Original scientific paper

Informacije MIDEM
Journal of Microelectronics, Electronic Components and Materials
Vol. 43, No. 1(2013), 50 – 57

Printed Electronics on Recycled Paper and Cardboards

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Abstract: RFID antennas can be manufactured in different ways, conventionally by etching, hot stamping or by printing. Printed RFID antennas are becoming increasingly common because of the possibility of producing RFID tags more economically, ecologically and rapidly, using roll-to-roll technology. Different printing technologies enable printing on rigid as well as on flexible materials. In our research the possibility of printing UHF RFID antennas on various low-cost and low-quality materials was analysed. Eighteen different printing materials appropriate for packaging (cardboard) and newspaper (recycled paper) printing were analysed. Firstly, the UHF antenna was designed, and then the antennas were printed using a semi-automatic screen printer. After printing, the optimal drying process was determined and the final resistance was measured. The influence of printing material roughness on line gain, print mottle and abrasion was analysed. Finally, the analysis of simulated and printed antenna was performed and, after chip integration, the final tag operation was checked.

Key words: RFID antenna design, conductive ink, antenna printing, cardboard, recycled paper.

Tiskana elektronika na recikliranem papirju in kartonu

Povzetek: Poznamo različne načine izdelave RFID anten. Lahko so proizvedene konvencionalno z jedkanjem, s folijo z vročim tiskom ali pa so natisnjene s prevodno barvo. Zaradi ekonomskih in ekoloških razlogov se v zadnjem času vse več raziskav dela na področju tiskanih RFID anten, ki so v prednosti tudi zaradi hitrosti, ki jo nudi tehnologija tiska iz zvitka na zvitek. Z različnimi tehnologijami tiska lahko dosežemo različne lastnosti odtisov, tiskamo pa lahko tako na toge kot tudi na fleksibilne materiale. V naši raziskavi smo preučili možnost tiska RFID anten na različne nizkocenovne in nizkokakovostne tiskovne materiale. Analizirali smo osemnajst tiskovnih materialov primernih za tisk embalaže (karton) in časopisov (recikliran papir). Najprej smo načrtovali UHF RFID anteno in jo natisnili s polavtomatskim strojem v tehniki sitotiska. Po tisku smo določili optimalno sušenje za doseganje minimalne upornosti prevodnih linij. Določili smo vpliv hrapavosti tiskovnega materiala na prirast linij, tiskarsko neenakomernost in abrazijo odtisov. Raziskavo smo zaključili z analizami smernega diagrama in impedance natisnjene antene, integrirali čip in preverili delovanje RFID značke.

Ključne besede: načrtovanje RFID antene, prevodna barva, tisk antene, karton, reciklirani papir

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1. Introduction

Even though printing technology has existed for centuries, as in other industries there are new opportunities for development and progress. Products that include electronic components integrated on flexible printed materials, especially different thermoplastic polymers (foils) [1-3], paper-based materials [2-10], Kapton [5, 11, 12], etc., have been developing rapidly, but no studies have analysed the potential of printing RFID antennas on recycled paper and cardboard. An increase of printed electronics is a consequence of searching for new technologies for mass and low-cost production. Both requirements can be achieved by using roll-to-roll technology with different printing techniques [13].

In the literature, the most commonly researched topics in this field are simple passive electronic components, such as RFID antennas, made using screen printing [14-17], inkjet [14, 18-20] and gravure printing [21, 22] and less commonly with flexo and offset printing technology. Many studies have also been undertaken in regard to the performance of RFID printed antennas [1, 23-27].

RFID technology is an automatic identification technology that consists of RF tags, a reader, an antenna and a deployment environment [28]. The RF tag is composed of an antenna and a chip, and can operate on different operating frequencies [29] (LF: 125–134 kHz, HF: 13.56 MHz, UHF: 860–960 MHz). With these frequencies, UHF RFID tags are mostly used for tracking in logistics; the reading distance is longer in comparison to LF or HF RFID tags.

Since the printing technologies enable printing on rigid as well as on flexible materials, in our research the possibility of printing UHF RFID antennas on different low-cost and low-quality printing materials was analysed. The antennas were printed on different types of recycled paper and cardboard appropriate for packaging (cardboard) and newspaper (recycled paper) printing. Firstly, a UHF antenna the size of a credit card was designed, and then the antennas were printed using a semi-automatic screen printer. After printing, the optimal drying process was determined for obtaining the lowest sheet resistance or maximum electrical conductivity.

The influence of printing material roughness on line gain, print mottle and abrasion was analysed. Then an analysis of simulated and printed antenna was performed. Finally, the chips were integrated with the printed antennas, and the operation of the final tags was checked.

2. Experiment

The experiment began with a selection of 18 printing materials: 9 types of cardboard (C1–C9) and 9 types of recycled paper (P1–P9). The principal characteristics of the printing materials (grammage and thickness) are shown in Table 1.

Table 1: Properties of the used printing materials.

Sample	Grammage [g/m^2] ISO 536	Thickness [μm] ISO 534
C1	245	400
C2	295	505
C3	230	285
C4	270	410
C5	230	280
C6	300	425
C7	300	380
C8	350	525
C9	300	500
P1	59.7	62
P2	80.2	75
P3	58.9	113
P4	71.6	127
P5	79.9	127
P6	60.2	80
P7	97.8	104
P8	96.5	104
P9	53.5	65

For all printing materials, roughness was determined using a TR200 profilometer. The arithmetic mean deviation of profile (arithmetic mean of the absolute values of profile deviation from mean) within the sampling length was measured. The average roughness of 15 measurements for each sample is presented in Figure 4.

The experiment was further divided into six steps (see Figure 1). Firstly, the antenna was designed and printed. Printed samples were dried and afterwards printing materials and conductive print layers were analysed. The final printed antennas were evaluated and finally the chip was integrated. At the end, a final check of the tag's operation was made.

2.1 UHF antenna design

A UHF RFID antenna at an operating frequency of 868 MHz was designed in accordance with chip specifi-

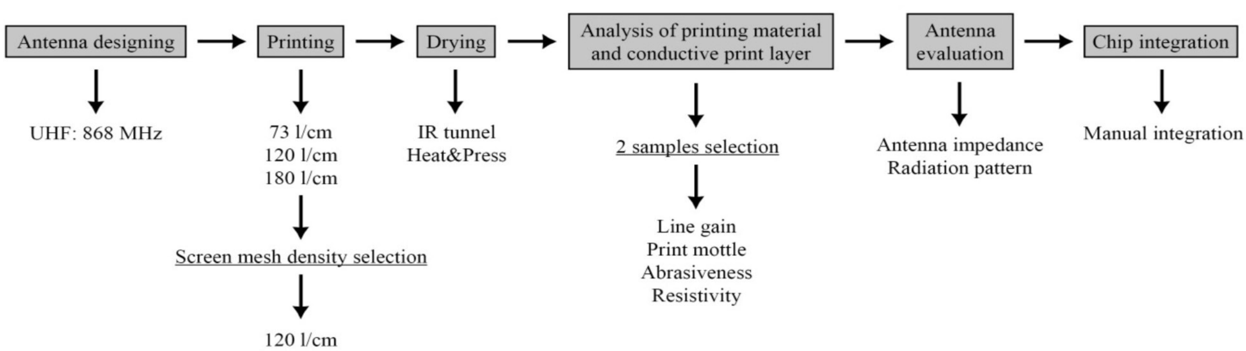

Figure 1: Scheme of experimental.

cation SL900A EPC Class 3 Sensory Tag Chip, the required size, and the printing material (cardboard and recycled paper). The specified chip impedance was Z = 20 – j325 Ω. The type of the antenna was chosen to be the capacitive-loaded (planar) dipole, which fits the standard credit-card size (Figure 2). The impedance and radiation pattern were first simulated using a commercial 3D numerical solver (Ansoft HFSS). The electrical properties of both antenna substrates (cardboard and recycled paper) were the same in the simulation, since a small deviation in the relative permittivity does not change radiation properties much. The electrical properties of both substrates were taken from the published values and were not measured or verified. The modelled antenna comprises a 0.5 mm thick substrate (relative permittivity 3.2, relative permeability 1.0, dielectric loss tangent 0.003, zero surface roughness) simulating the paper and a metallization layer with a 10 µm thickness (1.71*10e6 S/m conductivity as measured from the printed samples, zero surface roughness) simulating the conductive ink. Both surface roughnesses were set to zero in the simulation, since at the design frequency of 868 MHz a major influence on antenna parameters due to the metallization surface roughness is probable. The published relative permittivity of the paper varies from as low as 2.5 to as high as 5, depending on the composition and moisture levels, however chose an intermediate value of 3.2 in our case. The simulated impedance of the antenna model was found to be Z = 20 + j270 Ω with a radiation efficiency of 87% at the specified design frequency.

After the antenna was printed onto several samples it was also evaluated with measurements. We measured the radiation patterns (in the E and H planes) and the impedance using a custom made balun. The comparison between the simulation and measurements is given in the section 3.4 RFID antenna evaluation.

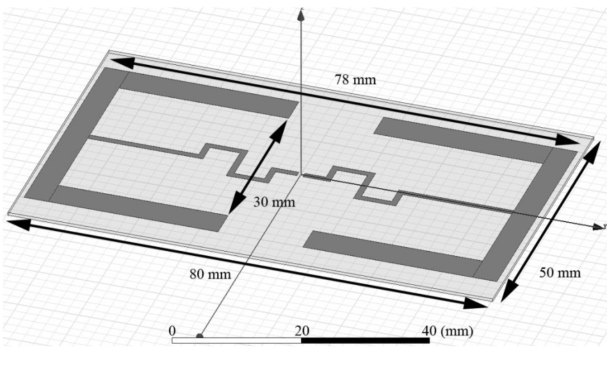

Figure 2: The antenna design.

2.2 Printing

After the antenna was designed, the printing form was prepared (Figure 3). The test elements for measuring line gain, sheet resistance and the newly designed antenna were applied. After that, all various printing materials were printed using SunChemical conductive printing ink (CRSN2442, SunTronic Silver 280, Thermal Drying Silver Conductive Ink). Tree SEFAR® high-modulus monofilament polyester plain weave meshes were applied: 73 l/cm (with theoretical ink volume 26.7 cm^3/m^2), 120 l/cm (with theoretical ink volume 16.3 cm^3/m^2) and 180 l/cm (with theoretical ink volume 9.1 cm^3/m^2) for printing with a semi-automatic screen printer.

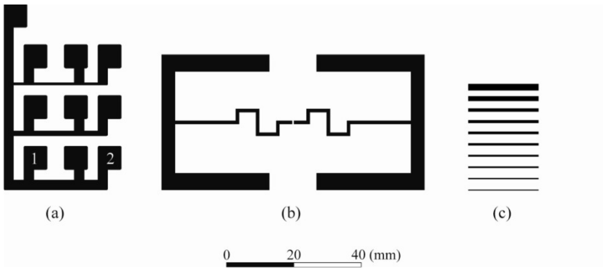

Figure 3: Printing form for printing on recycled paper and cardboard: (a) test element for measuring resistance, (b) antenna design, (c) test element for line gain determination.

2.3 Drying

After printing, the optimal drying process was determined. In accordance with the printing ink specification, drying in an IR tunnel was performed. Firstly, the drying time and temperature were varied for samples printed with all three screen mesh densities (Figure 5). The best results (the lowest sheet resistance) were obtained when samples were heated in the IR tunnel and then additionally dried with a Heat&Press process. When the optimal drying process was determined, the properties of the conductive printed layer were analysed.

2.4 Analysis of conductive print layer

Line gain, print mottle and abrasiveness

Line gain was determined by measuring the area of the ideal line on digital print form (A_{id}) and the area of the same printed line (A_p). The area of lines was determined using ImageJ software and the final ΔL was calculated (Eq. 1).

$$\Delta L = \frac{A_p * 100}{A_{id}} - 100; [\%] \quad (1)$$

Print mottle or print uniformity was determined in accordance with the traditional STFI method [30]. The calculation of the coefficient of variation (CV) was made through Eq. 2, where σ is standard deviation of the grey values, R is the mean grey value:

$$CV = \frac{\sigma}{R} * 100; [\%] \quad (2)$$

The abrasion resistance of the printed samples was analysed according to standard ASTM D 5264 on a Param RT-01 rub tester instrument. Printed samples were laid on the table and a 0.9 kg test block (mounted with an unprinted receptor of the same material) positioned on the printed sample was rubbing 500 times (cardboard) or 100 times (recycled paper). One stroke is one back-and-forth rub. While paper is rougher than cardboard, the total area coverage on the unprinted receptor comparable to cardboard was reached after only 100 strokes were applied. After rubbing, an analysis of the unprinted specimens was made and the total area coverage (%) with rubbed printing ink was determined using image analysis. The results represent the proportion of area coated with the rubbed ink on the receptor surface.

Sheet resistance

The resistance (*R*) of samples was measured using a digital multimeter DT-890G on test elements, shown on Figure 3 (a), between points 1 and 2. The normal length (*L*) between points 1 and 2 is 22 mm and width (*W*) is 3 mm. The resistance (*R*) was measured after 24 hours conditioning at 50% relative humidity and at 23°C. The nominal number of squares N_{sq} (Eq. 3) and the final sheet resistance R_{sh} (Eq. 4) of the conductive ink layer in mΩ/sq was calculated.

$$N_{sq} = \frac{L}{W} = 10.3 \quad (3)$$

$$R_{sh} = \frac{R}{N_{sq}}; \left[\frac{\Omega}{sq}\right] \quad (4)$$

2.5 RFID antenna evaluation

The printed antenna impedance was measured on a vector network analyser with the help of a balun. The latter was an interface between the symmetrical antenna port and the asymmetrical coaxial cable. The radiation patterns in the E (electric field) and H (magnetic field) planes for the printed antennas on paper and cardboard were measured at the outdoor antenna-measuring polygon.

2.6 Chip integration

After antenna evaluation, the chips were integrated on printed antennas. The manual integration of SL900A chip was applied with isotropic electro-conductive adhesive with silver particles (Bison, Netherlands). While the chip had 18 pads, the pads that are not appropriate for the connection to the antenna were covered with dielectric ink to avoid the connection of the conductive glue with inappropriate pads. The conductive ink was applied with a needle to both appropriate pads and glued to the printed antenna as a flip chip. The glue was heated for 10 min at 100°C. The final check of the RFID tag operation was made using an IDS-R902 reader with a Patch A0025 antenna (Poynting GmbH, Germany) that also measures the strength of the modulated signal backscattered from the tag. The reader supports ISO18000-6C or EPC Gen2 protocol. Its antenna (gain 6.5 dBi) emits circularly polarised UHF radiation with a frequency of *f* = 867 MHz. The reader's output power is +26 dBm (400 mW). It uses amplitude shift keying and has a maximal input sensitivity of –76 dBm.

3. Results and discussion

3.1 Roughness

The roughness of all analysed samples differs from 0.5 µm to almost 6 µm. As expected, coated cardboards have lower roughness than recycled papers, but there are also some exceptions; i.e., cardboard C3 has higher roughness than recycled papers P1 and P2. While one goal of our research was to establish the influence of surface roughness on printability, the comparison and analysis of the most and the least rough material was performed. The lowest roughness was detected on cardboard (C1) and the highest on recycled paper (P3) (Figure 4).

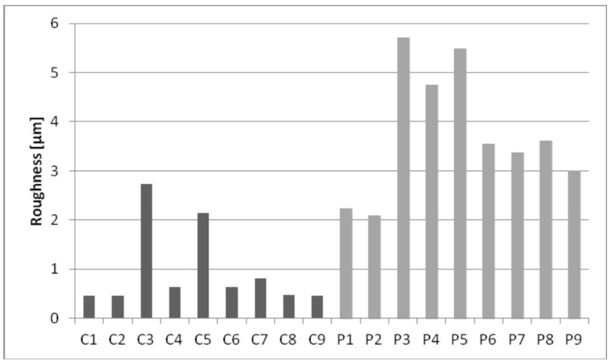

Figure 4: Roughness of all 18 printing materials.

3.2 Drying optimisation

Before drying optimisation, one of the cardboard samples (C1) was printed using all three different screen mesh densities in order to establish the influence of screen mesh density and film thickness on print layer sheet resistance. The optimal screen mesh density was determined after heating for 90 seconds at 115°C (Figure 5).

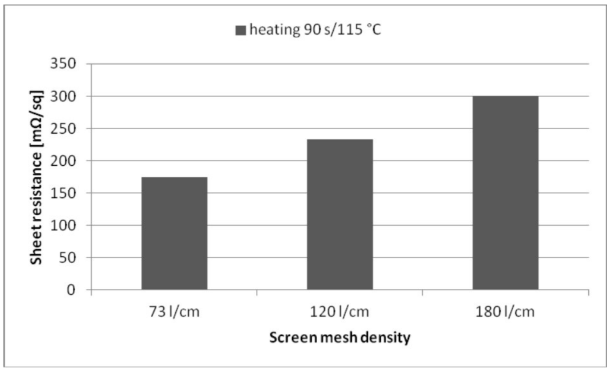

Figure 5: Sheet resistance depending on the screen mesh density and drying time (on cardboard C1).

On the basis of the results presented in Figure 5, one can see that the sheet resistance becomes higher with higher screen mesh density, but the differences are not as high as expected. Because the quantity of ink used influences the sheet resistance of the conductive printed layer, the screen density 120 l/cm was chosen for further investigation, as a compromise between sheet resistance and quantity of printing ink used. While the sheet resistance of the samples was still high after drying in the IR tunnel, additional drying with the pressure (Heat&Press device) at 3 bars was applied. With the aforementioned two-stage drying process the drying was optimised and the sheet resistance of the printed lines on all samples fell below 100 mΩ/sq. Prolonged drying or drying at a higher temperature did not influence the change of sheet resistance. Values remained constant. Final drying conditions are presented in Table 2.

Table 2: Drying conditions.

	Hot zone		Heat&Press	
Printing material	Time [s]	Temperature [°C]	Time [s]	Temperature [°C]
Cardboard	135	115	10	150
Paper	90	115	10	150

3.3 Analysis of conductive print layer

The roughness of printing materials has an impact on the positioning of the flakes of the conductive ink on the material surface [31]. Roughness also affects the quality of the prints (printability), the stability of prints, and, consequently, on abrasiveness, line gain, printing mottle and sheet resistance. In accordance with the results of roughness presented in Figure 4, two printing materials were selected: one with the lowest (C1-coated cardboard) and one with the highest (P3-uncoated recycled paper) surface roughness. This selection was made to determine how surface roughness affects the line gain, print mottle and abrasiveness of the conductive printed layer.

Line gain, print mottle and abrasiveness

The results of the analysed line gain, print mottle and abrasiveness are presented in Figure 6, where it is seen that the higher roughness of the sample P3 causes higher line gain, print mottle and abrasiveness. The difference in line gain is small (2%) - a similar result was obtained with print mottle: the largest difference is in abrasiveness where the cardboard C1 was rubbed 5 times more than recycled paper P3, but the abrasiveness is still much lower than on recycled paper.

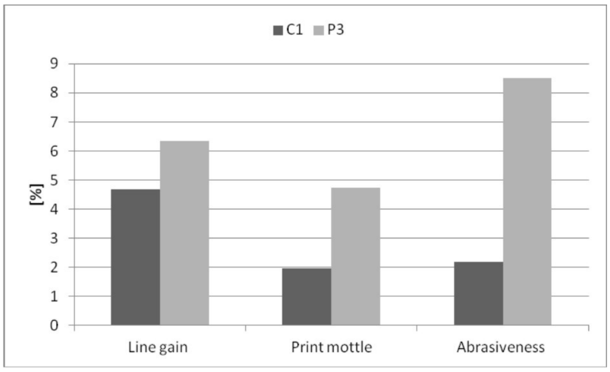

Figure 6: Line gain, print mottle and abrasiveness of selected printing materials.

Sheet resistance

The sheet resistance of printed conductive layers was measured on both selected samples. The values were almost the same: 90 ± 3 mΩ/sq. The result revealed that the printing material (and its surface properties) in our case did not have any influence on the final sheet resistance. The sheet resistance was dependent only on screen mesh density (consequently on conductive layer thickness - see the section 2.2 Printing) and on drying conditions.

3.4 RFID antenna evaluation

The radiation patterns were evaluated with measurements of the antennas printed on the selected coated cardboard C1 and the uncoated recycled paper P3. The results revealed that the patterns are nearly the same for simulated and both printed antennas, regardless of which printing material was used (Figure 7).

In addition to the radiation pattern, the impedance of the antenna was also simulated and measured (Figure 8). The correlation between the measured and the simulated antenna impedances is good. Nevertheless, there is a small deviation between the simulated and measured impedance curves, which is a consequence of the balun used for the measurement. The balun's impedance was subtracted from the measured impedance. We believe that the electromagnetic coupling be-

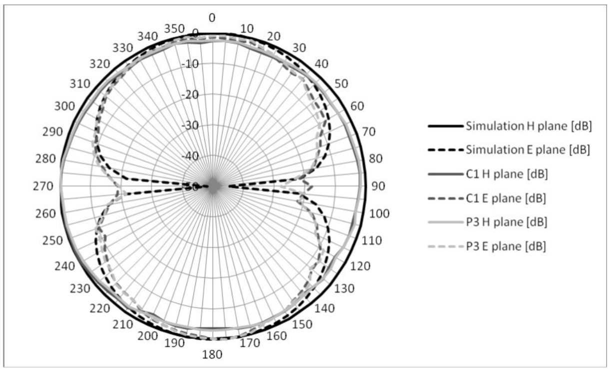

Figure 7: The simulated and measured radiation patterns of the antennas printed on both printing materials.

tween the balun and the antenna structures caused a small effect on the impedance of the printed antenna, making a slight difference between the impedances of the simulated model and the measured antenna.

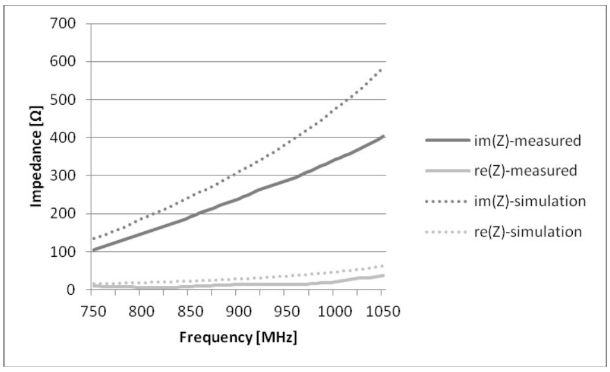

Figure 8: Simulated and measured antenna impedances.

3.5 Chip integration

When the tag was completed (Figure 9), the final operating check was made. It was found that the tags were operational and that momentary temperature could be measured, but only in the near vicinity of the reader antenna. With manual integration, the contact between the antenna and chip is definitely worse and the tag's readability is not optimal. Therefore, much effort towards optimisation remains to be done for better RFID tag operation.

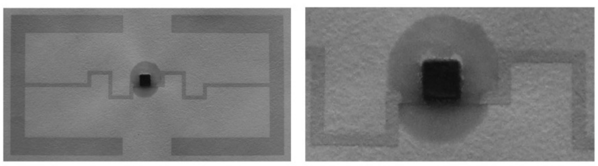

Figure 9: Final RFID tag with printed antenna and integrated chip (left), chip close-up (right).

4. Conclusions

This analysis presented the entire process of manufacturing UHF RFID tags. At the beginning, the UHF antenna was designed in accordance to the chip specification, size limitation, working frequency, and also regarding the printing material. The antenna was printed using three different screen mesh densities for obtaining three different conductive ink thicknesses (see the section 2.2 Printing) and consequently three different levels of resistance. While the resistivity was almost the same, the screen mesh density 120 l/cm was chosen for further analysis. The roughness of all eighteen samples was determined and two samples were selected, one with the highest and one with the lowest roughness. The line gain, print mottle and abrasiveness of both selected samples were analysed. Based on the results, we can conclude that the roughness of printing material has a crucial impact on the quality and the stability of the printed conductive layer. Higher roughness of the recycled paper induces higher line gain, print mottle and abrasiveness. The printed antennas were also evaluated by measuring radiation patterns and impedance. A slight difference in impedance can be observed between the measured and the simulated antennas, but mainly because of the balun used for the connection of the printed sample with the instrument. At the end, the RFID chip was integrated with the antenna and the tag's operation was checked.

We can conclude that the printing material has an impact on the printing properties of the printed antennas, and that it has a small effect on the final sheet resistance and antenna operation. The final tag was detected by the reader and momentary temperature could be measured but some improvements need to be made for better operation and reading at greater distances.

In our further research with the help of the company ams R&D, a chip with a temperature sensor will be modified to allow easier integration in the manner of a strap flip chip.

5. Acknowledgements

The authors express their gratitude to the companies ams R&D d.o.o. and RLS d.o.o. Urška Kavčič acknowledges assistance from the European Social Fund ("Operation part-financed by the European Union, European Social Fund").

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Arrived: 27. 01. 2013
Accepted: 26. 02. 2013