Challenges in Realization of Curved Metasurfaces

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***Abstract*—Curved metasurfaces enable conformal and flexible antenna solutions but introduce challenges absent in planar designs. These include optimal surface reactance synthesis, mechanical flexibility of dielectric and metallization layers, RF integration on curved geometries, and complex experimental characterization. This paper addresses each of these aspects, providing design, fabrication, and validation methodologies for curved metasurface structures.**

***Index Terms*—curved metasurfaces, flexible substrates, metallization, metasurface design, assembly of active circuitry**

I. Introduction

While planar metasurfaces have been extensively studied and their design and fabrication methodology is well developed [1], curved metasurfaces introduce additional effects not present in the planar case. For example, creeping wave losses induced by the curvature of the structure can significantly degrade metasurface radiation properties. Addressing these effects requires synthesis methods capable of retrieveing the optimal surface reactance distribution that tailors the radiation to the desired pattern. Furthermore, the development of flexible dielectric materials and reliable metallization that can be bent without mechanical or electromagnetic degradation, along with the physical and electrical co-integration of suitable RF circuitry with the curved geometry, represent additional challenges for the realization of curved metasurface structures. Experimental characterization is also nontrivial, as making robust electrical contacts and using connectors on a bent surface demands new measurement strategies. Therefore, the aim of this paper is to discuss and propose solutions for each of these challenges.

II. Synthesis of flexible dielectric materials

Flexible dielectric materials (DM) have attracted considerable attention because conventional DMs, such as inorganics (TiO_2, Al_2O_3, $BaTiO_3$ etc.) lack mechanical flexibility and are therefore unsuitable for emerging applications in antennas, wearable electronics, sensors, and actuators [2]. In contrast, intrinsically flexible polymer-based DMs provide a tuneable platform for such applications that combines favourable electrical and mechanical properties [3]. These materials can tolerate mechanical deformation without loss of their functionality, which enables their integration into deformable systems and conformal surfaces.

Permittivity and dielectric loss (particularly in high-frequency applications) are key parameters for evaluating the performance of DMs. Flexible polymers generally exhibit low permittivity [2] compared to their inorganic counterparts [4], which limits their polarization under an applied electric field. Dielectric loss, which reflects energy dissipation, varies widely in polymers. Although both parameters depend on the frequency of the applied field, temperature, and morphology, they are also strongly influenced by the chemical structure (presence of polar groups) and composition of the polymer. Therefore, maintaining the mechanical properties of polymer materials, while simultaneously tuning their dielectric properties, can be successfully achieved via molecular structure modification [5], by incorporating dielectric additives via a blending approach [6].

For structural modification, considerable effort has been devoted [5] to modifying the dielectric properties of intrinsically flexible polymers by selecting or introducing specific functional groups, using homopolymerization, copolymerization, or post-modification synthetic strategies. On the other hand, blending polymers with different polymers, or forming composites with ceramics or conducting nanoparticles via solution-mixing and casting processing also offers exceptional versatility for tuning dielectric properties, as the overall dielectric and mechanical properties of the final material can be adjusted to desired levels by tuning the amount of additives [5], [6].

In summary, advances in polymer synthesis and blending techniques are expected to enrich our understanding of structure-property relations, further expanding the potential of polymeric dielectrics, and their use for future electronics devices. For realization of metasurfaces with arbitrary curvature in the mmWave band we have synthesized flexible substrate with relative permittivity 2.85 and losses smaller than 10^{-3}.

III. Metallization of flexible dielectric materials

The metallization of flexible dielectrics for curved metasurfaces must reconcile electrical conductivity, mechanical durability, and compatibility with an increasingly diverse range of substrates. Beyond conventional polymer films such as PET or polyimide, future applications will involve substrates with stricter constraints on maximum processing temperatures, as well as bio-derived and sustainable substrates in response to societal demands. Additive manufacturing, particularly printing technologies inherited from the graphic arts, is emerging as a promising solution, though it faces challenges such as inhomogeneous film thickness caused by drying and spreading phenomena. Conductive inks can now be sintered at temperatures as low as $100°$C while maintaining high performance, with typical screen-printed silver inks achieving conductivities in the range of $1–5{\cdot}10^6$ S/m. Copper-based inks, once hindered by oxidation, are increasingly viable thanks to improved stabilization, while stretchable inks with elongation capabilities exceeding 200–300% significantly enhance the conformability of radiating or sensing structures.

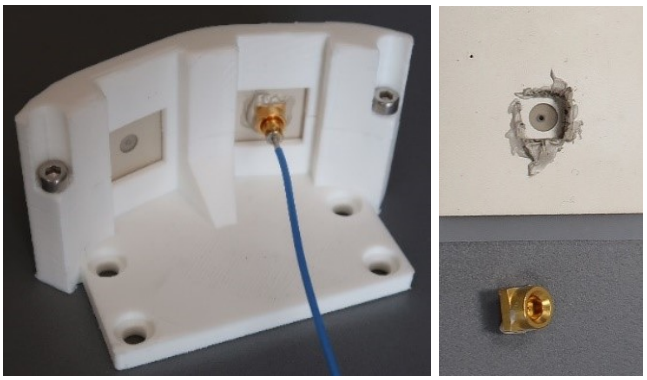
A useful way to classify metallization approaches is by considering whether the target geometry corresponds to a developable or non-developable surface. For developable surfaces (e.g., cylinders, cones), planar patterning followed by forming or transfer methods is generally sufficient, and scalable deposition or printing techniques can be readily applied. In contrast, non-developable surfaces (e.g., spheres, complex double-curvature geometries) require more advanced strategies to accommodate strain without compromising conductivity. In this domain, the literature highlights stretchable electronics [7], origami- and kirigami-inspired architectures [8], substrate-free transfer methods (where pre-fabricated metallized patterns are laminated directly onto 3D objects [9]), as well as water transfer printing, which has recently been demonstrated as an efficient approach for conformal metallization of highly curved geometries [10]. Direct printing on curved objects also represents a promising route; however, current limitations in printhead miniaturization and process speed restrict its applicability, particularly for sharp or re-entrant curvatures.

Overall, the choice of metallization strategy must be guided not only by the trade-off between conductivity, process temperature, and flexibility, but also by the geometric class of the target surface. This perspective opens a clear framework for aligning fabrication methods with the future requirements of conformal and sustainable metasurfaces. Curved metasurfaces, realized by screen printing technology with conductive silver ink have excellent electrical and mechanical properties that will be demonstrated in detail at the conference.

IV. Connectors and joining technologies

A. Electrical Contact to Connectors

Regarding antenna applications based on flexible substrates, electrically conductive connections to COTS RF connectors present a challenge. Conventional solder is rigid and for a dense distribution of radiating elements, flexibility of the MTS might be degraded. Furthermore, temperatures above $150°$C can damage the screen-printed metallization and can lead to thermoplastic deformation of the polymer. Therefore, an alternative contacting solution was achieved with flexible conductive glue (Fig. 1.a), with typical curing temperatures in the range of $80 - 130°$C [11]. This approach prevents thermoplastic deformation of the synthesized polymers. It was observed that bending or twisting of the substrate does not lead to a sudden detachment of the SMP connectors and the metallized areas underneath. The glue retains a relatively soft structure after curing while providing a sufficient adherence, which results in RF signal stability. Stress tests showed that the adherence between the conductive ink and polypropylene (substrate suitable for realization of curved metasurfaces) is stronger than between the glue and the RF connector (Fig. 1.b).



(a) (b)

Fig. 1: Flexible conductive glue applied to connect a screen-printed antenna on flexible polypropylene (a). Connector pull test result with intact screen printed groundplane (b).

B. Calibration of multi-port metasurfaces

Metasurfaces for advanced applications are often implemented as multi-port components, whose port count may exceed that of standard measurement instruments or backends. The full characterization of multi-port metasurfaces requires an independent excitation of each port, which can be achieved by utilizing RF switch matrices that act as time multiplexer. Although conceptually simple, the addition of a switch matrix introduces challenges in calibration and can increase measurement uncertainty. Fig. 2 illustrates the measurement setup as a model of three layers: the bottom level is given by a conventional network analyzer with N ports. The top layer corresponds to the metasurface, which has M ports

that emit and receive EM fields. Between these layers, the switch matrix is embedded within two interconnection layers with N and M transmission lines, respectively. The state of the switches $Z_k, k = 1, 2, \ldots, L$ is set externally and the VNA is configured to store L measurements of $[S_S]_k$ in its respective state. A full short-open-load-through (SOLT) calibration on the level CAL MTS requires many intermediate measurements, all to be done with great care. An alternative type of calibration directly in the "plane" of sensing, CAL OBJ in Fig. 2, is investigated and assessed in terms of accuracy and calibration effort.

The flexible interconnections may lead to increased measurement uncertainty in both magnitude and phase. Thus, the derivation of an uncertainty budget is essential to allow for a validation of the measured data.

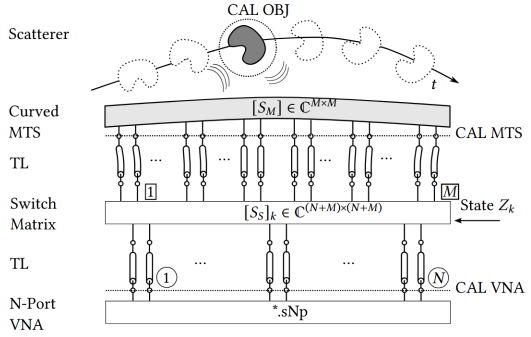


Fig. 2: Extension from N ports (VNA) to M ports (MTS).

V. Design of Curved Metasurfaces

In designing a curved metasurface, one must determine a suitable reactance distribution to achieve the desired radiation properties. Various methods have been proposed, including direct design approaches [12], [13] and numerically driven techniques [14]. Regardless of the method, special attention must be given to electromagnetic effects unique to curved surfaces, such as creeping waves and their associated losses, which must be accounted for and mitigated [15].

As an example, the design of a cylindrical metasurface antenna to radiate a pencil beam is considered (see Fig. 3). The antenna is composed of a cylindrical ground plane with radius a, on which lies a substrate with thickness d and permittivity ε_r. The metasurface is then patterned on the substrate forming a curvature radius $b = a + d$. We assume that the metasurface and the grounded substrate are infinite and invariant along the axial direction. The feeder is modeled as an infinitesimal dipole wall oriented along the radial direction in the middle of the substrate. The problem can therefore be reduced to a two-dimensional (2D) problem.

A. Holography-inspired approach

The holography-inspired approach combines an initial design based on physical reasoning, with an efficient Method of Moments (MoM) code, and an optimization routine for tuning the radiation parameters. The in-house developed MoM code, which implements roof-top basis functions [15], leverages the fact that the considered structure is essentially 2D. As a result, the needed computation time is several orders of magnitude shorter than that of commercial EM solvers (CST Suite in our case). This approach begins by building a database of creeping-wave losses, obtained by numerically solving the dispersion relation of the system for various uniform sheet reactances covering the dielectric layer. An average surface reactance is then selected to ensure that losses remain sufficiently small, after which the holographic method is applied to obtain an initial design for a desired pencil-beam radiation pattern. Finally, the resulting modulated surface reactance is optimized using gradient-based optimization routine, mostly to further reduce the side-lobe level (SLL) in the radiation pattern.

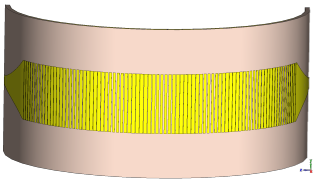


Fig. 3: Illustration of a cylindrical metasurface pencil-beam antenna.

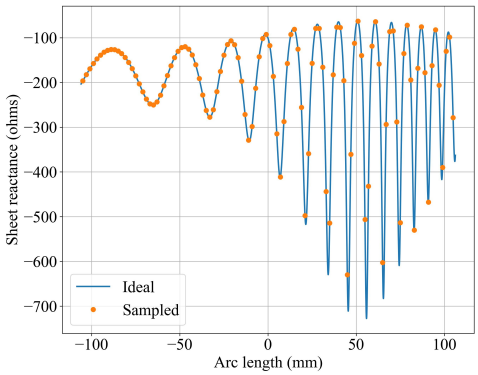


Fig. 4: Sheet reactance distribution for MTS with pencil beam radiation pattern at $+30°$.

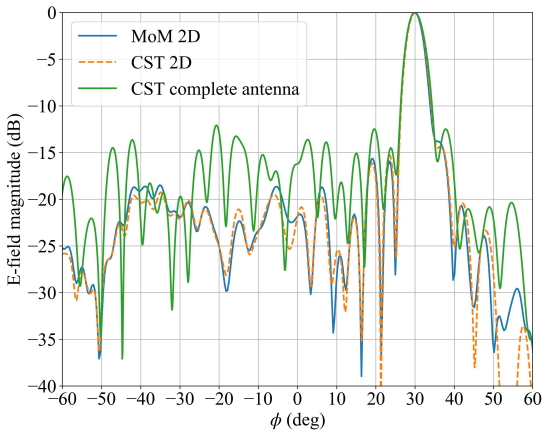


Fig. 5: Comparison of MoM calculated radiation pattern with the radiation patterns calculated in CST.

For the antenna with a pencil-beam radiation pattern at $+30^\circ$ pointing at 24 GHz, the resulting sheet reactance distribution and radiation pattern are shown in Fig. 4 and Fig. 5, respectively. The selected antenna parameters are $a = 10$ cm; $d = 1.5$ mm; and $\varepsilon_r = 2.26$. Note that Fig. 5 gives both the radiation diagrams of the metasurface model and those of the complete metasurface antenna, including the excitation network (edge-connector + tapering structure). Fig. 5 shows that the results from our MoM code agree closely with both the simplified CST model and the full-wave simulations of the complete structure. The influence of the feeding structure is limited to an acceptable increase in the SLL.

B. Direct solution of the integral equation

The second considered synthesis approach is based on the direct solution of the integral equation [16]. Since the metasurface antenna of interest is 2D, the sheet impedance Z_S, the current distribution on the MTS J, as well as the radiation pattern F are all functions of the azimuth only. It is further assumed that the sheet impedance is capacitive and modulated around an average value Z_0. First, the radiation pattern is translated into a current distribution, decomposed into harmonics:

$$J_{vis} = \sum_{n=-N_{vis}}^{n=N_{vis}} i_n e^{jn\phi}, \tag{1}$$

where $N_{vis} = k_0/b$ delimits the visible and invisible (evanescent) parts of the spectrum, and k_0 is the free-space wavenumber. Once the visible current is obtained, the invisible part of the current is selected as that corresponding to the average (i.e. unmodulated) impedance $Z_0 = jX_0$. The integral equation is then inverted (using a procedure similar to that presented in [16] for the planar case) to derive the required reactive sheet impedance in the least-squares sense. Once the sheet impedance is computed, a MoM code is used to calculate a new estimate of the surface current J from which its visible content is replaced by the desired visible one. The integral equation can then be inverted again. This iterative process continues until a maximum number of iterations is reached. At each iteration, the directivity of the antenna is computed. The following parameters are chosen for the design: $f = 24$ GHz; $a = 6\lambda$; $d = 1.5$ mm; $\varepsilon_r = 2.26$; $X_0 = -485.46$ Ω. The goal is to generate a pencil beam at $\phi = 90^\circ$. The obtained solution, decomposed into harmonics is then optimized with the fminsearch routine of MATLAB to slightly improve the performance. Fig. 6 shows the reactance modulation after integral-equation synthesis, as well as that obtained after optimization.

Once the impedance is optimized, it is implemented with strips. For that purpose, the CST (commercial package) eigenmode solver is used to generate a database of various strip sizes and their corresponding surface impedances, assuming a local periodicity with unit cell size of $\lambda/6$. The finally obtained radiation pattern is provided in Fig. 7 (black curve). As can be seen, the sidelobe level slightly increases due to the implementation of sheet impedances into strips, given the fabrication constraints.

The antenna is now being fabricated, using a flexible RF substrate, which is pressed onto a 3D-printed support, and includes a feeding network ending in 8 pins that protude into the metasurface dielectric substrate. These pins are soldered to a microstrip corporate feeding network and are excited simultaneously with equal power magnitude and phase through a single connector. This array of pins generates surface waves that combine to form a planar wavefront, exciting the strips uniformly. Contact between the metasurface and the microstrip ground planes is ensured using conductive glue, as discussed in Section IV.

Measurements of both designed antennas are expected to take place before the conference.

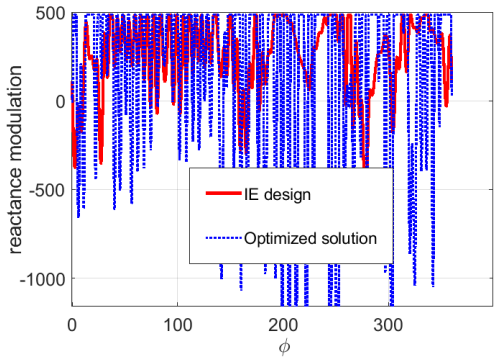


Fig. 6: Reactance modulation of the considered cylindrical metasurface. The average impedance is $X_0 = -485.46$ Ω

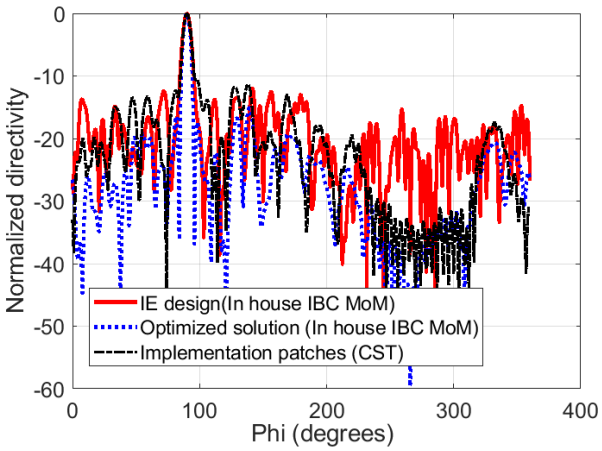


Fig. 7: Comparison of calculated radiation patterns.

VI. Co-assembly of the RF-modules with curved metasurfaces

Flexible, deformable, stretchable, lightweight, and conformal EM structures integrated with active circuitry comes with critical challenges as the multi-physics (electromagnetic, thermal, mechanical) performances are intimately linked to the physical dimensions and their space-time unfolding variations.

Innovative methodologies and tools are therefore required for properly co-designing active circuitry with metasurfaces fabricated on flexible substrates, along with the associated integration and assembly technologies. Multi-physics EM-Thermal-Mechanical co-design and co-simulation methodologies, obtained by combining CST, IVCAD [17] and eV-Technologies' broadband RLC tooling solutions in a unified co-design platform [18], [19], are proposed for dealing with flexible electronics enabling time-varying boundary conditions using noise and correlation-aware technologies. The platform's ability to account for the dynamic impedance loading of antennas by multi-harmonic (MH) nonlinear RF electronics is demonstrated through energy-efficient hybrid 3D heterogeneous front-end module technologies that integrate adaptive biasing and antenna tuners (load-aware matching).

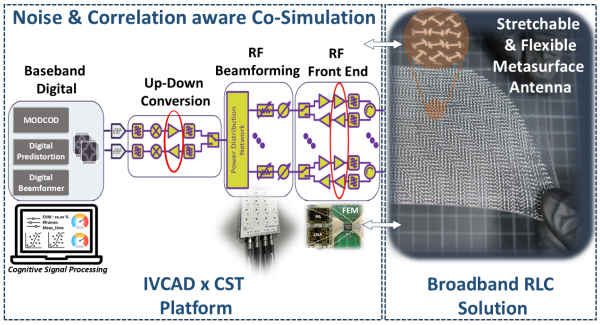


Fig. 8: Multi-physics IVCADxCST co-design & co simulation platform for flexible electronics using broadband RLC representation of antennas for full time domain transient analysis.

The developed multi-physics platform is used to design a conformal metasurface antenna for sensing applications, integrated with energy-efficient adaptive front-end-module (FEM) electronics (Fig. 8) [20]. The proposed co-design and co-integration approach of flexible metasurface antennas with 3D heterogeneous FEM accounts for thermal-dissipation management while accommodating curved and flexible supports for broadband RF characterizations. The sensing of nearby objects (size, position and distance) is enabled through the correlation of signals transmitted and received by all pairs of ports connected to the surface. Multi-port correlation metrics are introduced to evaluate system performance as function of folding angles. This distinctive method of transmitting/receiving EM waves enables directive beam scanning using sparsely distributed ports, i.e. with only a few active electronics channels. This opens new possibilities for measurement and sensing systems, particularly in robotics and other autonomous mobile systems that may use conformal antennas as a "smart skin" for joint communication and sensing.

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