Embedding Inkjet-printed Antennas into Plywood Structures for Identification and Sensing

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Abstract— **The embedding of radio frequency identification (RFID) tags into plywood boards will enable the identification and tracking of individual plywood boards and end products of plywood. Even more benefits can be achieved by adding sensing functions into these tags. We present tags that are embeddable inside plywood by direct inkjet-printing on pure birch veneer. The use of passive UHF RFID technology in the plywood industry is discussed, two tag antenna designs for plywood are presented and the tag fabrication procedures are described. Furthermore, tag performance measurement results from various setups are presented to verify the concept of embedding RFID and sensor antennas into plywood structures. Measurements show that tags printed on veneer and embedded inside 2 mm thick plywood board exhibited theoretical read ranges from 7.9 meters to 10.3 meters. The read ranges obtained meet the demands of the plywood industry and offer reliable identification even in challenging environments.**

Keywords-identification, inkjet printing, plywood, RFID, sensing

I. Introduction

Embedding identification and sensing functions to products plays a paramount role in creating future intelligent environments and more efficient supply chains. This makes also integration of electronics and wood, especially plywood, an interesting research area.

The plywood industry needs an automated identification system which would provide identification and tracking of plywood boards throughout their whole lifetime: from production and warehousing to end products. Nowadays, identification during production and warehousing is mainly done manually by using various codes to indicate the type, production date and batch of plywood boards. The packages of plywood are bar coded after the goods leave the factory for further processing. Manually identification is prone to errors and misreads that could lead to delays or wastage. Also, external bar code labels can be easily damaged or lost.

RFID (Radio Frequency IDentification) is an effective automatic identification technology for variety of objects. With RFID systems, supply chain control and full real time visibility of the supply chain become easily obtained. Resent research results also show that integrated RFID tags may be used in sensing parameters such as moisture, temperature, and deformations, which offers even more potential use of RFID for plywood industry [1]-[4].

In this paper, we present inkjet printed UHF RFID antennas embedded into plywood structures. Our solution allows tagging of individual boards and as the tag is already inside the board, the end products of the plywood are also identifiable and traceable. Even more potential could be achieved by adding sensing functions into these tags. This paper concentrates on analyzing the use of inkjet-printed passive UHF RFID tags in plywood boards and presents tag designs for direct printing on veneer. Moreover, the inkjet fabrication process is described and results from various measurements performed on the embedded tags are presented.

II. Passive UHF RFID in the Plywood Industry

Plywood is made from thin sheets of wood veneer. These veneers are dried, glued together, pre-compressed, and then baked in a press to form the plywood panel. The panel can then be patched, re-sized, sanded or otherwise refinished, depending on the application for which it is intended. Typical end uses of plywood are e.g. floors, walls and roofs in house constructions and transport vehicles, wind bracing panels, packages and boxes, fencing, scaffolding materials, die-cutting boards, and furniture. More information can be found e.g. in [5].

This section discusses the benefits, considerations, and requirements related to the use of UHF RFID technology in the plywood industry. Lastly, the approach to directly print tags onto veneer and embed them inside plywood boards is presented.

A. Benefits of passive UHF RFID technology in the plywood industry

Commonly used barcode readers require a direct line of sight to the printed barcode, where as RFID tags can be read much faster, through various materials, and at much greater distances. In addition, the printed barcode must be exposed on the outside of the product, where it is subject to greater wear and tear. In the case of plywood, the safest place for the tag would be inside a plywood board, where it can stay the whole lifetime of the plywood product.

The RFID IC can store additional data if needed and RFID-based warehouse management can eliminate current drawbacks with the help of advanced scanning. RFID also offers a great help for after-sales services. When a customer files a complaint, the manufacturer needs to check all the information on manufacturing, transportation, and storage of a specific board. With an integrated RFID tag, the board can be quickly

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identified even in its end product form after many years in field use.

Last but not least, RFID has a lot of unused potential to increase its functionality in plywood industry by adding sensor functions to a single tag. An RFID tag with sensor functions could be used e.g. to track different environmental conditions and deformations. In addition, passive RFID sensors inside plywood structures offer long lifetime without the need for changing batteries or maintenance [4].

B. Considerations in embedding RFID tags into plywood

In the case of embedding RFID tags inside plywood boards, the tag needs to be thin, small and its coating needs to be compatible with the adhesives used to bond veneer into plywood to prevent the plywood gluing from popping open. It was found out that commercial RFID labels caused the gluing to pop open during pressing of the board. The thickness of the commercial, polymer coated tags is too large for plywood-embedding.

The read ranges of a few meters are sufficient for plywood board identification in plywood industry and much longer read ranges would not give significant benefits to the supply chain management of plywood boards or for identifying boards during field use and after-sales services.

C. Embedding RFID tags into plywood using direct inkjet-printing

To overcome the challenges in the veneer bonding, tag antennas need to be fabricated directly on pure, non-coated veneer. Such fabrication is only possible by means of additive fabrication methods such as screen printing or inkjet-printing.

Inkjet-printing was chosen for this study, as the metallization produced by the conductive ink was found to be compatible with the adhesives used in the veneer bonding process, i.e. veneer attachment was successful. The compatibility was enabled by the surface properties of the ink and by the low thickness of the ink metallization layer. Moreover, inkjet-printing has a proven track record of producing high performance tag antennas on a variety of substrate materials [6][7]. Benefits of inkjet-printing are that it is cost-efficient, since no materials are wasted and no masks are needed, and fast, since the patterns are formed from digital images. These facts enable a single printer to print countless types of planar tag antenna designs on the plywood boards. Therefore, boards can be equipped with application-specific type of tags.

After inkjet-printing the tag antennas, the RFID IC is attached using for example tape carrier package or flip chip bonding. Direct attachment of the IC with electrically conductive adhesive (ECA) bonding would probably be ideal because of a low temperature process and low cost. After the tag is assembled it can be embedded into the plywood during the standard process of veneer bonding.

III. Tag Antenna Designs for Veneer

A veneer surface is challenging for inkjet-printing due to its porosity and high surface roughness. The ink droplets are easily absorbed by the wood, preventing the nanoscale metallization particles, which are contained within by the ink, to form a conductive layer.

A unique characteristic of wood and veneer surfaces are their grain. A close-up examination of the grain reveals that the surface has valleys and hills that vary according to the grain. In the direction of the grain such variations in the surface are low, whereas against the grain variations in the surface roughness are significant. Therefore, to maximize the performance and fabrication process throughput, tag antennas should be printed in layers in the direction and against the grain. In fact, tag antennas printed only in one direction did not function even with several layers on ink.

Our preliminary tests showed also that tag antennas which had the antenna geometry printed along the grain showed the best performance. Tag antennas printed on wood should be therefore designed so that most of the surface area in the antenna is located on one axis, to the direction of the grain. This 'one axis design rule' has been one of the main design aspects in the tag antenna's presented in this paper.

The spread of the ink on the plywood surface is also a major concern. The ink spread is highest in the direction of the grain. Therefore, tag antenna designs should be optimized so that there are no narrow gaps in the direction of the grain as the ink spread can cause short circuits in these areas. The amount of ink spread is related to the size of the grain as well as on the printing resolution, which should be kept as low as possible.

Next, two different tag antenna designs, which were developed for birch veneer substrate are presented.

A. Tag antenna design parameters for veneer

The design goals for tag antennas for veneer were to achieve an omni-directional read pattern and long read range. First of these goals meant that two types of planar tag antenna types were available: a slot or a dipole antenna. A slot type tag antenna requires significantly more metallization and a larger foot print than a dipole. This led us to choose the dipole as it can be manufactured with lower production costs.

The maximal read range of a passive UHF RFID tag depends on the sensitivity of the RFID IC as well as on the gain and quality of impedance matching between the tag antenna and IC [8][9]. The read range of an arbitrary tag can be optimized by selecting an IC with a low sensitivity, maximizing the antenna gain and arranging a complex-conjugate impedance matching between the IC and tag antenna for maximal power transfer [10].

The criteria for a long read range was challenging for two reasons. Firstly, the conductivity and losses generated at UHF frequencies in inkjet-printed conductors inheritably reduce the efficiency of inkjet-printed antennas. Furthermore, plywood is a highly dissipative antenna substrate. Its losses are generally speaking over ten times higher than the losses in more traditional microwave substrate materials.

Losses caused by the inkjet-printed conductor can be minimized by printing multiple overlapping layers of conductive ink [11]. This increases the thickness of the conductor and reduces power losses. Losses caused by the plywood cannot be affected. Thus, the design of the tag antennas was focused on maximizing their radiation efficiencies, i.e. maximize antenna gain, and to optimize the tag antenna impedances to provide good power transfer to the RFID IC [12].

Table 1. Parameters used in HFSS 13.

Parameter	Value
Dielectric constant for birch plywood ε_r	2.2 (at 0.8-1 GHz)
Loss tangent δ for birch plywood	0.1 (at 0.8-1 GHz)
Plywood thickness on front | back side of the antenna	1 mm | 1 mm
Plywood size	300 mm by 300 mm
Ink conductivity	25 MS/m
Ink layer thickness	5 µm
RFID IC input impedance*	15-j150 Ω

* *example value calculated at 866 MHz*

Ansys HFSS 13, a finite element based 3-D full-wave electromagnetic simulator was used to optimize the two tag antenna structures presented in this paper. The antennas were optimized to operate with a passive Higgs-3 RFID IC from Alien Technology [13] while embedded inside oven dry, two millimeter thick, uniform birch plywood. The parameters used to model the inkjet-printed conductor silver, birch plywood, and RFID IC are listed in Table 1. The input impedance of the Higgs-3 IC was modeled using a frequency-dependent model from [14] and the dielectric properties of birch plywood were estimated from [15][16].

B. *Tag antenna designs for birch veneer*

First of the tag antenna designs for birch veneer was designed to exhibit wide operating bandwidth, referred as *wide band tag antenna*, while obeying the one axis rule. Tag layout is shown in Figure 1 and key dimensions are listed in Table 2.

A second tag antenna design, later referred as *compact tag antenna*, was created to offer a smaller physical size and faster fabrication time. The layout of the tag is presented in Figure 2 and the key dimensions of the design are listed in Table 2. The tag antenna's geometry is utilizing the one axis rule more strictly than the wide band tag design and should allow for more reliable printability.

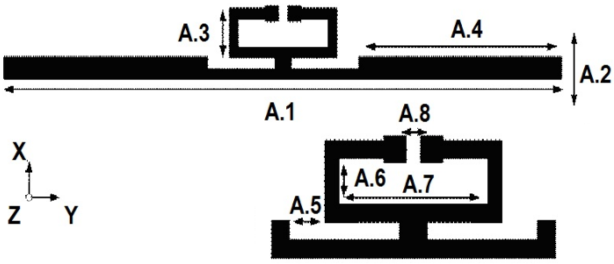

Fig. 1. Dimensions of the wide band tag antenna design for plywood.

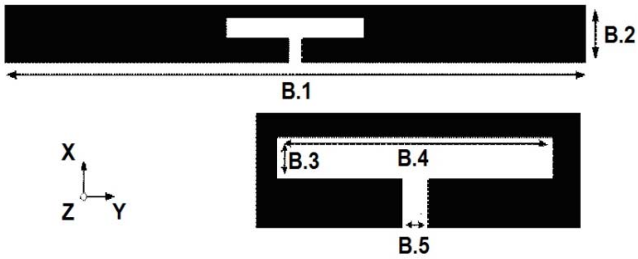

Fig. 2. Dimensions of the compact tag antenna for plywood.

Table 2. Key dimensions of the tag antenna designs for plywood.

Dimension	Wide band design A. [mm]	Compact design B. [mm]
1	123.9	86.8
2	13.2	7.0
3	9.2	2.5
4	45.1	20.7
5	4.8	2.0
6	5.1	
7	20.0	
8	2.0	

IV. TAG FABRICATION PROCESS

Samples of both tag antenna types were inkjet-printed using a Dimatix DMP-2800 material printer equipped with 10 pl print head nozzles. Harima NPS-JL [17], a silver nanoparticle ink, was used as the conductive ink. The substrate used was a 0.4 mm thick sheet of birch veneer. The key parameters of the inkjet-printing process that produced minimal ink spread are listed in Table 3.

Table 3. Key parameters of the inkjet-printing process.

Parameter	Value
Jetting voltage	24 V
Jetting frequency	9 kHz
Cartridge temperature	40 ˚C
Platen temperature	60 ˚C
Drop volume	10 pl
Printing resolution	423 dpi (60 µm drop spacing)

In the first stage of the fabrication process, the tag antennas were printed in the direction of the grain using five layers of ink. In the second stage, additional five layers of ink were added in the direction against the grain. This ensures that the plywood grain is fully filled with ink.

After the second stage, samples were sintered at 150 ˚C for 60 minutes. After sintering, the abovementioned process was repeated a second time. This was made to ensure sufficient conductor thickness for the antennas. After printing, Higgs-3 RFID ICs were attached to the samples using a conductive silver epoxy resin. Figure 3 shows a picture taken from both fully fabricated inkjet-printed tags.

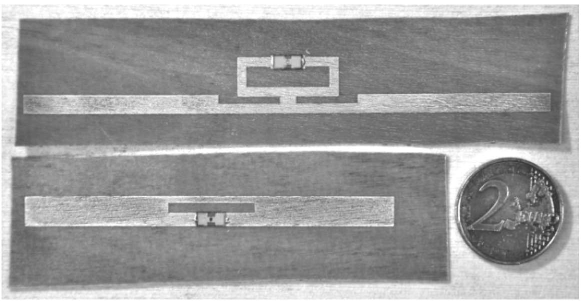

Fig. 3. Inkjet-printed samples of wide and compact tag antennas with Higgs-3 ICs on plywood.

The fabrication process can be accelerated by sintering the samples at 200 ˚C for 15 minutes in the first curing stage. The final sintering should be done for full 60 minutes to maximize the conductivity of the ink layer. Furthermore, the amount of pattern repetitions can be reduced by using printed nozzles with higher drop volumes. After inkjet-printing and attaching the ICs, the tags were embedded inside a 2 mm thick, 50 cm by 50 cm sheet of plywood.

V. Measurement Results

This section presents results from measurements that were performed to characterize the performance of the plywood-embedded inkjet-printed wide band and compact tags in various conditions.

All of the measurements were performed using UHF RFID measurement unit. It was used to characterize two key properties of passive UHF RFID tags: threshold power and theoretical read range. Threshold power describes the minimum transmit power, at the transmit port, to activate the tag. The measurement system calculates the theoretical read range based on the measured path-loss and threshold power, i.e. transmit power level at the generator output required to activate the tag under test. This calculation is made according to the following equation

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}}, \qquad (1)$$

where *EIRP* is the maximal allowed equivalent radiated power by the regulations (3.28 W in Europe), P_{TS} is the threshold power of the tag under test and L_{fwd} is the measured path-loss in the forward link in the measurement setup.

A. Plywood-embedded tags at the plywood factory

The first measurement focused on determining if the factory environment (See Figure 4) would allow measurements at the European UHF RFID band. The measurement unit was used in a monostatic configuration, i.e. single linearly polarized reader antenna (6 dBi gain) was transmitting and receiving power.

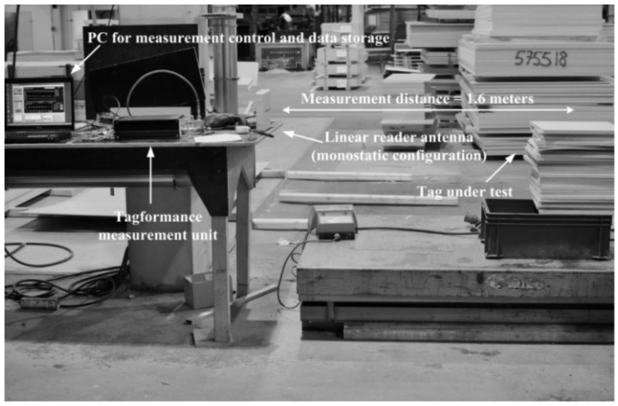

Fig. 4. Measurement setup at the plywood factory.

The acquired threshold power levels from both tag types are shown in Figure 5. The index shown in the legend describes the amount of 18 mm thick birch plywood slabs stacked on top of the tags. In the measurement setup, the tags were backed by a 40 cm tall plywood slab stack. The results verify that the fabricated embedded tags are readable in their proper application environment and that both tag types remained operational after the plywood bonding process. Both tags are readable from 1.6 meters, even when additional plywood is added on top of the tags.

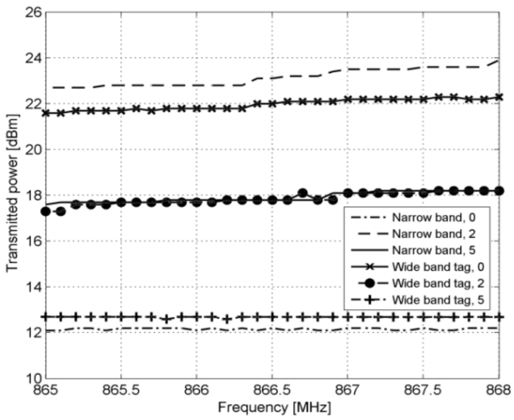

Fig. 5. Threshold sweep results acquired at the plywood factory.

B. Threshold power and theoretical read range of non-embedded and plywood embedded tags

The threshold power and theoretical read ranges of the samples were measured before and after embedding them inside the plywood from 800 MHz to 1000 MHz in a compact anechoic chamber. The measurement unit was used in conjugation with a 6 dBi linear patch antenna. The measurement distance inside UHF RFID measurement unit was 45 cm.

Figure 6 shows a comparison between the threshold power levels and theoretical read ranges of both tag types on the 0.4 mm thick plywood and once embedded in the center of a 2 mm thick plywood layer. The compact tag is showing its highest read ranges at the European UHF RFID band once embedded. The peak read range of 7.9 meters is found at 870 MHz. The wide band tag has a wider bandwidth of longer read range than the compact tag, as expected. The wide band tag could be tuned toward higher frequencies for added read range performance throughout the whole global UHF RFID band. The peak read range of 10.3 meters is found at 838 MHz.

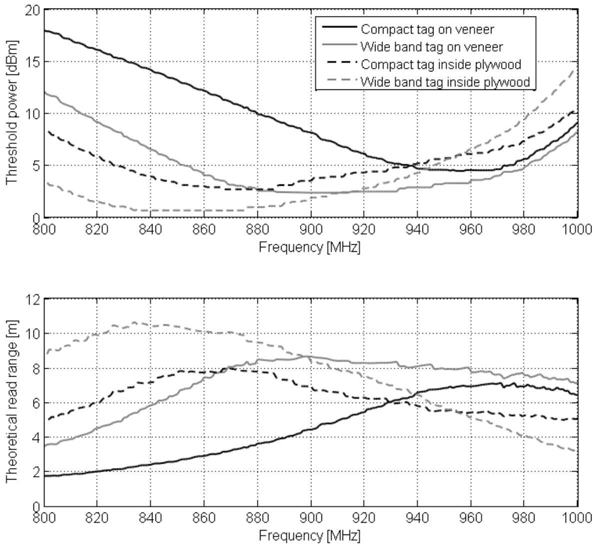

Fig. 6. Threshold and theoretical read range of non-embedded and plywood-embedded samples.

C. *Threshold power and theoretical read range of plywood embedded tags in a stack of birch plywood*

The amount of plywood around the tag can be drastically different from the design point. To evaluate the effect of added plywood layers, pieces, 18 mm thick 40 cm by 40 cm, of birch plywood (24 ˚C, 14 %wt) were added underneath and on top of the samples. The tag under test was placed in the center of the plywood stack, 20 cm from the edges of the of plywood sheet.

Figures 7 and 8 present the threshold levels and theoretical read ranges of the compact and wide band tags once additional plywood is added. The amount of birch plywood pieces added are indicated in the figure legends using a notation *number of pieces underneath | number of pieces on top* of the sample.

The embedded compact tag, in Figure 7, exhibits excellent robustness towards the amount of plywood around it. The tag has not been detuned; the tag is readable from over 5 meters throughout the whole global UHF RFID band. The read range of the tag is gradually decreased as more plywood is added.

The results obtained with the wide band tag are shown in Figure 8. The effects of the added plywood are more significant in this case. The tag is readable from a distance of 3.1 meters at 866 MHz once 90 mm of plywood is added on both sides. In this case, the tag is readable throughout the global UHF RFID band from a distance below 1.8 meters.

The results show that the decrease in the read range of the tags gets gradually smaller as more plywood is added. Therefore, the tags should be readable from a few meters away, even when stacked in to tall piles of plywood.

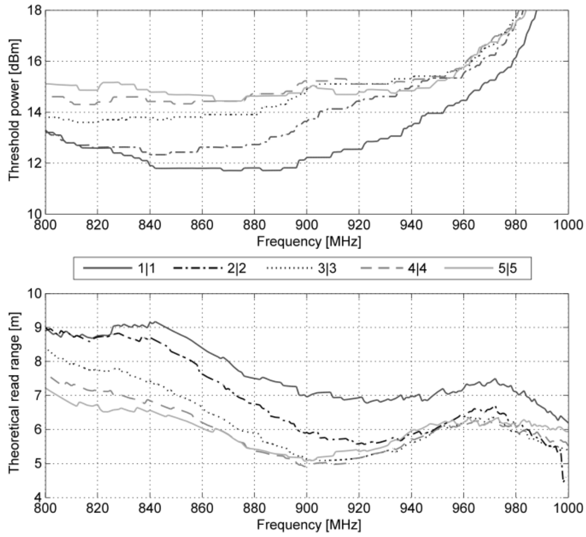

Fig. 7. Threshold and theoretical read range of the compact band tag in different plywood configurations.

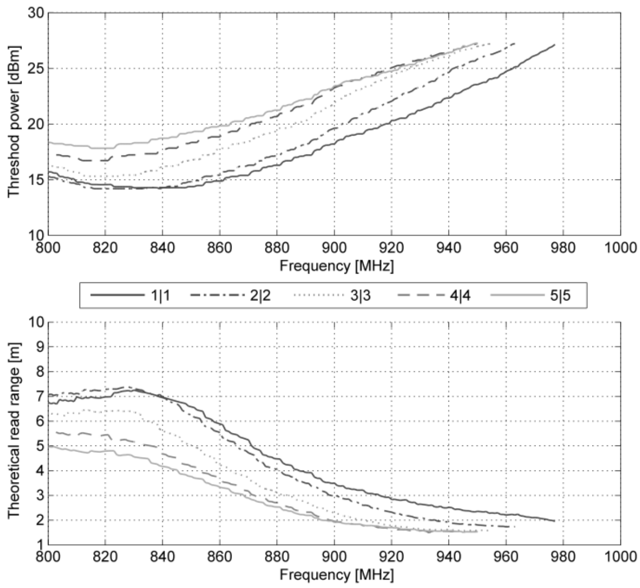

Fig. 8. Threshold and theoretical read range of the wide band tag in different plywood configurations.

VI. Practical Implications of Measurement Results

This section summarizes the finding of the measurements and discusses their implications on the usability of plywood-embedded tags.

Tags embedded in the 2 mm thick plywood sheet had a theoretical read range of 5-10 meters throughout the global UHF RFID band. The result is very applicable to many challenging identification environments.

The size and thickness of the plywood stack had a significant effect on the read range of the tags. As more plywood is piled on top of the tag, its read range is gradually decreased. This is due to the dissipated power on the plywood as the incident power from the reader is attenuated.

It should be noted, however, that all of the measurements were performed in situations where there were no adjacent tags in close proximity. In practice several tags may lay in close proximity in the plywood piles. As tags are brought closer to one another, their operation characteristics can alter significantly [18][19]. If the mutual coupling effect is not taken into account when stacking the sheets of plywood with embedded tags, the readability of the tags could be degraded.

Conclusions

Plywood-embedded tags were fabricated using direct inkjet-printing on pure birch veneer and tested for use in the plywood industry and in its end products. Also the benefits, challenges and opportunities enabled by the use of UHF RFID technology in the plywood industry were discussed.

Inkjet-printed tags are needed as the tag antenna needs to be extremely thin and compatible with the adhesives used in the plywood manufacturing process to prevent popping of the plywood sheets. It was shown that passive UHF RFID tags are inkjet-printable directly on to veneer and embeddable into plywood. The read range of the inkjet-printed plywood-embedded samples ranged between 7.9 and 10.1 meters at the European UHF RFID band. Moreover, the samples exhibited read ranges of 5-10 meters throughout the whole global UHF RFID band. The performance of the tag is more than sufficient for the requirements of the plywood industry: tags are readable from a few meters away even when stacked in tall piles of plywood and end products.

Many factors need to be taken into consideration to achieve maximal reliability and performance from tags, e.g. tag mutual coupling and the thickness of the plywood boards have effect on the operation of passive UHF RFID tags.

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References

[1] S. Merilampi, T. Björninen, L. Ukkonen, P. Ruuskanen, and L. Sydänheimo "Embedded wireless strain sensors based on printed RFID tag" Sensor Review, vol. 31, no. 1, 2011, pp. 32-40.

[2] C. Occhiuzzi, G. Paggi, and G. Marrocco "Passive RFID strain-sensor based on meander-line antennas" IEEE Transactions on Antennas & Propagation, vol. 59, no. 12, 2011, pp. 4836 -4840.

[3] M.M. Tentzeris, L. Yang, A. Rida, A. Traille, R. Vyas, and T. Wu "Inkjet-printed RFID tags on paper-based substrates for UHF "cognitive intelligence" applications" IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2007, 4p.

[4] J. Virtanen, L. Ukkonen, T. Björninen, and L. Sydänheimo "Printed humidity sensor for passive UHF RFID systems" IEEE Sensors Applications Symposium, 2010, pp. 269-272.

[5] Finnish Forest Industries Federation, Handbook of Finnish Plywood, Kirjapaino Markprint, 2002.

[6] G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M.M. Tentzeris, and L. Roselli "Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology" Microwaves, Antennas & Propagation, vol. 5, no. 8, 2011, pp. 993-1001.

[7] J. Virtanen, T. Bjo□rninen, L. Ukkonen, and L. Syda□nheimo "Passive UHF inkjet-printed narrow-line RFID tags" IEEE Antennas and Wireless Propagation Letters, vol. 9, 2010, pp. 440-443.

[8] P.V Nikitin and K.V.S Rao "Performance limitations of passive UHF RFID systems" IEEE Antennas and Propagation Society International Symposium, 2006, pp.1011-1014.

[9] K.V.S Rao, P.V. Nikitin, and S.F. Lam "Antenna design for UHF RFID tags: a review and a practical application," IEEE Transactions on Antennas and Propagation, vol. 53, no. 12, 2005, pp. 3870- 3876.

[10] K. Kurokawa, "Power waves and the scattering matrix" IEEE Transactions on Microwave Theory and Techniques, vol. 13, no. 2, 1965, pp. 194–202.

[11] J. Virtanen, T. Björninen, L. Ukkonen, K. Kaija, T. Joutsenoja, L. Sydänheimo, and A.Z. Elsherbeni "The effect of conductor thickness in passive inkjet printed RFID tags" IEEE International Symposium on Antennas and Propagation & CNC/USNC/URSI Radio Science Meeting, 2010, 4 p.

[12] K.V.S Rao, P.V. Nikitin, S.F. Lam, "Impedance matching concepts in RFID transponder design," *Fourth IEEE Workshop on Automatic Identification Advanced Technologies, 2005*, pp. 39- 42, 17-18 Oct. 2005.

[13] Alien Technology, Higgs-3, EPC Class-1 Generation-2, RFID Tag IC, Product Overview, Available Online: http://www.alientechnology.com/docs/products/Alien-Technology-Higgs-3-ALC-360.pdf

[14] T. Björninen, M. Lauri, L. Ukkonen, R. Ritala, A.Z. Elsherbeni, L. Sydanheimo, "Wireless Measurement of RFID IC Impedance," *Instrumentation and Measurement, IEEE Transactions on*, vol.60, no.9, pp.3194-3206, 2011.

[15] A. Koubaa, P. Perr, R.M. Hutcheon, J. Lessard, "Complex Dielectric Properties of the Sapwoods of Aspen, White Birch,Yellow Birch and Sugar Maple," *Drying Technology*, vol. 26, no. 5, pp. 568-578

[16] M. Tabssum, B. Colpitts, K. Galik, "Dielectric Properties of Softwood Species Measured with an Open-ended Coaxial Probe,", *8th International IUFRO Wood Drying Conference*, 2003, pp. 110-115.

[17] Harima, NPS-JL Silver Nanoparticle Ink, NanoPaste series, Metal Paste for Thin Film Formation, Datasheet, http://www.harima.co.jp/en/products/pdf/16-17e.pdf. Viewed on March 3, 2012.

[18] H.-J. Li, H.-H. Lin, and H.-H. Wu "Effect of antenna mutual coupling on the UHF passive RFID tag detection," IEEE Antennas and Propagation Society International Symposium, 2008, pp. 1-4.

[19] F. Lu, X. Chen, and T.T. Ye "Performance analysis of stacked RFID tags," IEEE International Conference on RFID, 2009, pp. 330-337.