Holographic Metasurfaces for Wireless Communications and Extended Reality

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Abstract: We present our progress in developing tunable metasurfaces for microwave holographic imaging and for its application to wireless communications and virtual/augmented reality (VR/AR). Our methodology starts from the analysis of ideal metasurface apertures and moves to tunable static prototypes designed for fabrication with cost-effective techniques, e.g., 3D printing or conductive inks. We envision to translate the proof-of-concept study, and associated devices, to printed circuit board technology, implementing practical reconfigurable metaholograms for wireless communications and VR/AR.

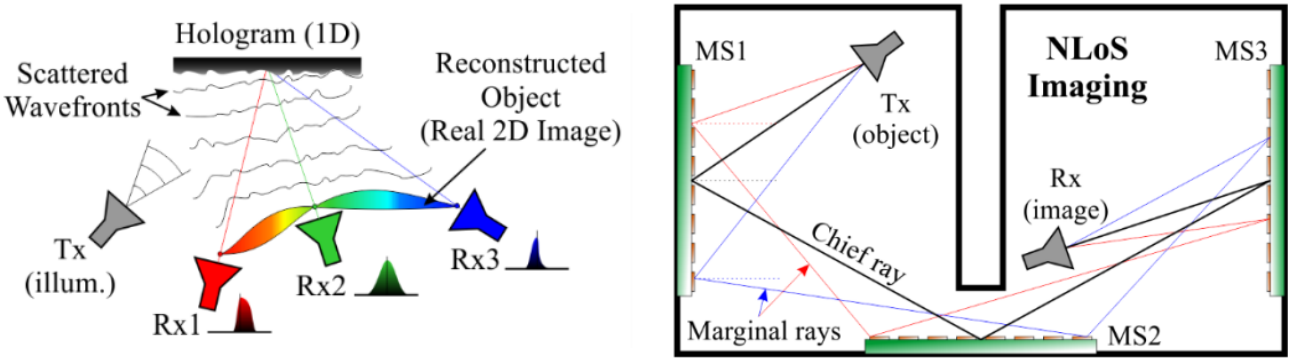
The reconfigurable intelligent surface (RIS) archetype has recently gained traction, as an abstract electrically tunable aperture that can filter and manipulate the scattering of wavefronts in ways transcending the elementary geometric optics prescriptions, i.e., the standard laws of reflection and refraction. Metasurfaces (MSs), ultrathin sheets with subwavelength-sized resonators on their exposed face, are the physical implementations of RISs. Varactor or PIN-diode assembled printed-circuit boards (PCBs) are currently the go-to technology for microwave and mmWave band devices. This operation mode means that, by electrically tuning the microwave value of the loading element (varactor or diode), we can tune the equivalent reactance of a metasurface, i.e., tune its resonance to the desired frequency, polarization, and direction of scattering. This enables tunable functionalities such as perfect absorption, anomalous reflection (steering), focusing/imaging, and holography.

In this work we cast MSs as holograms [1], i.e., as devices storing phase and amplitude profiles that, when illuminated with a specific wavefront, can re-construct real images of the stored objects in 3D space, by coherent interference. For wireless communications, holography can be considered as the 3D extension of beam forming: In the latter we direct beams to desired directions in the farfield (so we have only two dimensions, the θ_{el} and φ_{az} angles), whereas in holography we can focus an arbitrary wavefront to any point or scatter/diffract it anywhere in 3D space, Fig 1(a). Envisioning widely deployed reconfigurable metaholograms, e.g., covering all the walls of a room, essentially implements a programmable wireless environment (PWE) in a rigorous and holistic way, i.e., overcoming the limitations of geometric optics approximations (neglect of near-field effects etc.). This framework enables us to design and optimize practical applications that are sensitive to power considerations and real-world "non-ideality", e.g., non-line of sight links, interference, obstructions, fabrication imperfections, fading, etc.

Back/front hauling of information for extended reality (XR) devices, a portmanteau for both virtual and augmented reality (VR/AR), is an application that stands to benefit from holographic metasurface imaging: Immersive interaction between remote users in an XR world is currently limited by latency, mostly imposed by

digital signal processing and by traversing multiple OSI (Open Systems Interconnection model) layers. To overcome this hurdle, we are developing a system where a PWE, enabled by reconfigurable metaholograms, can record the wavefronts scattered from the source object, in real-time, and then reconstruct (image) them in a remote location; the transmission happens at the speed of light, either over-the-air (for small distances) or over fiber (for larger distances). Reconfigurable metasurfaces play a twin role in this system: (i) on the source location, they operate as a distributed imaging lens, i.e., gathering all the rays scattered from the illuminated object, and focusing them onto a microwave imager; (ii) on the remote location, they operate as a distributed projection lens, i.e., scattering the reference beam in such a way so that a real 3D image of the source object is formed.

The aim/scope of our work can be broken down in three parts: Firstly, we develop the theoretical framework for holographic imaging in arbitrary environments, Fig. 1(b), assuming a set of ideal reconfigurable metasurfaces, both in the "imaging lens" and in the "projection lens" configuration; from this framework, we extract performance metrics related to sharpness and quality of object-image formation etc. Subsequently, we design and manufacture static but cost-effective metahologram boards, using additive manufacturing (3D printing) and/or conductive inks, for an experimental proof of concept. Lastly, we develop designs for reconfigurable boards in PCB technology [3].



(a) (b)

Figure 1. (a) Abstract off-axis holographic 2D projection by illuminating a reflective 1D hologram with the reference coherent source Tx. The real image of the reconstructed object is the twisted ribbon, where colors represent frequencies. In a wireless communications analogy, the hologram is focusing the broadband signal from Tx to three receivers, each at a different band. (b) Three MSs implementing a non-line of sight (NLoS) link by conjugate point-object/image formation on the Tx-Rx antennas; each of the three MSs aperture is custom phase-profiled, as can be seen by the anomalous reflections of the chief and marginal rays across MS1.

Acknowledgement: This work was funded by the Foundation for Research and Technology - Hellas (FORTH) via the Theodore Papazoglou synergy grant 2022 – Project WISAR.

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