Research Statement

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I. Research Overview and Goals

My research is in metamaterials, metasurfaces, computational electromagnetics algorithms, optimization algorithms, antennas, and infrared photonics. I really enjoy the power of being able to design an antenna or metamaterial/metasurface for any desired field transformation or beam configuration. For example, my Ph.D. research involved metamaterial lenses. I pioneered algorithms which could design the lenses for any desirable aperture field or beams and the realization techniques to realize them via 3D printing in the end. During my postdoc, I develop synthesis algorithms which could design metasurfaces for any desired field transformation and new realization techniques for aperiodic arrays to allow prototypes to be built and measured. I really like the idea of being able to engineer human perception by developing metasurfaces which operate at visible wavelengths and can be viewed by the naked eye. One of my goals is to develop new one-algorithm-fits-all antenna design methods with practicality in mind from the outset. These design algorithms will take in any combination of arbitrary defined excitation, desired scattered fields, geometry, number of frequencies, and bandwidth and output a metasurface or metamaterial antenna which can meet the specifications. Another goal of mine is to develop spacetime metamaterials which are dynamic and reconfigurable in order to realize electromagnetic and optical illusions independent of the observer's motion or of the configuration of the scatter. A third goal is to develop programmable materials and antennas with cognition by introducing tunable materials into metasurface elements and software control. I, in fact, have a proposal out for such an reconfigurable antenna based on BST tunable permittivity materials. In what follows, I will first give an overview of my research contribution in recent years, and then discuss several future research directions that I am passionate about.

II. Main Contributions and Research Achievements

a. *Contribution 1: 3D-Printed Inhomogeneous Metamaterial Lens Design (Sponsor: NASA Jet Propulsion Laboratory)*

With the expiration of the of Fused Deposition Modeling (FDM) 3-dimensional (3D) printing patents in 2009, it was prime time to develop new antenna design approaches which could make use of 3D printing. Of primary importance was inhomogeneous materials as these needed expensive and complex manufacturing processes prior. Around the same time, NASA expressed interest in designing the next-generation of wind scatterometer instruments. In particular, all-electronic variants of their mechanical predecessors. I was contracted by NASA to develop 3D printed all dielectric, inhomogeneous, metamaterial lens antennas for their new scatterometer vision. I developed new synthesis algorithms for inhomogeneous metamaterials which could design metamaterial lenses for any specified number of beams in any configuration [1-7]. The synthesis algorithms are based on curved-ray geometrical optics (GO) coupled with Particle Swarm Optimization (PSO). GO is an efficient way to calculate the fields propagated through inhomogeneous media. The surfaces of the lenses and the inhomogeneous permittivity of the material filling the lenses are parameterized. The parameters are optimized using PSO for the specified aperture fields. New novel ways to 3D print structures with overhanging parts without support trussing using FDM printing was pioneered by me. The work lead to 4 journal papers, 5 conference papers, **one first prize student paper competition award at the 2019 URSI NRSM conference**, 47 total citations, a nomination for the IEEE R.W. King best transactions paper award, and a Ph.D dissertation. The work led also to two summer internships at NASA Jet propulsion laboratory where very strong professional contacts were cultivated.

b. *Contribution 2: Electromagnetic Illusions (Sponsor: Office of Naval Research)*

When light interacts with the atoms in natural matter, different processes such as scattering and absorption cause the object to appear as it does to the observer. Imagine being able to 'play the almighty' and design matter atom by atom as if by tweezer in order to engineer a specific response to incident light. In metamaterials and metasurfaces, matter is assembled meta-atom by meta-atom to engineer a specific response to incident electromagnetic radiation. This concept can be used to create electromagnetic or optical illusions where a solid object, with its surface patterned in a particular way, will appear to an observer as a completely different object. Hence, you could go to pick up the object and would fumble, as it looks like a cylinder but in reality, is a small cube for example. To enable these types of electromagnetic illusions, a few technologies need to be developed. Over the past few years, I have developed novel metasurface design techniques to achieve these technological goals. These are (1) complete control of amplitude phase and polarization state of fields reflected from metasurfaces [8-11], (2) multiband metasurfaces [12,13], (3) metasurfaces which can lay conformal to arbitrarily shaped surfaces, (4) fast metasurface optimization strategies for large metasurfaces [11,14], and (5) metasurface realization techniques for aperiodic and/or conformal arrays [15]. The metasurfaces are designed using integral equations which are solved by the method of moments. They are optimized using various accelerated forms of gradient descent. Some applications of the design approach are direct fed metasurface antennas with perfect aperture efficiency [16] and metasurface beamformers [10]. The work has led to 5 journal articles, 9 conference papers of which 4 were invited papers, and 1 invited book chapter, totaling 37 citations in the past year.

c. *Contribution 3: Information Processing Antenna Systems (Sponsor: Army Research Office)*

The U.S. Army Research Office had expressed interest in obtaining new infrared cameras which can see through dust. Dust is kicked up by the spinning propellor blades resulting in poor visibility for the pilot during landing. This phenomenon is referred to as Brownout. At a particular wavelength in the Midwave Infrared Band, the dust becomes invisible due to the Christiansen Effect [17]. Infrared photodetectors which operate at this wavelength will allow perfect visibility through the dust and could avoid Brownout disasters. However, the infrared photodetector would need to operate at high operating temperatures (room temp) with good signal-to-noise ratio (SNR) and focal plane array (FPA) resolution. Since the noise power is a direct function of the operating temperature, the detector can operate at a higher temperature at the cost of reducing the SNR. The dark current (noise) is a direct function of the detector volume when the detector is designed such that it is diffusion limited. By reducing the detector dimensions, the noise power is reduced allowing higher operating temperatures. This leads to reduced signal. The solution is to couple a noiseless infrared antenna, in this case a dielectric resonator antenna (DRA), to the reduced dimension detector to capture more signal and hence increase the SNR. Since the DRA is a resonant cavity, it has subwavelength dimensions leading to high FPA resolution. Infrared photodetectors in the LWIR band were designed with a 6.02dB improvement to the SNR allowing operation at higher temperatures. The project was in collaboration with Ohio State University and has resulted in 1 journal paper [18], 5 conference papers [19-23] totaling over 13 citations in the past year.

d. *Contribution 4: Reflectarray Antennas for CubeSat Missions (Sponsor: NASA Jet Propulsion Laboratory)*

Reflectarray antenna design for CubeSat missions require novel strategies to pack a high gain antenna into the small form factor of a CubeSat chassis. I developed a new Gregorian dual reflector high gain antenna system for CubeSats with a reflectarray main reflector and a deployable ellipsoidal subreflector [1,24]. The deployable subreflector allows deployment with no moving cables since the feed antenna and microwave circuitry are fixed within the CubeSat housing. This increases reliability in space. I pioneered new acceleration techniques for the spectral domain method of moments algorithms used for reflectarry synthesis and design [25,26]. Furthermore, we were the first to look at specular reflection mitigation approaches in offset fed reflectarray geometries [27], which is my highest cited paper thus far. **The work also won best poster at the 2012 IEEE CLAS-TECH meeting**. The work has led to 4 conference papers and 1 dissertation totaling 37 citations.

III. Future Directions

a. *Direction 1: SpaceTime Metamaterials and Reconfigurable Dynamic Metasurfaces*

Bianisotropic boundary conditions known as the GSTC [28], allow the most general metasurface modelling in the time-harmonic domain. By adding the possibility for temporal modulation, new phenomena and applications are unlocked [29-31]. In addition to varactor tuning of metasurface elements, Barium-Strontium-Titanate (BST) tunable materials can be integrated with metasurface elements to make them dynamic and reconfigurable. This material also allows for fast temporal modulation leading to metasurfaces which can not only control the spatial spectrum but also the temporal spectrum offering beam scanning or beamforming and frequency up/down conversion. The temporal modulation also leads to novel effects in non-reciprocity.

Applications: Non-reciprocity full-duplex Communication Systems, Reconfigurable Antennas, Dynamic Beamformers, Frequency Agile Antennas, Cognitive Antennas, Parametric Amplifying Antenna Systems

b. *Direction 2: Optical Antennas for Optical Illusions and 3D RGB Holograms*

Nanoantennas which operate at optical frequencies would allow the electromagnetic illusion design strategies I developed to be pushed to visible wavelengths. This would lead to optical illusion metasurfaces which can engineer human perception. For example, a tri-band, multilayer, conformal metasurface could be wrapped around a cube and to the naked eye the cube would appear as a sphere. In addition to nanoantennas for optical wavelengths, matrix compression techniques such as Adaptive Cross Approximation (ACA) applied to the design and analysis algorithms used at RF frequencies would accommodate the increased number of elements inherent to large scale optical illusion metasurfaces. Since at optical frequencies plasmonic metal losses become unmanageable, all-dielectric resonator antennas similar to the ones used in the *contribution 3* above could be used. Forming a strong partnership with the nano fabrication facilities at the start would be a priority. Developing the design, analysis, fabrication, and measurement capabilities for these optical nanoantennas would be the focus.

Applications: Optical Illusions, Three Color Hologram Communications Systems, Optical Antennas

c. *Direction 3: Metasurface Skins, Illusions, Camouflage, and Cloaking*

By combining the nanoantennas and conformal metasurface design approaches, metasurface skins and cloaks could be developed. These cloaks would be capable of hiding an internal object. Most cloaks presented in scientific works to date have been for canonical geometries such as planes, rooftops, cylinders, or spheres. The conformal metasurface design approach I pioneered would allow conformal metasurface skins for any arbitrary shape. Furthermore, the unit cell extraction technique for aperiodic environments also applies to surfaces with aperiodic curvature. Remember, there are no periodic expansions or Floquet like theorems for arbitrarily and aperiodically curved surfaces. In these cases, my extraction approach would allow the prototype realization of metasurface skins and cloaks.

Applications: Stealth, Cloaking, Illusions, Camouflage, Military

d. *Direction 4: Metamaterials and Metasurfaces Coupled with Information Processing and Sensing Systems*

The next generation of metasurfaces will undoubtably be integrated with sensing systems or analog processing materials. By coupling metasurfaces to semiconductor devices, new information processing and sensing systems could be envisioned. This would reduce the complexity needed in the beamforming networks or back-end electronics. Magnetoelectric nanoparticles which can convert a time-varying magnetic field into an electric potential difference and vice-versa could sense neuronal depolarization events. Furthermore, integrating semiconductor LED's and photodiodes into the nanoparticle could lead to read-write nanoparticles for neurons in the brain.

Applications: Augmented Reality, Brain-Machine Interface Magnetoelectric Nanoparticles, Infrared photodetectors, MIMO beamforming antennas, Sensors

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