Towards In-mould Antennas for Geolocation Tags

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Abstract— **This paper presents a preliminary study for the construction of an in-mould smart tag as a robust flexible and battery-free label with a radiofrequency energy harvesting sub-system and enhanced geolocation features. The proposed flexible geolocation tag is realized by means of a specific production process applied over printed antennas and hybridized rigid control module. Advanced materials such as highly conductive inks and nanocellulose-based substrates, as well as innovative manufacturing processes covered by the in-mould electronics framework, are investigated. Through simulations and experimental validation, the effect over printed antennas of an over-moulded layer of Thermoplastic Polyurethane (TPU) is explored. Such material due to its dielectric properties and thickness tends to down-shift the resonance frequency of the antenna, favouring miniaturization, but also increases its loss resistance. A 1.25 mm thick TPU was chosen for the final tag to ensure both flexibility and a realized positive gain of +0.7 dBi at 865 MHz. For further development of the tag, materials electrical and dielectric properties must be clearly defined in simulation to correct frequency shifts.**

Keywords— injection moulding, hybrid integration, printed electronics, antenna, wireless power transmission, geolocation

I. INTRODUCTION

Conventional tags based on Printed Circuit Board (PCB) with a protective casing limit the type of objects to be tracked according to their shape and surface material. The proposed in-mould flexible tag is intended to be attached to objects such as tools, vehicles, and parts in assembly lines compatible with curved surfaces for their geolocation. It is developed using in-mould electronics (IME), prompted as a high-speed and competitive manufacturing methodology to ensure robustness and conformability of the tag. IME combines two dissimilar manufacturing processes, which are printed electronics and plastic processing, an already established high-volume production technology based on plastic injection and thermoforming [1]. Polymer embedded antennas have been proven advantageous due to the enhanced protection towards harsh environments, temperatures, wetness and the low-permittivity of polymers which make them a suitable option for higher-frequency applications [2].

The battery-free solution to geolocate assets is proposed by Uwinloc, a company that develops and commercialises an indoor location solution. The tag is wirelessly powered thanks to an Ultra High Frequency (UHF) antenna that captures Electromagnetic (EM) waves in the European Radiofrequency Identification (RFID) frequency range from an RFID source. The accurate positioning signal is then transmitted by a UWB antenna with a centre frequency at 4 GHz [3].

The key innovation of the tag is that it is obtained by a IME processing applied over printed antennas with a directly hybridized rigid control module both elements protected by an over-moulded superstrate. Customized highly conductive inks and substrate foils are developed while the inject moulding material is appropriately chosen to both have interesting radiofrequency transparency and flexibility. This work is a part of the MADRAS project [4], which is an European project to enable the future market deployment of flexible and wearable Organic Large Area Electronics (OLAE) based products.

II. ANTENNAS DESIGN THROUGH MATERIAL CHOICE

A. Device concept

The main constraint in any wireless device is the optimisation of the antenna to efficiently receive or transmit the signal. Therefore, the solution presented in MADRAS for the flexible geolocation tag is based on two antennas:

(1) The UHF antenna used for RF WPT on the frequency range between 865 MHz and 868 MHz.

(2) The UWB antenna to transmit the location signal at the centre frequency of 4 GHz (with a bandwidth higher than 20%) to dedicated beacons in the same area.

The antennas will be connected to the RF input of a PCB electronic module that integrates a high efficiency RF to DC converter chip, a microcontroller and a UWB System on Chip (SoC). Figure 1 shows a preliminary schematic of the geolocation tag, consisting of a flexible foil based on nanocellulose with a combination of the two printed antennas and a small rigid module. These parts are integrated into a robust and flexible plastic piece through an over-moulding process. Apart from paving the path to mass production, the objective of the over-moulding is to add mechanical stiffness and protection to the vulnerable circuit elements and control module. In this paper, only the UHF antenna will be presented.

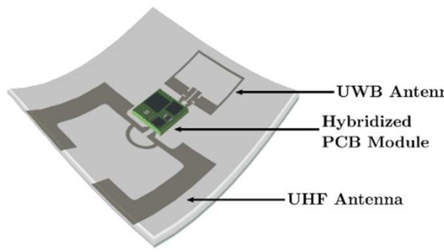

Fig. 1. 3D view of the in-mould geolocation tag. The module will be directly hybridized on the future versions of the two complex conjugate antennas. The electronic module is a 15 x15 mm all-in–one board.

B. Materials choice

The performance of antennas depends on the properties of the conductive ink, the dielectric properties of the surrounding materials, and the mismatch losses. For high efficiency antennas high conductive inks are required (less than 100 mΩ/sq of sheet resistance). Therefore, silver nanoparticle (Ag NP) ink for screen printing has been developed by Genes'ink due to its outstanding electrical properties compared to standard Ag µflakes inks (Table 1) [5, 6]. Two variants of Ag NP-based inks containing nanocellulose crystals - CNC with high conductivity (HC) and adhesion promoter (IA) were developed.

Concerning the substrate, the use of a nanocellulose-based foil (NCF) is proposed by Arjowiggins as a substitute of polymeric substrate with high recyclability and a very good oxygen barrier. The bare NCF substrate has a dielectric constant of 4.4 at 900 MHz and a dissipation factor of 0.15 at 1 kHz for a 60-µm thick foil.

Compatibility between Ag NP inks and NCF was firstly evaluated. Printed layers of the first customized Ag NP (HC) showed good adhesion to PET and paper substrates, but loose adhesion to NCF substrate. Then another version of Ag NP ink (IA) was adapted for suitable printability and adhesion on nanocellulose-based substrates. 5B adhesion (ASTM D3359 standard) was achieved with IA ink printed on NCF, though at the expense of a decrease in conductivity, as shown in Table 1, due to the presence of adhesion promoters.

TABLE I. ELECTRICAL PROPERTIES OF CONDUCTIVE LAYERS

Ink name	Rsq (mOhm/sq)	Resistivity (µOhm.cm)	Thickness (µm)
Ag µflakes ink	30-60	$30 \cdot 10^4$	7-15
Ag NP HC	22 ± 8	4.8 ± 0.8	2.3 ± 0.3
Ag NP IA	130 ± 30	20 ± 1	1.7 ± 0.3

For a successful over-moulding procedure adhesion of the NCF with the chosen injected resin is essential. In order to increase their compatibility different coatings are tested on NCF, e.g. layers of Polyvinylidene Chloride (PVDC) or polyurethane (PU) [7]. Concerning the injected resin, the most standard thermoplastic used for injection moulding of flexible plastic parts is Thermoplastic Polyurethane (TPU). Then compatibility between NCF and different grades of TPU, e.g. conventional or with higher peel strength values [8], is being evaluated.

III. IN-MOULD ANTENNAS MANUFACTURING

The in-mould antenna manufacturing process takes place at Eurecat's facility. An UHF antenna was screen printed on NCF with the two selected Ag NP inks and cut with a plotter into the shape fitting the chosen mould for plastic injection, as shown in Figure 2a.

Functional foils were over injected with TPU using a squared-shaped mould of 7 cm x 7 cm (Figure 2b) and two different thicknesses of 1.25 mm and 2.5 mm. Suitable injection flow rates, as well as pressure and temperature ranges, must be tuned to prevent washouts of the printed inks and warping [9]. To avoid excessive warping, various injection parameters were modified: lower holding pressure, higher holding pressure time and higher switch-over position. These parameters allow the polymer-NCF interface to release stresses before being injected from the mould. As a previous step to full integration of the control unit on the injected part, the resulting in-mould antenna is characterized using an external PCB with a U.FL connector [9].

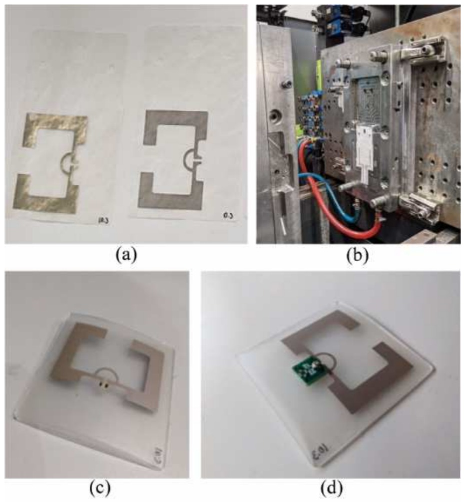

Fig. 2. (a) UHF antennas printed on NCF; (b) Injection moudling set-up; (c) View from the backside of TPU over-moulded UHF antenna printed on NCF with exposed connection pads and (d) with hybridized PCB with U.FL connector.

As shown in Figure 2d, a U.FL connector (RF Connector AMC Straight PCB Jack Surface Mount 50 Ω) was welded on one side of a simple PCB, and the other side was hybridized on the printed antenna with conductive and structural adhesives. Prior to PCB hybridization, connecting paths filled with conductive epoxy resin between each side of the NCF were done, reinforced with connection pads (Figure 2c).

IV. ANTENNA DESIGN BY SIMULATION: EFFECT OF THE TPU

The design of antenna seeks two objectives: i) the overall size of the design should fit a 7 cm x 7 cm area and ii) the performance of the antennas must be optimised considering the insertion of a certain thickness of TPU. The design of the antennas by simulation has been carried out with Ansys HFSS software by Uwinloc, considering the presence of a TPU layer with different thicknesses over the printed UHF.

Theoretically, the dimensions of an antenna are related to the dielectric permittivity and the thickness of the used substrate. The higher the dielectric constant, the smaller the antenna as it affects the guided wavelength (λ_g). This is the wavelength of the signal propagating inside a transmission line. Its value in a microstrip transmission line (MTL) can be computed thanks to formula 1:

$$\lambda_g = c/f\sqrt{\varepsilon_{eff}} \quad (1)$$

where c is the speed of light, f is the resonant frequency, and ε_{eff} is the effective dielectric constant. The last is related to the width of the MTL and the height of the substrate. It can also be affected by different elements around (e.g., housing) according to their dielectric parameters. For the preliminary simulation, the dielectric parameters of the TPU found in [10] (relative permittivity ε_r = 4.8 and dissipation factor tanδ = 0.05) were considered. Electrical properties for printed layers (Table 1) and dielectric properties of NCF were determined and introduced into the simulations as well. Thereafter, printed and over-moulded prototypes were characterised and compared to the simulated values in order to optimise the simulation's model.

A. *UHF antenna simulation*

The UHF antenna under study obtained by simulation is represented in Figure 3. The antenna must present a 50 Ω input impedance to be characterised with a standard RF connector to avoid significant measurement inaccuracies and losses. The choice to use such a RF connector allows for easily validating the results on the antenna simulation with the dielectric properties of the materials obtained. The shape of the design is based on the antenna presented in [11]. It was simulated without (wo) TPU and with TPU (1.25 mm and 2.5 mm thick) to predict the effect of the materials on the return loss and the radiation efficiency. A comparison of the simulated return loss (S11 in decibels (dB)) as function of the TPU thickness is presented in Figure 3. It is observed that the resonant frequency is downshifted by the TPU layer. This difference can be explained by the formula (1) where the guided wavelength is inversely proportional to the effective permittivity (function of the thickness). Therefore, the dielectric parameters of the TPU must be carefully characterised to have accurate simulation results.

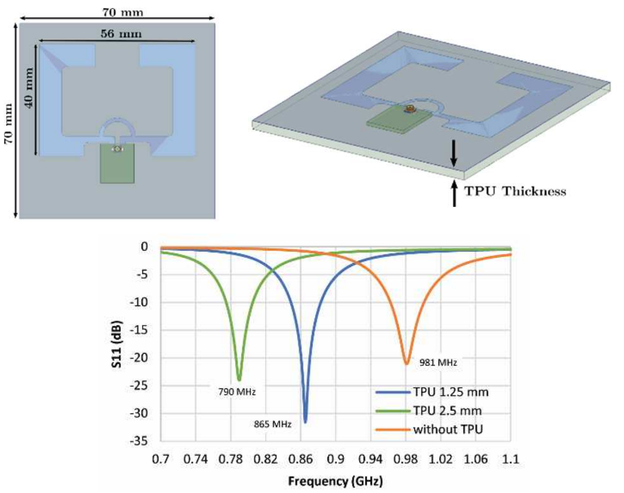

Fig. 3. Proposed design with dimensions of the UHF Antenna (top); Simulated return loss of the UHF antenna as function of the TPU thickness (bottom).

Table 1 shows the evolution of the radiation efficiency (ratio between the radiated power to the accepted power) at the desired frequency for the geolocation tag (866.5 MHz) with the TPU effect. This comparison is made on the UHF antenna printed with IA Ag NP ink on NCF substrate. It can be noticed that the radiation efficiency decreases with a thicker TPU layer at the same frequency. This difference is mainly due to the dielectric losses of the TPU given that the same substrate and same conductive ink are chosen. The reduction in efficiency is also observed at the resonant frequency of each sample (from +1.3 dBi without TPU to -0.8 dBi for with 2.5 mm thick TPU).

TABLE II. RADIATION EFFICIENCY AT 866.5 MHZ AND GAIN AT THE RESONANT FREQUENCY FOR DIFFERENT TPU THICKNESS OF THE UHF ANTENNA DESIGNS

UHF antenna designs	Radiation Efficiency at 866.5 MHz)	Radiation Efficiency / Realised Gain at the resonant frequency
without TPU	73.7 %	88.8 % / +1.3 dBi (981 MHz)
TPU 1.25 mm	73.1 %	73.3 % / +0.7 dBi (865 MHz)
TPU 2.5 mm	62 %	61.9 % / -0.8 dBi (790 MHz)

Printed layer characteristics made of different inks (HC or IA) were also introduced in the simulation. As shown on the Table 3, the antenna with the IA ink is less efficient due to its higher resistivity (the accepted power is roughly the same for both inks). Nevertheless, it was concluded that this efficiency is sufficient for a good performance of the tag, although the lower the resistivity, the better for a competitive tag.

TABLE III. SIMULATED POWER AND RADIATION EFFICIENCY OF THE ANTENNA FOR THE TWO FORMULATED INK

Ink name	Incident Power	Accepted Power	Radiation Power	Radiation efficiency
HC	30 dBm	29.9 dBm	29.62 dBm	93%
IA	30 dBm	29.85 dBm	29.22 dBm	86%

B. *Antennas characterisation*

The characterisation was performed in an anechoic chamber with the antenna placed on a Rohacell foam ($\varepsilon_r \simeq 1$; $\tan\delta \simeq 0.001$) to emulate the software simulation condition in free space. The measured return loss is obtained after SOLT calibration on the Vector Network Analyser Anristu 37397D. The results are summarized in Figure 4. A shift on the resonance frequency is observed due to the insertion of the TPU layer that is much more pronounced for the 2.5 mm-thick TPU over-layer in comparison with the 1.25 mm-thick case.

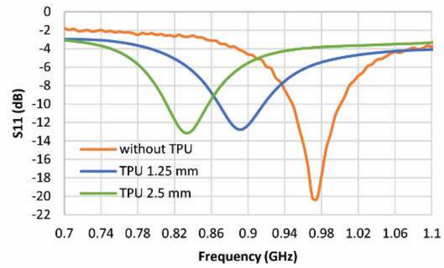

Fig. 4. Measurement of the return loss of UHF Antenna considering the effect of TPU layer.

Concerning the effect of TPU, the measurements are in good agreement with simulations: for thicker TPU, the resonant frequency of the UHF antenna is downshifted. The final geolocation tag will not work efficiently if the TPU layer changes the resonant frequency of the antenna. Hence, TPU parameters must be clearly defined on simulations before having an estimation of the antenna's performance. In fact, characterisation of each material properties used is required to obtain an accurate simulation without any significant difference in the matching and the radiation efficiency.

V. CONCLUSIONS

In this work, the feasibility of integrating a printed geolocation tag into a flexible plastic part through an innovative manufacturing process as is IME is demonstrated. The advanced materials proposed (NCF, Ag NP inks and TPU) constitute an appropriate assembly for the tag manufacturing in terms of both compatibility and appropriate antenna's performance. The use of TPU-over-moulding for antennas is interesting for miniaturization because of the guided wavelength modified by TPU dielectric permittivity. However, it can also induce loss and antenna radiation efficiency reduction.

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References

[1] Beltrão, M., Duarte, F. M., Viana, J. C. & Paulo, V. A review on in-mold electronics technology. *Polym. Eng. Sci.* 1–24, 2022.

[2] B. Mohamadzade, R. M. Hashmi, R. B. Simorangkir, R. Gharaei, S. Ur Rehman, and Q. H. Abbasi, 'Recent advances in fabrication methods for flexible antennas in wearable devices: State of the art', *Sensors*, vol. 19, no. 10, p. 2312, 2019.

[3] 'ETSI standard', Accessedon : Apr. 05, 2022. [Online]. Available: https://www.etsi.org/technologies/ultra-wide-band?jjj=1649159238342.

[4] 'MADRAS - Advanced materials and processing in organic electronics', Accessed on: Apr. 05, 2022 [Online]. Available: https://madras-project.eu.

[5] Suzuki, M.; Takahashi, T.; Aoyagi, S. 'Flexible Tactile Sensor Using Polyurethane Thin Film'. Micromachines, 3, 315-324, 2012.

[6] Salmerón, J.F., Molina-Lopez, F., Briand, D. et al. Properties and Printability of Inkjet and Screen-Printed Silver Patterns for RFID Antennas. J. Electron. Mater. 43, 604–617, 2014.

[7] D. D. Deavours, K. Demarest and A. Syed, "Effects of Antenna Material on the Performance of UHF RFID Tags," 2007 IEEE International Conference on RFID, pp. 57-62, 2007.

[8] 'Estane-ZHF_95AT3.pdf'. Accessed on: Feb. 24, 2022. [Online]. Available: https://www.lubrizol.com/-/media/Lubrizol/Engineered-Polymers/Documents/Engineered-Polymer-TDS/Estane-ZHF_95AT3

[9] 'AMC Straight PCB Jack Surface Mount 50 Ohm'. Accessed on: Feb. 8, 2022. [Online]. Available: https://www.amphenolrf.com/a-1jb.html

[10] 'ESTANE_ECO_12T80E.pdf'. Accessed on: Feb. 25, 2022. [Online]. Available: https://www.lubrizol.com/-/media/Lubrizol/Engineered-Polymers/Documents/Engineered-Polymer-TDS/ESTANE_ECO_12T80E.pdf

[11] A. Sidibe, A. Takacs, G. Loubet, and D. Dragomirescu, 'Compact Antenna in 3D Configuration for Rectenna Wireless Power Transmission Applications', *Sensors*, vol. 21, no. 9, p. 3193, 2021.