Reliability of Passive UHF RFID Copper Tags on Plywood Substrate in High Humidity Conditions

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Abstract

The growth of the wireless world, especially the increasing popularity of the Internet of Things, has created a need for cost-effective and environmentally friendly electronics. Great potential lies especially in versatile applications of passive UHF RFID components. However, the reliability of these components is a major issue to be addressed. This paper presents a preliminary reliability study of glue-coated and non-coated brush-painted copper tags on a plywood substrate in high humidity conditions. The passive UHF RFID components presented in this paper are fabricated using brush-painting and photonic sintering of cost-effective copper oxide ink directly on a plywood substrate. The performance of the glue-coated and non-coated tags is evaluated through wireless tag measurements before and after high humidity testing. The measurement results show that the copper tags on plywood substrate initially achieve peak read ranges of 7-8 meters and the applied coating does not affect to the read range. Moisture does not prevent the coated tags from working in a tolerable way, although the tag performance slightly temporarily decreases due to the moisture absorption. However, when the moisture exposure is long, the performance degradation comes irreversible. The absorbed moisture decreases the read range of the non-coated tags and the performance does not return back to normal after drying. Hence, the coating improves the reliability of the tags in a moist environment compared to the non-coated tags. Based on our results, the plywood material and the used manufacturing methods are very potential for low-cost, high-volume green electronics manufacturing.

Key words: brush-painting, copper ink, photonic sintering, plywood, RFID, wood

Introduction

The desire to integrate electronics into environmentally friendly structures increases together with the popularity of the Internet of Things (IoT). The future IoT demands a massive amount of wireless identification and sensing systems. One very attractive technology to fulfill the needs of the IoT is passive ultra high frequency (UHF) radio frequency identification (RFID). This battery-free technology uses remotely addressable electronic tags composed of an antenna and an integrated circuit (IC) by using propagating electromagnetic waves. The passive UHF RFID technology is already widely used, e.g., in logistics, retail stores, libraries, and transportation. Nowadays the most used manufacturing method for passive UHF RFID components is chemical etching with polymer substrates (e.g. polyimide and polyethylene terephthalate). However, this method is not suitable for new substrate materials, e.g., wood-based materials. In addition, etching is not an environmentally friendly method, and the green values are becoming more and more important in every field of manufacturing. Another issue to be pointed out is that together with the increasing amount of identification and sensing tags in the IoT, also the amount of electronics waste rapidly increases. Thus, the use of green materials and manufacturing methods in RFID tag manufacturing is extremely important, when considering the ever increasing amount of electronics waste, which causes serious environmental concerns [1].

Wood is an environmentally friendly and biodegradable material that has a huge potential as a cost-effective substrate material in various electronics applications. The passive UHF RFID tags presented in this paper are fabricated using brush-painting and photonic sintering of cost-effective copper oxide ink directly on a plywood substrate to be embedded into wooden structures. This manufacturing method eliminates the need of a separate substrate when the item itself acts as the substrate, thus reducing the amount of needed materials altogether, and also the number of process steps is reduced.

In addition, part of the manufactured tags is glue coated after manufacturing in order to study the effect of coating on the tag reliability in humid environment. The effects of humidity on the tag performance are examined with 100% relative humidity (RH) tests. The wireless performance of the tags is evaluated in normal room conditions, after two different 100% RH tests, lasting for 5 minutes and 1 hour, and after drying for 3 days in normal room conditions.

Brush-painting

Brush-painting is an additive antenna manufacturing method, which resembles screen-printing. In brush-painting the conductive ink is applied with a brush directly on the substrate, only onto the places where the conductive pattern shoud be. A stencil is needed, especially when small dimensioned patterns are manufactured. Brush-painting has been previously successfully used in tag manufacturing on plywood substrate with silver and copper nanoparticle inks [2] and with screen printable silver ink [3].

Photonic Sintering

Photonic sintering is a very attractive sintering method, especially when considering low-cost and high-volume production. The sintering is done using a xenon flash lamp in normal room conditions. The light energy in transferred to heat energy in the surface of the conductive ink, and the ink is sintered and this way an electrically conductive structure is formed. The process time of photonic sintering is only milli- or microseconds [4], which is a huge advantage compared to widely used heat sintering, which can take tens of minutes. In addition, photonic sintering is suitable to heat sensitive materials, e. g. wood, paper and many low-cost polymers. In photonic sintering only the ink is very rapidly heated. The substrate is not absorbing light energy and transforming it to heat energy. In addition, because the sintering process is very fast, the heat energy from ink does not significantly transfer to the substrate.

The energy from each flash pulse in photonic sintering can be calculated using the following formula:

$$E = (\frac{V}{3120})^{2.4} \cdot t, \quad (1)$$

where E is the energy in Joules per pulse, V is the voltage in Volts and t is the time in micro seconds [5].

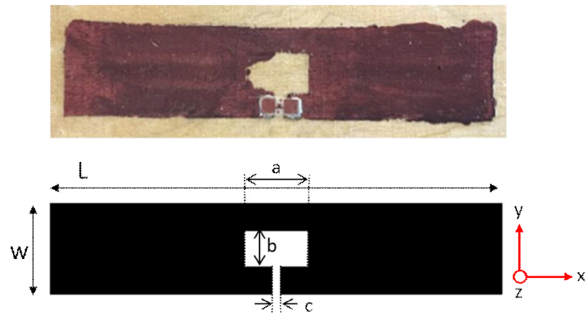
The photonic sintering of copper oxide inks has been found to be much more challenging than the photonic sintering of silver inks [6]. The copper oxide is not conducting, but the silver oxide is. On the other hand, it has been found that during the photonic sintering process the copper oxide reduces to copper [7]. The copper oxide ink can be successfully photonically sintered, but the sintering parameters need to be carefully tested for each ink and substrate material combination.

Conformal Coatings

As RFID tags are the critical enabling components of various wireless systems, they often operate in an extremely challenging environment, which requires them to endure different environmental stresses, such as high humidity. The humid environment is a challenge to a wood substrate. Wood absorbs moisture easily, and moisture affects its electrical and mechanical properties [8, 9]. For this reason electronics on a wood substrate or embedded inside wooden layers should be coated in order to increase the structure's tolerance to moisture. Many different kinds of conformal coatings can be used, e.g., epoxy, silicone, acrylic, polyurethane and parylene materials [10]. Especially epoxy is widely used in electronics because of its relatively low price combined with ease of processing, and excellent electrical, mechanical, thermal and moisture protection properties [1, 11].

Manufacturing of the Samples

In this study, cost-effective copper oxide ink (Metalon ICI-021 copper oxide ink [12]) was used. The tag antennas were brush-painted through a stencil (50 µm thick polyimide) on 4 mm thick birch plywood. Figure 1 shows the antenna design and a ready copper tag and Figure 2 shows a cross section of the used plywood material.



Geometrical parameters in millimeters

L	W	a	b	C
100	20	14.3	8.125	2

Figure 1: A ready copper tag (top) and the used antenna geometry (bottom).

Figure 2: A cross-section of the plywood substrate (thickness is 4mm).

In this study the used photonical sintering parameters were 2000 µs, 2400 V, and 2 flash pulses, the energy with these sintering parameters from the flash lamp calculated using Equation 1 is 2.1 kJ. These optimal sintering parameters for this ink and material combination were found in a previous systematic study [6]. In this study 2 flash pulses were used in order to confirm the thorough sintering result of the sample before high humidity exposure. A microscope image of the ready copper surface on plywood is presented in Figure 3.

The diagonal resistances immediately after tag antenna manufacturing are presented in Table 1. The resistances from antenna corner to corner have been measured with a Fluke 111 True RMS multimeter and the measured antenna resistances were in the range of 5.8 to 8.1 ohms. The resistances of antennas with the same design, which were fabricated with screen printable silver ink on the same substrate, have been measured to be in the range of 2 to 6 ohms [3]. The resistances of these copper antennas are thus in a good level as they are comparable to the resistances of silver antennas.

The tag chip utilized in this study was NXP UCODE G2iL series IC, which the manufacturer of the chip has mounted on a strap. We connected the strap to the antenna terminals using conductive epoxy (Circuit Works CW2400). Finally, half of the manufactured tags were coated with water-proof textile glue (Gutermann Creativ HT2).

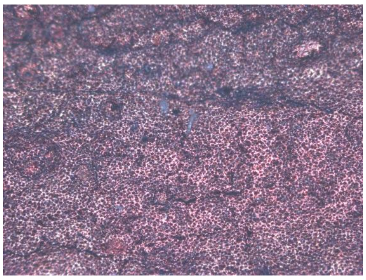


Figure 3: A microscope image (5x magnification) of a ready copper surface on plywood.

Table 1: Diagonal resistances of the samples (Ω).

Sample 1	Sample 2	Sample 3	Sample 4
5.8	6.4	6.8	8.1

Humidity Testing and Wireless Measurements

In order to find out the humidity absorbtion of the tags, the weights of the tags in normal room conditions, after two different 100% RH tests, lasting for 5 minutes and 1 hour, and after drying for 3 days in normal room conditions, were measured. The temperature in these test conditions was normal office temperature. The exact temperature in the office was not measured at the test time. The results are shown in Table 2. The sample weights were measured using Sartorius Extend ED124S precision scale. The accuracy of this scale is 0.1 mg, and it gives the result with 5 digits. The weight changes in Table 2 are in percents, and the weight is compared to the initial results for the non-coated samples and to the after-coating results for the coated samples. The weights after drying for 3 days in office conditions are very near to the initial values, indicating that the moisture has dried off almost completely.

Table 2: Tag weight measurements.

	5 min moisture	1 h moisture	After drying
Non-coated	+ 9.37 %	-	+ 0.05 %
Non-coated	-	+ 18.70 %	´+ 0.22 %
Coated	+ 7.13 %	-	+ 0.23 %
Coated	-	+ 20.34 %	+ 1.02 %

Voyantic Tagformance RFID measurement system was used to test the wireless performance of the tags in different conditions. We recorded the minimum transmitted power from the reader to activate the tag (threshold power) between 800 MHz - 1 GHz. The attainable free-space read range (d_{tag}), or theoretical read range, of the tag was used to provide universal tag characterization. The d_{tag} can be calculated based on the measured threshold power of the tag under test and a system reference tag as:

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}\ , \qquad (2)$$

where λ is the wavelength transmitted from the reader, effective isotropic radiated power (EIRP) is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, Λ is a known parameter (unit: watts) describing the sensitivity of the reference tag of the measurement system, P_{th*} is the measured threshold power of the reference tag, and P_{th} is the measured threshold power of the tag under test. In this article, all the read range results are reported under the European RFID emission regulation.

The read ranges of the non-coated and glue-coated samples were measured after manufacturing, after coating, after exposure to 100% RH, and after 3 days in normal office conditions. The results are presented in Figures 4-7, where the tag’s theoretical read range can be seen according to frequency. In general the UHF RFID tags are designed to have a clear peak frequency, in Europe this peak frequency is 865.6 MHz - 867.6 MHz. In this study the d_{tag} measurements have been done covering the whole global UHF RFID frequency band (860 MHz - 960 MHz). The most interesting information in Figures 4-7 is the European UHF RFID peak frequency, and how long the d_{tag} is in that frequency. In addition, in

Figures 4-7 interesting is also the change in d_{tag} according to tag's coating process or humidity exposure, in other words interesting is, how these affect to the d_{tag}. It is seen in Figures 4-7 that the tags manufactured in this study have good theoretical read ranges, initially over 4 meters, throughout the global UHF RFID band.

Initially all the tags achieve peak read ranges of 7-8 meters, which is well enough for most normal RFID applications. As can be seen in Figure 5 and Figure 6, the coating process and the used coating material does not have a significant effect on the read range of the tags.

It can be expected that the exposure to high humidity conditions will have an effect on the tag performance. The absorbed moisture can affect the impedance matching of the tag, as well as the dielectric constant and loss tangent of the plywood substrate [13]. As can be seen, the exposure to 100% RH reduces the d_{tag} of the non-coated tags significantly, which can be seen in Figures 4 and 5. In addition, the performance does not return back to initial after drying. The coated tags seem to endure 5 minutes exposure to 100% RH quite well, as it only causes a shift of the peak dt_{ag} to a lower frequency, and the d_{tag} returns back to initial after drying. This is shown in Figure 6. However, 1 hour exposure to 100% RH seems to cause a permanent slight decrease of the d_{tag} even for the coated tags. This is seen in Figure 7. The weight measurement results in Table 2 show that the moisture content after drying for 3 days is almost the same as before the moisture exposure, which indicates that moisture causes irreversible changes to the tag performance.

Both glue-coated and non-coated silver tags on the same substrate material have been found to recover after drying [3]. This indicates that the copper oxide ink is not as reliable in high humidity conditions as the silver ink. However, these humidity tests were very extreme, and the performance of the coated tags after 5 minutes in high humidity can still be considered to be suitable. In addition, copper oxide ink is more cost-effective, and it could definitely be an option for silver ink in dry environments.

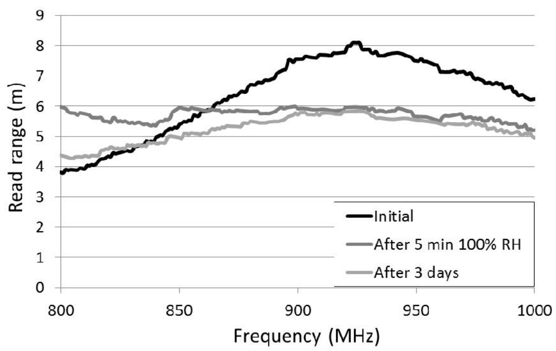


Figure 4: Measured read range for a non-coated tag after 5 min exposure for 100% RH.

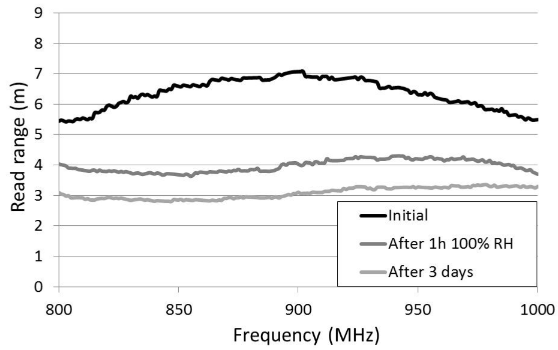


Figure 5: Measured read range for a non-coated tag after 1 h exposure for 100% RH.

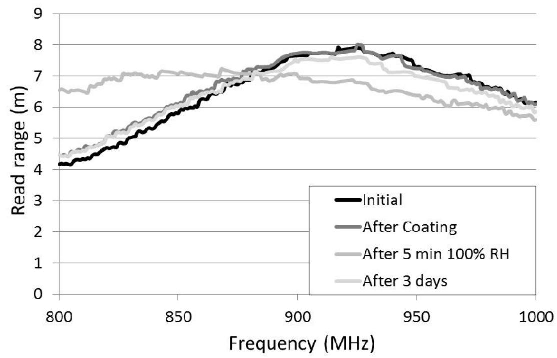


Figure 6: Measured read range for a glue-coated tag after 5 min exposure for 100% RH.

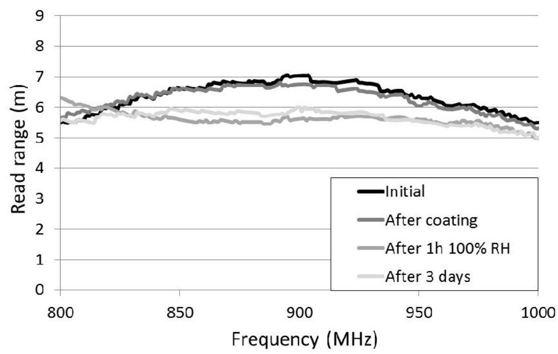


Figure 7: Measured read range for a glue-coated tag after 1 h exposure for 100% RH.

Conclusion

This paper presented a reliability study of glue-coated and non-coated brush-painted and photonically sintered passive UHF RFID copper tags on a plywood substrate in high humidity conditions. According to our results, brush-painting and photonical sintering can be used to effectively fabricate environmentally friendly passive UHF RFID tag antennas. The high humidity conditions did not prevent the glue-coated tags from working, although their wireless performance was temporary slightly decreased due to the absorbed moisture. The moisture had a stronger effect on the wireless performance of the non-coated tags and they cannot be considered to be suitable for high humidity conditions.

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