Flexible temperature sensor integrated with RFID tag

Kamil Janeczek, Tele and Radio Research Institute
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Abstract

Storage and transportation conditions of goods need to be often controlled because of their sensitivity for elevated temperature or other environmental factors (like for example humidity). Nowadays, such a control is carried out mostly using indicators or complicated and expensive sensors. The last one contains batteries and other electronic components and performs a function of a recorder. Because of this, such sensors are not flexible. On the other hand, indicators can be bended multiple times without any damage in their structure but their state is read optically. In this study, a flexible temperature sensor read wirelessly integrated with RFID tag was described. It was fabricated with silver pastes applied by screen printing techniques on low cost flexible substrate. Antenna of a RFID tag worked in UHF frequency range in order to provide a read distance up to 1m. Its parameters were evaluated by reflection coefficient measurements and compared with simulation results. Assembly of a RFID chip was carried out with a conductive adhesive. Properties of elaborated temperature sensor were investigated depending on applied materials and a level of a testing environment temperature.

1. Introduction

One of the applications of Radio Frequency Identification (RFID) is supply chain management [1]. Stored and transported goods can be often exposed to harmful conditions. It results in the deterioration of their properties or even in their loss, like it can happen in the case of food. For this reason, it is necessary to control conditions of their storage in order to avoid waste.

Currently, mentioned above control is carried out mostly using indicators. Their color is changing after exposure on elevated temperature which can vary from 29 to 280°C [2]. However, their state is identified optically what is inconvenient and decreases a control efficiency. Apart from indicators, more and more studies are conducted on sensors integrated with RFID tag. Yao et al. [3] presented a low power temperature sensor characterized with an excellent power supply variation rejection ability for RFID tags. Similar investigations were also performed by Zhang et al. [4] and by Shenghua et al. [5]. A low power RFID tag chip equipped with temperature sensor proposed by them was fabricated with 0.18µm standard CMOS process.

Other solution of passive RFID-enabled temperature sensor was described by Guerin et al. [6]. It was a platinum-deposit based wireless temperature sensor. Along temperature variations its resistance was changing and in the consequence, the frequency of backscattering modulated signal was varied.

Temperature sensors integrated with active RFID tags were also investigated. Yang et al. [7] elaborated wireless sensor transmitter produced with inkjet printing technique. It was a registrar equipped with a temperature sensor and other electronic components, like quartz oscillator or battery. Thus, it was not flexible.

In this study, temperature sensor integrated with RFID tag fabricated on flexible substrate with screen printing technique was described. Its antenna worked in UHF frequency range. Assembly of RFID chip was carried out using a conductive adhesive. Properties of elaborated temperature sensor were determined by measurements of reflection coefficient. Influence of a level of applied testing temperature and used conductive paste on sensor properties was evaluated.

2. Materials

A paste consisted of conductive polymer PEDOT:PSS and silver flakes was used in the performed study for antenna printing. PEDOT:PSS contained in the paste EL-P3040 was bought from Agfa Gavaert [8]. Silver flakes AX-20L were purchased from Amepox Microelectronics [9]. The average particle size was
2 ÷ 4 μm and maximum agglomerate size 6 ÷ 12 μm. No additional solvent was added.

The silver paste was prepared according to following procedure. Silver flakes were added to PEDOT-PSS in the amount of 70 wt%, grinded in a mortar and finally three-roll-milled in order to break agglomerates.

Apart from mentioned above paste two other conductive materials were applied for printing of a sensing element. The first one (SF) was consisted of silver flakes dispersed in the polymer carrier poly(methyl methacrylate)-poly(butyl methacrylate) PMMA-PBMA which was dissolved in butyl carbitol acetate in the concentration of 10 wt%. It was prepared according to mentioned above procedure.

For comparison the commercial silver paste PF-050 (OEM Electronics) was used. All the screen printed conductive materials were cured in an oven in 120°C for 15 min.

Assembly process of a RFID chip was carried out with the conductive adhesive Ecolit 3654 produced by Panacol. For this material following curing conditions were applied: 120°C for 10 min [10]. Assembled chip was encapsulated with the polymer resin Epidian-53 with 10 wt% addition of the hardener Z-1. The encapsulant was dried in the ambient condition for 24 h.

The polyethylene naphthalate foil PEN (Teonex Q51) of thickness 125 μm was used as a substrate for sensor printing. It was bought from DuPont Teijin Films.

3. Antenna pattern

The antenna of RFID tag (Fig. 1) used in the elaborated temperature sensor worked in UHF frequency range.

Its dimensions were 40 x 75 mm. It was matched to a size of credit cards.

4. Results and discussion

4.1. Antenna simulation / measurements

The antenna of RFID tag was designed and simulated in IE3D. Its reflection coefficient was taken into account (Fig. 2). During simulation it was assumed that the antenna was printed on PET foil with the thickness of 125 μm, dielectric constant 2.9 and dissipation factor 0.0050. The conductivity level of used material was 2.1·10^5 S/m. The thickness of the antenna layer equaled to 17.8 μm.

The achieved results showed that the characteristic of the antenna reflection coefficient revealed a minimum -7.41 dB for the frequency 902.5 MHz (the load impedance was Z_L = 32 – 216 j [Ω]). On this basis, it can be affirmed that the designed antenna worked according to the initial assumption in UHF frequency range.

The obtained simulation results were verified by reflection coefficient measurements using a differential probe [11]. Its characteristic exhibited a minimum -8.15 dB for the frequency 832.5 MHz. Observed variation between simulation and measurements might be a result of a difference in the assumed electrical parameter of PET foil.

Despite observed variation in the basic resonant frequency it was confirmed that the antenna was designed properly.

4.2. RFID chip assembly

In the performed investigation a RFID chip in the SOT-323 packaging was assembled to the printed antenna (Fig. 4).
conducted with the Force Testing System Mecmesin i-1. The obtained shear strength equaled to 0.82 N. Its low value caused that even small mechanical stresses can result in a damage of a chip joint. For this reason, the chip after assembly process was encapsulated. It provided a huge increase in the shear strength (Fig. 5).

Achieved results implied that it is necessary to encapsulate RFID chips after their assembly process in order to increase their mechanical durability.

4.3. Sensor simulation / measurements

The conception of elaborated temperature sensor consisted in the fact that under influence of external exposure its resistance was changing rapidly, i.e. it characterized with a memory state (Fig. 6).

Proposed conception of a temperature sensor was carried out by a rapid change of connection resistance in the circuit antenna – chip under the influence of elevated temperature. It resulted in a change of matching on the input of antenna.

Reflection coefficient $S_{11}$ can be expressed by following equation [12]:

$$S_{11} = \frac{Z_{\text{ant}} - Z_{\text{obc}}^*}{Z_{\text{ant}} + Z_{\text{obc}}}$$

Antenna impedance $Z_{\text{ant}}$ is equal to:

$$Z_{\text{ant}} = R_a + jX_a$$

where:

$$R_a = R_{\text{rad}} + R_{\text{str}}$$

$$X_a = X_L + X_C$$

In the designed temperature sensor integrated with RFID tag a change in the antenna resistance $R_a$ was taking place.

$$R_a = R_{\text{rad}} + R_{\text{str}} + R_s$$  \hspace{1cm} (5)

Along with an increase in the resistance $R_s$ the antenna loss resistance grew up. It resulted in a decrease of a power of backscattering signal reached to RFID reader what can be observed in the characteristic of antenna reflection coefficient (Fig. 7).

It was noticed that the increase of the resistance $R_s$ from 0 Ω to 10 Ω and respectively from 10 Ω to 100 Ω caused about double (in dB scale) growth of value of a minimum of $|S_{11}|$. This resulted in a decrease of a power of signal reached from a RFID tag to a reader.

Described conception of a temperature sensor integrated with RFID tag was verified in the conducted measurements. The sensor was built from a few layers (Fig. 8), i.e. 1 – substrate, 2 – contact pads, 3 – conductive paste, 4 – protection layer, 5 – stabilizing layer.

The temperature sensors were fabricated with two conductive pastes: SF and PF-050 (Fig. 9). Each of them was tested in an oven in 120°C. On the basis of performed simulation (Fig. 7) it was assumed that the change of sensor state occurred when its resistance decreases below 100 Ω.

The achieved results revealed that depending on applied conductive material a reaction time of the sensor was changing. The comparison
of work characteristics for two pastes (SF and PF-050) presented in Figure 9 showed that it varied in the range of 305 ÷ 310 s for the paste SF and 25 ÷ 50 s for the paste PF-050. However, an applied initial drying of the sensor at 40°C for 5 min did not have an influence on its properties.

It was also noticed that apart from used paste a testing temperature influenced on a sensor reaction time. Table 1 presents its comparison for the sensor printed with the paste PF-050.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Reaction time [s]</th>
</tr>
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<tbody>
<tr>
<td>80</td>
<td>1198</td>
</tr>
<tr>
<td>100</td>
<td>187</td>
</tr>
<tr>
<td>120</td>
<td>37</td>
</tr>
<tr>
<td>140</td>
<td>10</td>
</tr>
</tbody>
</table>

The dependence of temperature on sensor reaction time can be described with a power function (Eq. 6):

\[ y = 2.6 \times 10^{19} \times x^{-5.584} \]  

where \( y \) means reaction time and \( x \) temperature.

The practical tests of the elaborated sensor conducted with the RFID reader t8300 t+t netcom exhibited that its read distance was equal to about 80 cm. It confirmed a proper work of tested sensor structure.

5. Summary

In this paper, the investigation of a temperature sensor integrated with RFID tag. It was carried out on flexible substrate with screen printing techniques.

The achieved results revealed that the conception of temperature sensor was properly elaborated. The designed sensor had a read distance about 80 cm. The higher its testing temperature was applied the shorter its reaction time was obtained.

The presented sensor is a base for further research which can result in the elaboration of its other types sensitive to other factors.

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Bibliography

[2] Thermax Encapsulated Indicators
[8] Datasheet of the paste EL-P3040
[9] Datasheet of the silver flakes AX-20L
[10] Datasheet of the adhesive Ecolit 3654

Author:

Kamil Janeczek
Tele & Radio Research Institute
ul. Ratuszowa 11
03-450 Warszawa
tel.: (22) 619 01 64
telefax: (22) 619 29 47
email: kamil.janeczek@itr.org.pl