TECHNICAL NOTE

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Hemispherical coil electrically small antenna made by stretchable conductors printing and plastic thermoforming

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Abstract
A production scalable technique is presented to make hemispherical coil antennas by using a stretchable printed silver paste conductor and plastic thermoforming. To ease the fabrication process an unbalanced feed-structure was designed for solderless mounting on conductive materials. The manufactured antenna had a resonance frequency of 2.467 GHz with a reflection coefficient of −33.8 dB. The measured and simulated radiation patterns corresponded to that of monopole structure and the measured efficiency was 40%.

Keywords: stretchable conductors, stencil printing, 3D electrically small antenna, thermoforming

(Some figures may appear in colour only in the online journal)

Today, innovations in portable devices and wireless nodes often require communication components to be shrunk without compromising the performance or the fabrication cost. Even physically size constrained components such as antennas suffer from this requirement. Therefore, high performance three-dimensional electrically small antennas (3D ESAs) are attracting attention from both the scientific and industrial community [1–3]. 3D ESAs that should be usable on conducting surfaces generally suffers from even more design constraints than antennas on non-conducting surfaces. One way of achieving such a structure is using a spherical antenna based on the hemispherical design by Wheeler [4] and several subsequent authors [2, 5]. The performance of an ESA is very closely linked to the overall volume which it occupies. Due to this a 3D antenna, such as a hemispherical one, will be able to deliver better performance while keeping the same footprint compared to other two-dimensional (2D) antennas. Also, in order to radiate properly the antenna must not have currents directed tangential to nearby conductors, which means that many 2D antenna designs cannot be placed directly on a conductive surface. However, traditional 2D manufacturing techniques are not suitable for mass production of 3D ESAs. Therefore, it is necessary to develop new 3D techniques for these kinds of antennas. Three recent examples have demonstrated different strategies. With a dedicated 3D printer, silver based ink was printed on a hemispherical surface to make a 3D ESA [6]. By pneumatically shape a stretchable substrate with an embedded liquid alloy coil, a planar fabrication technique was proposed to make tunable hemispherical 3D ESAs [7]. Furthermore, one technique was proposed by combining transfer printing of a thin seeding layer on a thermoformed hemispherical polymer substrate and subsequent electroplating [8]. However, all these technologies still requires several steps which are not straightforward to translate into traditional low-cost manufacturing and may be difficult to scale up in production. In this note, plastic thermoforming of a

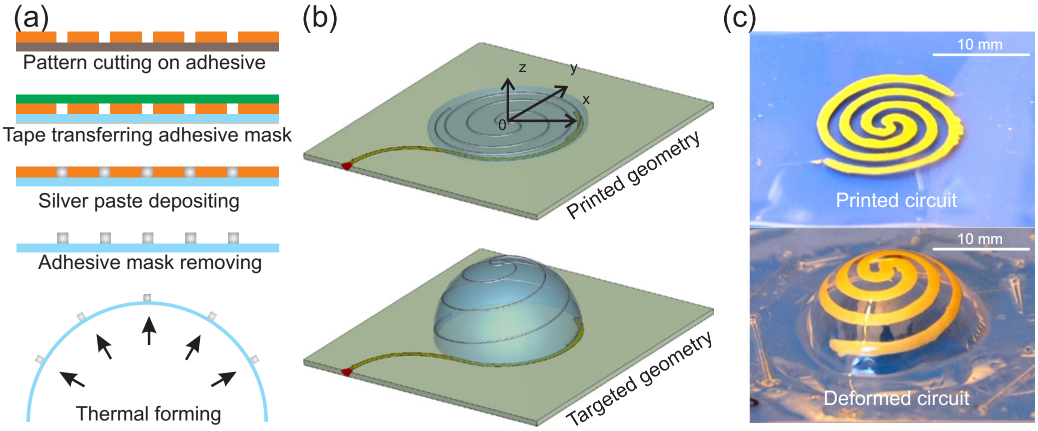

Figure 1. Schematic illustration of the fabrication of the antenna (*a*), the plastic thermoforming process (*b*), and the photos of the printed antenna before and after being thermoformed (*c*) with the conductive ink printed on the inside of the structure.

polymer substrate with a printed stretchable conductor was demonstrated to produce a hemispherical 3D ESA. The device showed a reflection coefficient of −33.8 dB at 2.467 GHz with a measured efficiency of 40%. This is a simple technique that should be compatible with large scale industry manufacturing processes.

Plastic thermoforming is widely used to make 3D structures in the food packaging industry while circuit printing techniques are widely used to make various circuits in the electronic industry. However, overlap between the manufacturing techniques used in these two industries is rare since the conductors often break when thermoformed [9]. In this note, these two techniques were combined to make a 3D ESA, enabled by a single time stretchable silver based paste. Differing from the traditional ones, this kind of silver paste was specially developed for the thermoformable processing. It can stick well to the substrate without significant delamination phenomenon during the single stretching in the thermoforming process, which is also the same process as sintering processing the traditional silver past printing. Figure 1 shows a schematic illustration of the process in a laboratory environment, the processing concept and optical photos of the fabricated samples. Here, we have to point out that the process presented here is only used for proof of concept and needs to be further refined for large scale production in industry environments. For instance, tape transferring could be replaced by a batch based screen or gravure printing [10] or even continuous rotary roll-to-roll based printing [11]. Regarding plastic thermoforming, there are a large number of industrial solutions with automatized and better controlled process to minimize human inaccuracy in the operation and hence improve the geometry and dimension uniformity, e.g. programmable pneumatic regulation of the uniformity and amplitude of the inserting force during thermoforming process and precisely regulation of the temperature when softening the substrate. We believe that such solutions will offer better dimensional control and significantly improve the performance of the antenna. Our solution still shows a strong potential for cost efficient mass production without introducing any high-cost serial processing equipment such as dedicated 3D printer [6] or deep reactive ion etching [8] as shown in the previous works.

In order to ease the fabrication process and enhance the reliability of the whole antenna, an unbalanced coupled feed design is used that enables solderless mounting of the antenna. The feed structure follows the design consideration from our recent work on a tunable microfluidic 3D ESA [7].

Our fabrication of the hemispherical part can be divided as following:

(a) The designed coil pattern was transferred to a cut adhesive tape (the thickness is around 75 μm) on wax coated paper liner (L and M series, RITRAMA, Italy) as a printing mask with a commercial cutting plotter (CraftRoboPro, Graphtec, Japan).
(b) After moving the undesired parts of adhesive tape, the adhesive mask was transferred to a 175 μm thick acrylic substrate (polymethylmethacrylate, PMMA, ME303016, Good Fellow, UK) via a transfer tape (ApliTape 4050, Rtape corp., USA).
(c) The theromoformable conductive silver paste (5043 silver conductor, Dupont, UK. According to the supplier, this silver paste was adapted from traditional silver paste with strong adhesion onto some polymer substrates to avoid delamination when stretched during the thermoforming process. The rest processing was similar to other silver paste. The resistivity is about 40 m Ω/sq/mil and can be single time stretched up to 75%. In the small radii such as sub millimeter, the stretchability will be reduced to half. After forming, the resistivity should be less than 6.5 times of the initial value.) was deposited onto the substrate via a plastic blade squeezer.
(d) The tape mask was removed and finally, after heating in a reflow oven (ProtoFlow S, LPKF, Germany) following a typical setting for small circuit board (warming up to 160 °C before sample in, warm the sample up 150 s in 160 °C, reflow 60 s targeted to 250 °C, fan cooling 70 s in the ambit air), the printed coil structure was thermoformed by pushing a home-made hemispherical silicone ball (a diameter around 16.5 mm) into a paring mold made of silicone (Elastosil RT601, Wacker Chemie, Germany), where the printed circuit was mounted in front of the opening of the mold (The paring mold of hemispherical

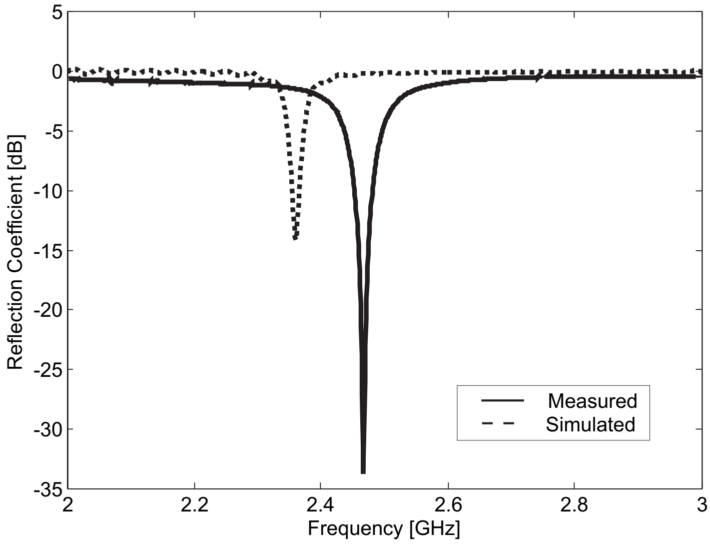

Figure 2. Measured and simulated S_{11} of the hemisphere coil ESA.

ball was replicated from a cut plastic toy ball by pouring silicone pre-polymer and curing them in the oven. And the hemispherical ball was replicated from its paring mold after silane (Trichlorododecylsilane, Sigma-Aldrich, Sweden) surface treatment in low-pressure chamber.). The final fabricated device with the conductor inside the thermoplastic hemisphere can be seen at the bottom of figure 1(*c*).

One advantage of the hemispherical coil antennas is that the electrical size can be adjusted by varying the number of turns, giving the designer a direct tradeoff between electrical size, bandwidth and efficiency. In this letter a low number of turns are used to compensate the impact of the overall efficiency due to the conductive losses introduced by using the stretchable silver paste as the antenna element conductor. The antenna is designed to be used in the 2.4–2.5 GHz industrial, scientific and medical (ISM) radio band. The size of the antenna was calculated using the equation defined in our previous paper [7] from which the required radius r_0 of a 2.45 GHz antenna using $N = 1.75$ turns can be roughly calculated as

$$r_0 = \frac{0.45c}{4f_0\sqrt{N^2 + \frac{1}{16}}E(k)}, \tag{1}$$

$$k = \frac{N}{\sqrt{N^2 + \frac{1}{16}}}, \tag{2}$$

where $E(k)$ is the complete elliptical integral as a function of the wave number k and c is the speed of light in vacuum. Using equation (1) the required radius is calculated to 7.7 mm. Using the dimensions stated above gives an ESA with $ka = 0.4$ (where a is the wavenumber and a is the radius of the smallest sphere enclosing the antenna). In the calculation of the ka value the antenna radius is taken as the hemispherical radius. Any antenna placed on a conductor exhibits ground currents which may cause the antenna to be 'virtually' larger. However, simulations indicate that the ground currents does not deviate much from the wire radius. A non-integer number of turns are used due to the manufacturing process causing the arm lengths to be slightly shorter at the ends. The actual resonance frequency from the manufactured antenna is expected to have a slightly different resonance frequency due to material loading. Regarding the processing technique used for making the presented antennas, the two major concerns which have to be considered are as follows:

(a) The printed stretchable conducting paste has considerably lower conductivity than, for example, pure copper. As the designed antenna is electrically small the radiation resistance can be expected to be low, because of this any sources of ohmic losses in the structure has large influence of the radiation efficiency of the antenna.
(b) The plastic substrate, albeit thin, adds a higher permittivity layer to the structure. This will cause the antenna resonance to be downshifted slightly. Also some losses in the dielectric layer can be expected.

Due to variations in the thermal deformation process the fabricated antenna is a bit flatter than a perfect hemisphere. The measured inner diameter of the bottom opening was around 15.5 mm while the height was around 7.2 mm. The designed line width is 800 μm, while 1 mm in width with a thickness around 60 μm was obtained after thermoforming. The slight change in the conductor cross section is not expected to impact the overall antenna performance to any considerable extent. The antenna microstrip based feed structure followed our previous design [7] and is manufactured on a Rogers 3003 1.52 mm thick ceramic-filled polytetrafluoroethylene (PTFE) substrate. The main motivation for using a coupled feed for the antenna is that it enables the use of printed stretchable silver paste for the antenna elements without the risk of using a soldering process, which may damage the plastic substrate or the paste itself. The spacing between the coil and the microstrip feed is roughly 1.5 mm. Thanks to the good stretchability of the printed conductor during the thermoforming process the total dc resistance of the printed silver paste coil was measured

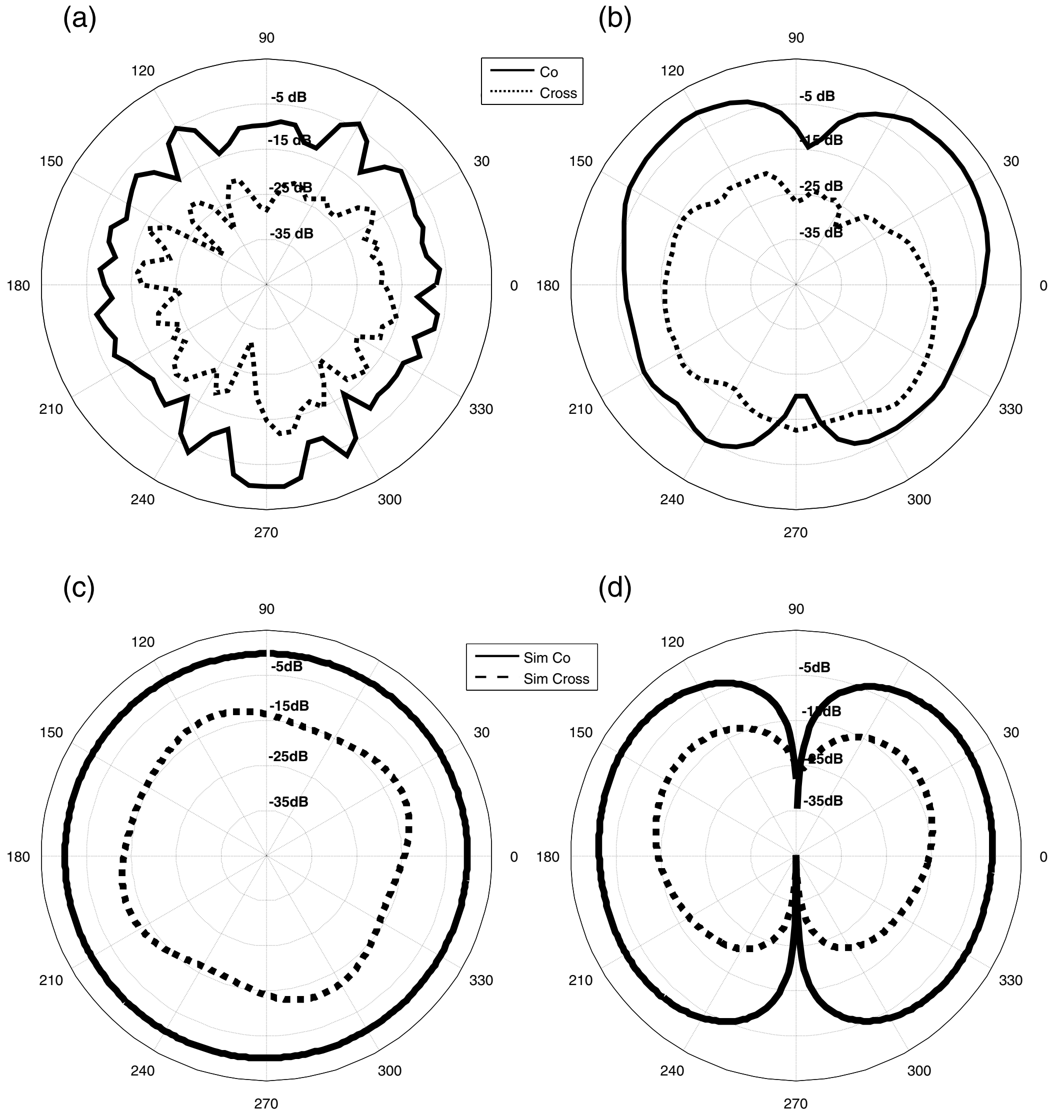

Figure 3. Measured (*a*, *b*) and simulated (*c*, *d*) radiation patterns of the ESA at its resonant frequency. The corresponding coordinate system is depicted in figure 1.

to 2 Ω between the end points. Although the ac resistance is assumed higher, the low dc resistance gives an indication about the expected antenna efficiency. The antenna reflection coefficient (S_{11}) is measured using an Agilent E8364B vector network analyzer and is presented in figure 2. The antenna exhibits a resonance frequency of 2.467 GHz with a reflection coefficient of −33.8 dB. The −12 dB bandwidth is 22 MHz and the −6 dB bandwidth is 50 MHz. At the specified resonant frequency the antennas *ka* value is 0.398. The simulated resonance frequency obtained using CST Microwave Studio was 2.36 GHz with a reflection coefficient of −14.2 dB. This is less than the measured and predicted one. The source of the difference between measured and simulated resonance frequencies is partially contributed to the difficulty of properly modeling the planar printed metal conductors for the antenna simulation.

The antenna efficiency was measured in an in-house reverberation chamber connected to the same network analyzer as were used for the reflection coefficient measurements. Two broadband high efficiency planar inverted cone antennas (PICAs) were used as reference and the efficiency was measured at 2.467 GHz. The total efficiency of the proposed antenna was 40%. The antenna radiation pattern was measured in a full-sized anechoic chamber and is presented in figure 3. The normalized antenna radiation pattern was measured in 5° resolution. Figure 3(*a*) shows the H-plane measured in both polarizations with the H-plane corresponding to the XY plane. Figure 3(*b*) shows the E-plane in both polarizations corresponding to the *XZ*-plane. As expected the antennas radiation pattern corresponds well to that of a monopole with the E-field along the *z*-axis. There are some asymmetries in the measured radiation pattern, primarily in the H-plane. These are mainly contributed to the impact of the feed connected to the antenna and the fact that the antenna ground plane is a square plate and thus not completely symmetrical. Figures 3(*c*) and (*d*) show the corresponding simulated radiation patterns obtained through CST Microwave Studio. The simulated and measured radiation patterns show good correspondence with the same difference between co and cross polarizations. The simulated values were obtained using the same type of truncated ground plane as the measured antenna.

In summary, a new concept for making hemispherical coil antennas was proposed by single repetition thermal deformation of a printed conductor patterned on a plastic substrate, and further proved by the realization of a 3D ESA based on plastic thermoforming and stretching of a printed silver conductor on an acrylic substrate. The manufactured acrylic based hemisphere helical antenna exhibited a low reflection coefficient and acceptable efficiency. This 3D ESA is suitable for mounting of conducting surfaces while maintaining good performance and small electrical size. The ease of manufacturing and the fabrication with a coupled feed (thus eliminating the need for a soldered connection to the printed antenna) allows for low-cost antenna solutions for conducting surfaces.

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References

[1] Kim O S 2010 *IEEE Trans. Antennas Propag.* **58** 2210
[2] Adams J J, Slimmer S C, Malkowski T F, Duoss E B, Lewis J A and Bernhard J T 2011 *IEEE Lett. Antennas Propag.* **10** 1425
[3] Ikonen P 2009 *Proc. 3rd IEEE European Conf. on Antennas and Propagation* (Berlin) pp 866
[4] Wheeler H A 1958 *Proc. IRE* **46** 1595
[5] Best S R 2002 *Proc. IEEE Antennas and Propagation Society Int. Symp.* (San Antonio) p 18
[6] Adams J J, Duoss E B, Malkowski T F, Motala M J, Ahn B Y, Nuzzo R G, Bernhard J T and Lewis J A 2011 *Adv. Mater.* **23** 1335
[7] Jobs M, Hjort K, Rydberg A and Wu Z G 2013 *Small* **19** 3230
[8] Pfeiffer C, Xu X, Forrest S R and Grbic A 2012 *Adv. Mater.* **24** 1166
[9] Arancio V, Dorfman J R and Nowak S 2012 *Proc. LOPE-C* (Frankfurt)
[10] Parashkov R, Becker E, Riedl T, Johannes H and Kowalsky W 2005 *Proc. IEEE* **93** 1321
[11] Krebs F C, Fyenbo J and Jorgensen M 2010 *J. Mater. Chem.* **20** 8994