Fig. 6. Normalized read-range pattern of the one-fold UHF tag on aluminum foil. (a) Pattern in E-plane. (b) Pattern in H-plane.

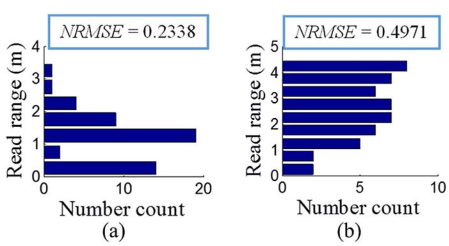

Fig. 7. Statistical measurement of 50 samples. (a) Tags with zero-fold slot. (b) Tags with one-fold slot.

one-fold slot. Therefore, with general fabrication errors under the same hot-press fabrication process, RFID tags with one-fold slot antenna provide preferable read range.

V. Conclusion

In order to integrate passive UHF RFID tag into medicine blister package with aluminum foil, the UHF tag antenna must be strictly restricted within a small design space, and effects of fabrication errors in hot-press fabrication of medicine aluminum blister should be considered.

Slot antenna is proved to be a satisfactory tag antenna for medicine blister. However, fabrication errors in hot-press fabrication of medicine blister exclude the use of multifold slot antenna although a tag with multifold slot antenna tends to have a large read range. Analysis based on $NRMSE$ indicates that RFID tag with zero-fold has the best tolerance to hot-press fabrication error. Judging from both the maximum read range and tolerance to fabrication errors, RFID tag with one-slot antenna deserves the highest recommendation.

In addition, we find that shape of aluminum blister and medicine types in blisters have little effect on the tag's radiation pattern and read range. By pressing the prototypes in different ways, it is measured that the maximum read range may be decreased by approximately 13% for tag of one-fold slot and 3% for tag of zero-fold slot. The tag with one-fold slot antenna still has read range larger than that of a tag with zero-fold slot.

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