

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 label with a radiofrequency wireless power transmission system and enhanced geolocation features. The proposed flexible geolocation tag is realised 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. The effect of the thermoplastic used for in-mould process on the antenna is explored by simulations and experimental validation.

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

I. INTRODUCTION

Conventional tags based on Printed Circuit Board (PCB) with 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. 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.

A battery-less solution to geolocate assets is proposed by Uwinloc [1], a company that develops and commercialises an indoor location solution. Its expertise in the field of Radiofrequency (RF) Wireless Power Transmission (WPT) and Ultra Wideband (UWB) technology has enabled the development of an ultra-sensitive miniaturised tag. 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.

The important innovation of the tag is that it is obtained by a specific production process based on IME applied over printed antennas and hybridized rigid control module. Innovative conductive inks and substrates are developed while the inject moulding material is appropriately chosen to both have interesting radiofrequency transparency and flexibility. This work is as a part of the MADRAS project [2], which is a

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 (in a bandwidth of 250 MHz at least) 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 3D view 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 a vulnerable sensor and circuit elements. In this paper, only the UHF antenna will be presented.

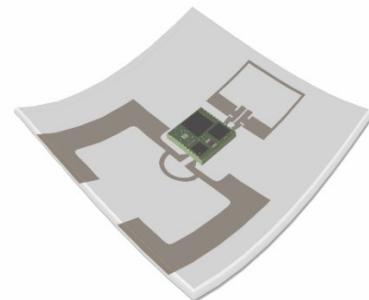


Fig. 1. 3D view of the in-mould geolocation tag. The module will be directly hybridized on a complex conjugate of the two antennas. The electronic module is a 15 x15 mm all-in-one board.

B. Materials choice

The performance of antennas depends on the properties of the conductive ink, the dielectric, 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 [3] due to its outstanding electrical properties compared to standard Ag μflakes inks (Table 1). 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 [4] 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 (um)
Ag μflakes ink	30-60	30·10 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). 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 [6], is being evaluated.

III. IN-MOULD ANTENNAS MANUFACTURING

The in-mould antenna manufacturing process takes place at Eurecat's facility [7]. A 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 [8]. To avoid excessive warping, various injection parameters were modified: lower compression force, higher compression time and higher switch-over position. These parameters allow the polymer-NCF interface to release stresses before being ejected from the mould.

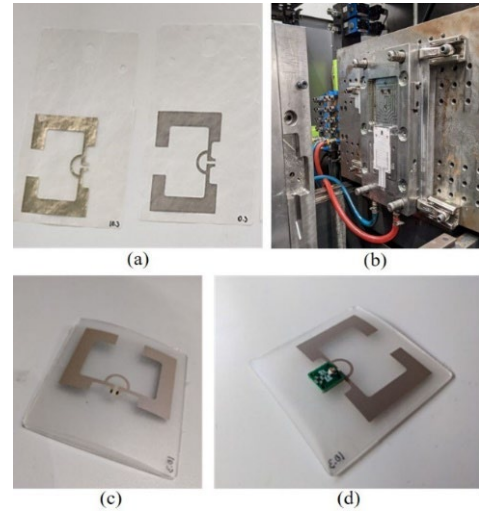


Fig. 2. (a) UHF antennas printed on NCF; (b) Injection moulding set-up; (c) View from the backside of TPU over-moulded UHF antenna printed on NCF with exposed connection pads and (d) with hybridized PCB with U.F.L connector.

To characterise the resulting in-mould antenna, a single PCB with a U.F.L connector [9] is hybridised after injection processing. As shown in Figure 2d, a U.F.L 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, connection pads and connection paths between each side of the NCF were done, filled with conductive epoxy resin (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 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 the formula 1:

$$\lambda_g = \frac{c}{f \sqrt{\epsilon_{eff}}} \quad (1)$$

where c is the speed of light, f is the resonant frequency, and ϵ_{eff} is the effective dielectric constant. This 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 [5] (relative permittivity $\epsilon_r = 4.8$ and dissipation factor $\tan\delta = 0.05$) 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 overmoulded 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. It is a conventional dipole antenna, which operates in the UHF frequency range (860 MHz-900MHz) used for RFID applications. It must present a 50Ω input impedance to be characterised with a standard RF connector to avoid significant measurement inaccuracies and losses. The shape of the design is based on the antenna presented in [10].

The proposed antenna 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 down-shifted 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.

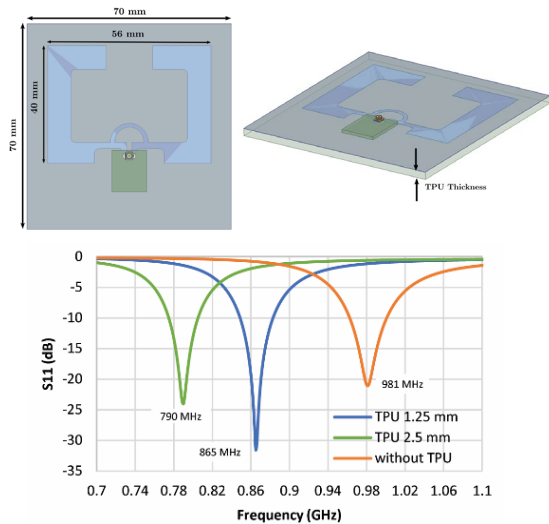


Fig. 3. Proposed design with dimensions of the UHF Antenna (top); Simulated return loss of the UHF antenna as function of the TPU thickness (bottom).

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 ($\epsilon_r \approx 1$; $\tan \delta \approx 0.001$) to emulate the software simulation condition. The results of the return loss measurement of in-mould antennas are summarized in Figure 4. A shift on the resonance frequency is observed due to the insertion of the TPU layer which is much more pronounced for the 2.5 mm-thick TPU over-layer in comparison with the 1.25 mm-thick case.

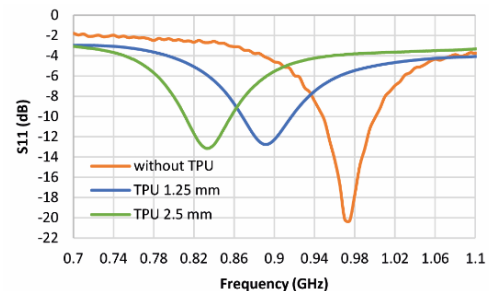


Fig. 4. Measurement of the return loss of UHF Antenna considering the effect of TPU layer.

Measurements are in good agreement with simulation: for thicker TPU, the resonant frequency of the UHF antenna is) is shifted at a lower frequency. 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 performances.

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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