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Suitability of roll-to-roll reverse offset printing for mass production of millimeter-wave antennas: progress report

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***Abstract*—In this work, we investigate different printing technologies suitable for mass production of millimeter-wave antennas and other devices, e.g., holograms and frequency selective absorbers, on flexible substrates. We concentrate especially on roll-to-roll reverse offset printing. The driving factors are low cost, high accuracy, high efficiency, and reliable performance. Therefore, we need to find and characterize suitable flexible substrates (permittivity and loss tangent at mm-wavelengths), conducting inks (viscosity, surface resistance of the resulting conducting layer), adhesion of the ink to the substrate, and feature size capable for printing mm-wave antennas and other passive devices in high volumes.**

Keywords—millimeter wave, printed electronics, flexible substrate, roll-to-roll printing, reverse offset, antenna, hologram, frequency selective absorber

I. INTRODUCTION

Internet of Things and 5G call for inexpensive electronics with high performance, e.g., high data rates, which then lead to the necessity of millimeter-wave technology. Mm-wave technology, however, has so far been rather expensive hindering its adaptation to consumer products.

Using printing techniques, different structures of large sizes can be manufactured on dielectric substrates at a very low cost compared to normal printed circuit technology. Printed electronics can also be advantageous in terms of weight, flexibility, and ease of integration into portable devices. Nowadays, there are different types of printing methods being investigated: screen printing, flexography, gravure printing, inkjet printing, offset, and reverse offset printing (RO). However, high printing resolution cannot be achieved by the first five techniques.

In this work, we concentrate especially on the capability of the reverse offset printing for fabricating millimeter-wave antennas and other devices, e.g., holograms and frequency selective absorbers, on flexible substrates, the driving factors being low cost, high accuracy, high efficiency, and reliable performance. Therefore, we first look for and characterize suitable flexible substrates (loss tangent at mm-wavelengths), conducting inks (viscosity, surface resistance of the resulting conducting layer), adhesion of the ink to the substrate, and achievable conductor thickness and accuracy when RO printing is used.

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We have started with characterization of known inexpensive substrates, such as PEN and PET, but also more specific substrates, such as Preperm 255, and measured their loss tangent at mm-wavelengths, and studied the adhesion of the inks containing silver nanoparticles to these substrates. Then we have studied the high-frequency conductivity of the resulting conductive layers. We have also designed several prototypes for printing experiments.

II. PRINTING OF ELECTRONICS ON FLEXIBLE SUBSTRATES

Printable electronics and high resolution roll-to-roll manufacturing methods have been an active topic of research for 15 years. Today we have novel methods and mature technology to demonstrate the target applications in a pilot scale. Several reviews have summarized the state of art of printed electronics materials and devices [1-5]. Many high resolution printing methods have been proposed, see, e.g., [3, 4] for producing optics and electronics, but so far techniques are limited due to the line resolution, materials, low speed or insufficient aligning accuracy. In this work, we aim at developing the reverse offset (RO) technology to the stage where a pilot-scale industrial manufacturing process is possible for target applications.

The status of roll-to-roll printing methods is presented in Fig. 1. Traditionally photolithography is widely used to print submicron scale structures, but it is quite a slow method compared to RO. Today, e.g., developments in ink-jet techniques has abled also printing of µm-scale features, but by ink-jet printing large area printing is very slow. Other often mentioned methods to produce sub-micron scale structures are e-beam lithography and self-organization, but they are not suitable for roll-to-roll manufacturing nor ready for the market (thus not shown in Fig. 1). As we can see in Fig. 1, there are no industrial methods suitable for high resolution printing (< 1 µm) with high throughput.

Fig. 2 presents the process diagram of the roll-to-roll RO printing method. First, a silicon coated polydimethylsiloxane (PDMS) blanket is covered with ink. In the second step the stamp cylinder, which can be made with high resolution

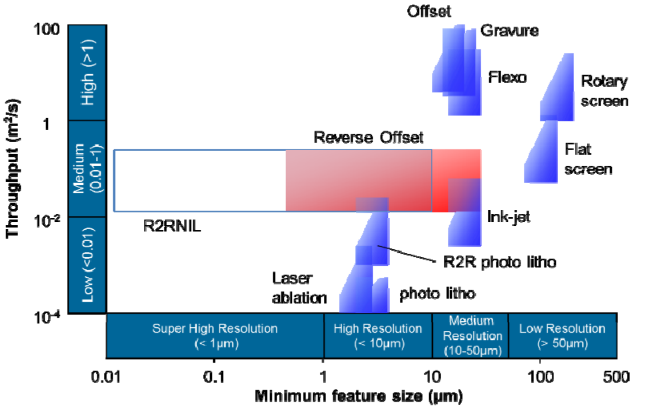


Fig. 1. Throughput and feature size of current printing methods for printed electronics (modified from OE-A Roadmap, 2013).

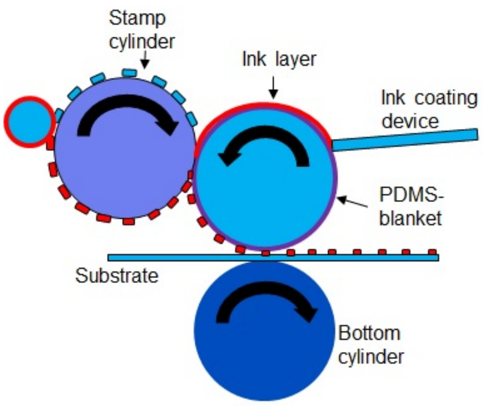


Fig. 2. Process diagram of the RO method.

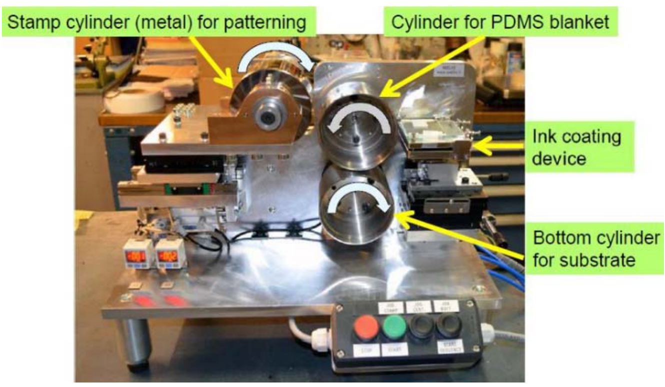


Fig. 3. RO printing equipment.

(submicron structures), removes ink from the PDMS blanket. The stamp takes all the ink in the contact area. In the third step the PDMS blanket is taken to a contact with the substrate and the remaining ink is transferred to the substrate. In Fig. 3, a photograph of our experimental RO printing facility is seen.

III. Materials and their Characterization

A. Flexible substrates and their characterisation at millimeter wavelengths

A search has been made for the suitable substrate materials for printing mm-wave components. Characterization is based on the transmission line method where the material sample is placed inside a short section of an enclosed transmission line, i.e. a rectangular waveguide, placed between two ports of a vector network analyzer [6]. The reflection and transmission S-parameter measurements are performed in the frequency range from 75 to 325 GHz, and the values of the permittivity and loss tangent are obtained in two ways: 1) fitting simulated (full-wave electromagnetic simulation with Ansoft HFSS™) S-parameters of the measured structure containing a sample of variable material parameters with the measured S-parameters ("simulated" in Table I), and 2) solving analytical equations [6] with the measured S-parameters ("measured" in Table I). Table I presents the extracted dielectric parameters of various test substrate materials at 90 GHz.

TABLE I. Dielectric parameters for different materials from simulations and measurements at 90 GHz.

Substrate material	ε_r (sim.)	ε_r (meas.)	$\tan\delta$ (sim.)	$\tan\delta$ (meas.)
Polyethylene Terephthalate (PET, Melinex)	3.5	3.4	0.035	0.03
Polymethyl Methacrylate (PMMA)	2.3	2.3	0.02	0.02
Polyimide film (PI, Kapton)	4.0	4.1	0.04	0.04
Polyethylene Naphthalate (PEN)	3.1	3.2	0.03	0.045
Preperm 255 (Plastic material)	2.5	2.4	0.005	0.004

B. Conducting ink - characterisation of the resulting conductive layers

The conductivity of an ink layer can change in a wide range depending on the original thickness of the printed (wet) ink, and the sintering time and temperature. Generally speaking, ink conductivity increases with the sintering time and temperature increase. In order to simplify the modelling of thin material sheets in simulation tools, the sheet impedance model was utilized to characterize the electromagnetic properties of ink layers. Methods based on transmission/reflection waveguide measurements were introduced for sheet impedance measurement in [7]. However, the inevitable gaps in wave-guide setups which have not been considered earlier may lead to inaccurate estimations of the sheet impedance. Here, we

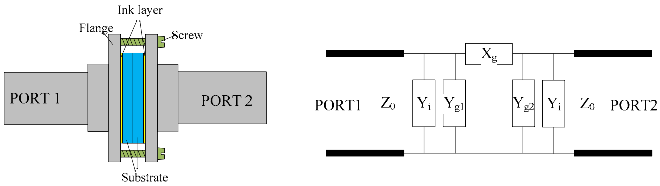


Fig. 4. The measurement setup and its equivalent circuit, where Y_i represents for ink sheet admittance.

propose a simple and accurate method which eliminates the influence of the set-up gaps, as shown in Fig. 4. The measurement contains two steps: 1) Two naked substrates were placed between waveguide flanges and the parameters of the gap X_g, Y_{g1} and Y_{g2} were extracted from the scattering parameters. 2) Two printed samples with the same size were inserted and X_g, Y_i+Y_{g1} and Y_i+Y_{g2} were obtained. After subtracting the measured admittances in these two cases, we calculate the ink admittance eliminating the influence of the gap.

The measurement results for samples at different sintering conditions are displayed in Fig. 5.

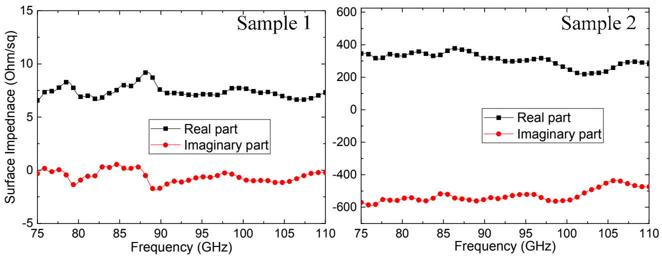


Fig. 5. Measurement results of Sample 1 and Sample 2. The DC resistance of Sample 1 is 10 Ω/sq. The sintering temperature and time of Sample 1 is 180°C /30min, while for Sample 2 it is 120°C/60min. Both samples have conductor thickness of the order of 150-200 nm.

IV. Antenna Design for Prototype Printing

For testing the suitability of roll-to-roll RO printing technique for mm-wave antennas we designed a 1x4 patch antenna array operating at 77 GHz on polyethylene terephthalate (PET) substrate. Different inks will be used in printing to identify the best suitable option in terms of conductivity. The designed antenna structure is a coplanar monopole antenna array with a ground plane below the antenna structure which allows concentrating the radiation of the antenna toward one direction [8]. Simulations of the antenna array are performed with the 3D full-wave electromagnetic field software Ansoft HFSS™. The antenna array was optimized by changing the length and width of the patch antenna elements. The antenna structure is presented in Fig. 6. The antenna array is well matched at 77 GHz. The value of the reflection coefficient at the resonant frequency is -29.2 dB.

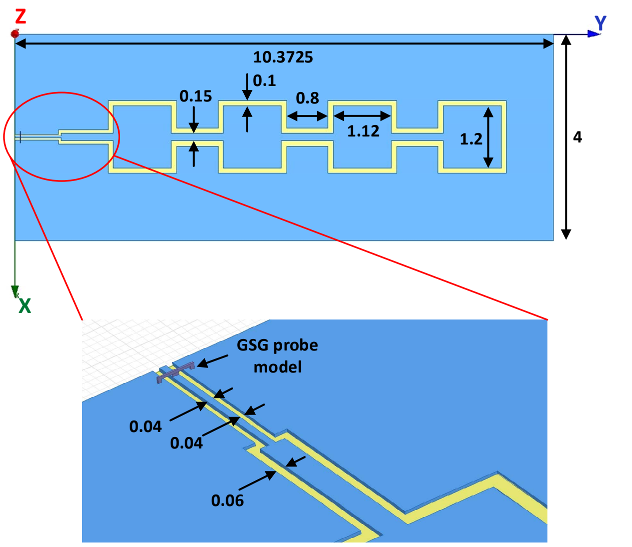
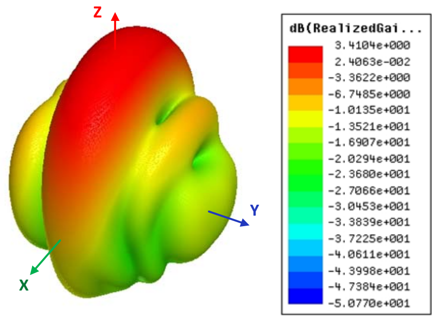
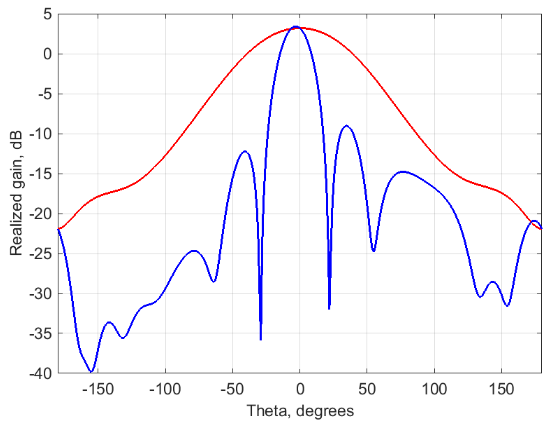


Fig. 6. Antenna array geometry (dimensions are in mm), blue color represents the ink.

In Fig. 7, 3D realized gain radiation pattern and cuts in the XZ- and YZ- planes are presented. The maximum realized gain value is 3.4 dB, which is rather low for such an antenna structure. This can be explained by high losses in the substrate material. Another low-loss substrate materials can be used to enhance the antenna performance. However, the main issue of this work is investigating the concept of the contact printing technology. When printed, the radiation pattern will be measured using the reflection coefficient method [9].



(a)



(b)

Fig. 7. Simulated (a) 3D radiation pattern and (b) realized gain radiation patterns (red line denotes XZ-plane, blue line denotes YZ-plane).

V. Hologram Based Reflector Antenna Design for Prototype Printing

Radio frequency holograms can be used for beam shaping, e.g., holograms are used as collimating elements to produce planar waves in compact antenna test ranges (CATRs) [10-13]. The planar holograms can also replace the reflector or the lens as the directive element in high-gain antennas. A novel reflection type phase hologram compatible with the reverse-offset printing technique is proposed to be used in a prototype CATR at 300 GHz. Fig. 8 shows the schematic of the CATR where a 100-mm diameter hologram is producing a quiet-zone of about 40 mm in diameter. Fig. 9 shows the cross-section of

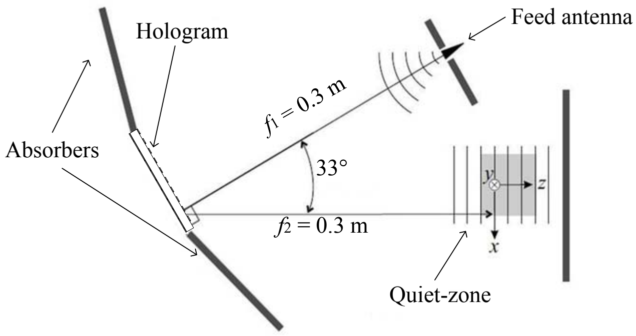


Fig. 8. Schematic of a compact antenna test range based on reflection type phase hologram.

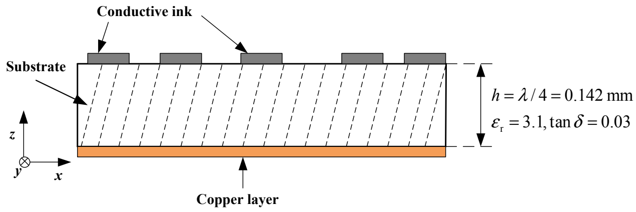


Fig. 9. Cross section of the proposed reflection type phase hologram structure for 300 GHz.

the proposed structure and the material parameters of the hologram. The conductive ink forms the binarized hologram pattern on top of the plastic substrate which has an effective thickness of about one quarter of a wavelength. Thus, a good efficiency of the hologram is expected because the wave reflected from the copper layer on the bottom of the substrate adds in correct phase with the wave reflected from the conductive ink layer on top.

VI. Frequency Selective Absorber Design for Prototype Printing

Since the sheet impedance of the ink appears strongly capacitive when the resistivity is high, as shown in Fig. 5, it is possible to utilize the high-impedance ink to make thin absorbers. The simplest design is shown in Fig. 10. The necessary resonant response is organized as a parallel-circuit of capacitive ink and inductive grounded substrate. At the resonant frequency, the *LC* circuit shows high reactance and can be viewed as a PMC (perfect magnetic conductor). The PMC response takes place only if the following resonance condition is satisfied:

$$j\,\mathrm{Im}(Y_s) + \frac{1}{j\eta_d \tan k_d d} = 0 \qquad (1)$$

where Y_s is the sheet admittance of the ink layer, and d is the substrate thickness, and η_d, and k_d are the wave impedance and wave number in the substrate, respectively. After the resonance condition is satisfied, perfect absorption occurs if the ink conductance is matched to the admittance of free space Y_0, which can be expressed as

$$\mathrm{Re}(Y_s) = Y_0 = \frac{1}{\eta_0} \qquad (2)$$

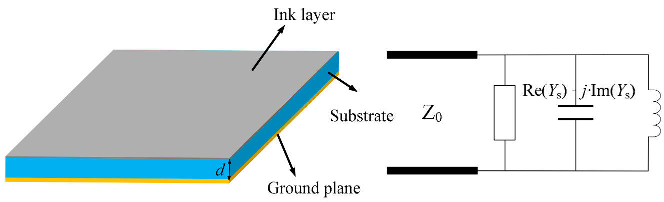


Fig. 10. A simple design of electromagnetic absorber and its equivalent circuit [14].

Suitable admittance of the ink can be obtained by different sintering environments to meet conditions (1) and (2). Supposing we get an arbitrary admittance value Y_s, the thickness of the substrate can be chosen according to resonance condition (1). Also, if Re(Y_s) is larger than Y_0, patterning the ink layer can effectively decrease its conductance.

Assuming the ink impedance be 75-150*j* Ω/sq between 75-110 GHz, the thickness of the substrate (ε_r=3.2, tanδ=0.045) is calculated from (1) to be equal to 210 μm. Strong resonance and absorption occurs at the designed frequency 92.5 GHz. The reflection coefficient as a function of the frequency is plotted in Fig. 11. As is seen, at the designed frequency the reflection level is about -38 dB that corresponds to a nearly full absorption in the ink layer.

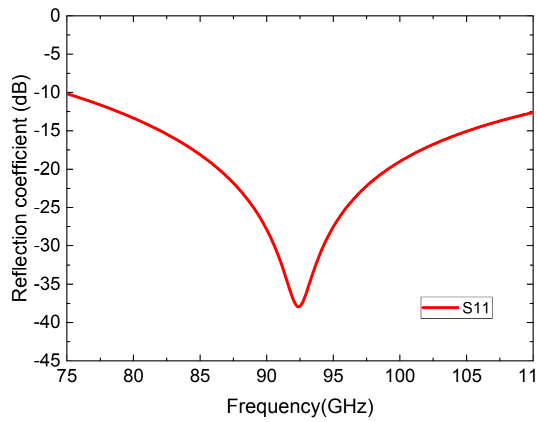


Fig. 11. The simulated reflection coefficient for Z_s=75-150j Ω/sq and d=210 μm.

VII. Discussion and Conclusions

Unfortunately, at the time of writing this report, we do not yet have any working mm-wave prototypes for testing. Problems appear in covering larger areas (~ several hundred micrometers square) with an ink layer of even thickness and even surface conductivity. In order to manage printing larger conductive areas, we are now studying how densely we can have rectangular or circular holes in the conductor not to deteriorate the conductor performance. Namely, such holes in the resulting conductor layer mean that we have extra supporting pillars in the stamp to provide more even pressure between different parts of the PDMS blanket and the stamp. Fig. 12 presents a microphotograph of a printed antenna structure with a grid-like conductors.

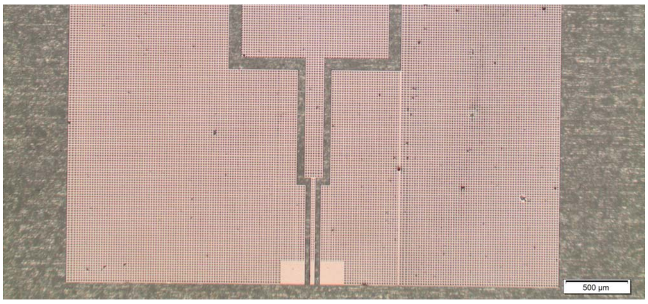


Fig. 12. Microphotograph of the manufactured antenna structure.

REFERENCES

[1] F.C. Krebs, "Fabrication and processing of polymer solar cells: A review of printing and coating techniques," *Solar Energy Materials & Solar Cells*, vol. 93, no. 4, pp. 394–412, April 2009.

[2] W. Clemens, W. Fix, J. Ficker, A. Knobloch, and A. Ullmann, "From polymer transistors toward printed electronics," *Journal of Materials Research*, vol. 19, no. 7, pp. 1963-1973, 2004.

[3] P.F. Moonen, I. Yakimets, and J. Huskens, "Fabrication of transistors on flexible substrates, from mass-printing to high-resolution alternative lithography strategies," *Advanced Materials,* vol. 24, no. 41, pp. 5526–5541, 2012.

[4] S. Khan, L. Lorenzelli, and R.S. Dahiya, "Technologies for printing sensors and electronics over large flexible substrates: a review," *IEEE Sensors Journal,* vol. 15, no. 6, pp. 3164-3184, June 2015.

[5] M. Koutake and Y. Katayama, "Reverse offset printing and specialized inks for organic TFTs," in *Int. Conf. on Electronics Packaging (ICEP2014)*, Toyama, Apr. 2014, pp. 279-282.

[6] S. Khanal, T. Kiuru, J. Mallat, O. Luukkonen, and A.V. Räisänen, "Measurement of dielectric properties at 75 - 325 GHz using a vector network analyzer and full-wave simulator," *Radioengineering Journal: Special Issue on Advanced RF Measurement*, vol. 21, no. 2, pp. 551-556, 2012.

[7] F. Costa, "Surface impedance measurement of resistive coatings at microwave frequencies," *IEEE Trans. Instrumentation and Measurement*, vol. 62, no. 2, pp. 432-437, Feb. 2013.

[8] V. Semkin, M. Kyrö, A.V. Räisänen, A. Bisognin, F. Ferrero, and C. Luxey, "Characterization of inkjet patch antenna on different ground planes at millimeter-wave frequencies," in *Loughborough Antennas and Propagation Conference (LAPC2013),* Loughborough, Nov. 2013, pp. 286-288.

[9] Z. Du, V. Viikari, J. Ala-Laurinaho, A. Tamminen, and A.V. Räisänen, "Antenna pattern retrieval from reflection coefficient measurements with reflective loads," *Progress in Electromagnetics Research*, vol. 148, pp. 15-22, 2014.

[10] J. Meltaus, J. Salo, E. Noponen, M.M. Salomaa, V. Viikari, A. Lönnqvist, T. Koskinen, J. Säily, J. Häkli, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, "Millimeter-wave beam shaping using holograms," *IEEE Trans. Microwave Theory and Techniques,* vol. 51, no. 4, pp. 1274-1280, Apr. 2003.

[11] T. Koskinen, V. Viikari, J. Häkli, A. Lönnqvist, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, "A reflection-type amplitude hologram as a collimating element in the compact antenna test range," in *Proc. 27th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, Newport, RI, USA, Oct. 30 - Nov. 4, 2005, pp. 417-421.

[12] A. Tamminen, A. Karttunen, M. Vaaja, E. Noponen, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, "Reflection-type phase hologram for beam shaping: experimental results at 310 GHz," in *30th ESA Antenna Workshop on Antennas for Earth Observation, Science, Telecommunication and Navigation Space Missions*, Noorwijk, The Netherlands, 2008, pp. 470-473.

[13] A. Karttunen, J. Ala-Laurinaho, M. Vaaja, T. Koskinen, J. Häkli, A. Lönnqvist, J. Mallat, A. Tamminen, V. Viikari, and A.V. Räisänen, "Antenna tests with a hologram-based CATR at 650 GHz," *IEEE Trans. Antennas and Propagation*, vol. 57, no. 3, pp. 711-720, March 2009.

[14] Y. Ra'di, C.R. Simovski, and S.A. Tretyakov, "Thin perfect absorbers for electromagnetic waves: Theory, design, and realizations," *Physical Review Applied*, vol. 3, p. 037001, 2015.