Impacts of Metasurface Antenna Technology in the Aerospace Industry

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Space-based communications has developed into a billion-dollar industry since the first satellite transmission in 1957. Through nearly 70 years of innovation and the launch of tens of thousands of communication systems, the space industry has reached scalability and reliability limitations that lead to high costs and system compromises. A relatively new antenna technology has been researched over the past 20+ years in the field of electromagnetics, seeking to develop "metasurfaces" as more scalable and capable versions of our traditional antenna systems. Metasurfaces are tailored, artificial materials composed of subwavelength components called "meta-atoms" that are designed to manipulate radio frequency and optical waves. This paper introduces the research behind metasurfaces and how their antenna characteristics could improve upon current technological constraints within the space industry. More specifically, it explores how advancements in the realm of metasurfaces will not only mitigate the trade-offs between size, mass, cost, and reliability, but will also enable scalable solutions across space manufacturing, communications, exploration, and transportation systems.

I. Introduction

Space communication is the backbone of all space exploration and satellite-based services. In fact, communication systems serve as the sole link between Earth and spacecraft across all space environments. As of June 2024, there are over 10,000 satellites and interplanetary probes active in space [1], with thousands more planned for launch. From internet services in low Earth orbit (LEO) to interstellar exploration in deep space, every space mission must meet specific requirements to overcome unique challenges in space communications.

Given the vast range of operational environments, communication systems - more specifically their antennas - must be adapted to meet mission requirements. Antennas, often the largest and most critical part of the system, must be designed to optimize many specifications such as power, directionality, and efficiency. For example, in the case of Voyager 1, which is currently 15.6 billion miles from Earth, transmissions to and from the spacecraft take over 23 hours each way [2]. Voyager 1's ability to precisely align its antenna and efficiently transmit is critical for the successful communication of telemetry data and scientific measurements. In a modern case much closer to Earth is SpaceX's Starlink constellation, consisting of thousands of satellites in LEO. Here, size and efficiency, as well as the ability to electrically control the orientation of the antenna, are at the forefront of its antenna design.

However, this optimization can come at a cost, with many traditional antennas being bulky, expensive, and often limited in flexibility [3]. Emerging technologies, such as metasurface antennas, offer new possibilities in space communications by providing similar, if not better performance than traditional antennas. At the same time, they can offer advantages such as ease of fabrication, lightweight design, and the ability to control wave propagation [4]. These advancements could lead to more efficient, compact, and adaptive communication systems, addressing the limitations of conventional antennas. The following sections will explore space-based antenna architectures and the potential for metasurface technology to revolutionize this field.

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II. Metasurfaces

Metasurfaces are artificial, planar devices that interact with electromagnetic waves [3-9]. The word "meta" - a Greek word translating to "beyond" - is a fitting descriptor for these surfaces, as their properties can "go beyond" what is found in nature [3-6]. Surprisingly, research in these two-dimensional (2D) surfaces came about after their three-dimensional (3D) counterparts, known as metamaterials [5], and the term "metasurface" was not actually coined until around 2011 when it first appeared in published research. Although research in metamaterials (and subsequently metasurfaces) has become increasingly popular over the past 30 years, the theory and fundamental concepts date back to the early 1900s [6].

A. Metamaterials

Metamaterials exhibit properties that produce a desired effect on incident electromagnetic waves, namely through their subwavelength constituent elements [3-9] referred to as "meta-atoms" [5, 7]. Meta-atoms can be made of materials like gold, silver, and ceramic [6], and be arranged in periodic patterns to produce a bulk effect on the wave. But before diving into the details behind meta-atoms, it is important to understand how materials are classified as they relate to electric and magnetic fields.

Conventional materials are characterized by their electric permittivity, ε, and magnetic permeability, μ, which describe the electric polarization and magnetization of the material, respectively. These quantities are averages of homogeneous materials, where it is assumed that the material is of uniform density and thickness [6]. Electric permittivity (simply called permittivity) is a quantity that characterizes how well the atoms in a material will polarize in response to an applied electric field. This value is typically given in terms of relative permittivity, ε_r, which is the relative value compared to that of free space, ε_0. Similarly, magnetic permeability (or just permeability) is the measure of how easily the atoms in a material will align with a magnetic field - or how easily it will become magnetized. Materials are typically characterized by the value of their relative permeability, μ_r, which compares their permeability to that of free space, μ_0. We can characterize materials in this way under the previous assumptions and when the wavelengths of interest are much larger than the size and spacing of constituent elements [5, 6]. In this fashion, electromagnetic waves *see* metamaterials as homogeneous structures rather than individual meta-atoms and *feel* their bulk effects [5, 6]. Analogous to this concept is the structure of table salt, where the naked eye sees table salt as a solid material, but at the atomic level, sodium (Na) and Chlorine (Cl) atoms are arranged in periodic patterns that form its lattice structure.

Since meta-atoms are the constituent elements of metamaterials, they must be designed to produce a specific electric and magnetic response. At a basic level, this can be achieved with the combination of so-called rods and loops [5, 6]. A rod, such as a straight piece of copper wire, produces an electric field parallel to the rod and a magnetic field rotating around the rod on the perpendicular plane. A loop, like a circular piece of copper wire, produces a magnetic field around the wire and through the loop, and an electric field circling along the loop. When two or more rods are in parallel, their individual magnetic fields cancel, leaving only the electric response, and a similar result occurs with the magnetic response of parallel loops. These effects can be tailored by combining these loops and rods in various periodic patterns, and even by combining the two elements into "loop rods" [5]. This produces a desired response to the electromagnetic waves and ultimately provides control over these waves.

Oftentimes, the combined value of a material's permittivity and permeability is grouped in a term called refractive index, n. The refractive index is solely dependent on the relative permittivity and permeability of materials, where

$$n = \sqrt{\varepsilon_r \mu_r} = \sqrt{(\varepsilon/\varepsilon_0)(\mu/\mu_0)}\,.$$

This phenomenon is well known for the apparent bending of a straw as it enters a glass of water. Since water has a refractive index of 1.33, and that of air is approximately 1, the straw appears to bend toward the surface of the water. Metamaterials can be created using this phenomenon of bending light for a variety of applications. Perhaps one of the most popular creations pertains to the invention of so-called "invisibility cloaks," which came about after the development of a negative refractive index in the early 2000s [5], and the production of anisotropic materials [6]. For a negative refractive index, the values of the material's permittivity and permeability are both negative, which causes waves to bend in the opposite direction than normally expected. As for anisotropic materials, their properties vary with direction, meaning that their electric and magnetic responses differ depending on the electromagnetic wave's direction of travel. These "invisibility cloaks" are just one example of how materials can be designed with different values of ε and μ to achieve a variety of effects.

B. Metasurfaces

Metasurfaces (a.k.a. metafilms or single-layer metamaterials) are the 2D counterparts of metamaterials, effectively replicating their properties onto a flat surface. The obvious benefits of replacing a 3D structure with a 2D surface are size and mass, but in terms of electromagnetics, this also amounts to fewer losses as waves interact with the surface [5, 6].

The loops and rods concept for tailoring permittivity and permeability still applies, except now these periodic variations and combinations are flattened. Over the years, the loop rod shapes evolved into various designs (Fig. 1) [9] exhibiting desired characteristics, which can be stacked in layers to achieve multiple degrees of freedom in wave control [5]. These added degrees of freedom provide a multitude of possibilities, like polarization-selectivity, beam shaping, and the ability to produce these characteristics on non-planar surfaces [5]. These devices are also capable of achieving controllable frequency tuning and beam steering with the addition of passive devices, such as varactor diodes [4]. Research has demonstrated the relative ease of fabrication [4, 6], where these materials can be fabricated using printed circuit board (PCB) techniques [3, 8], which are popular and relatively inexpensive.

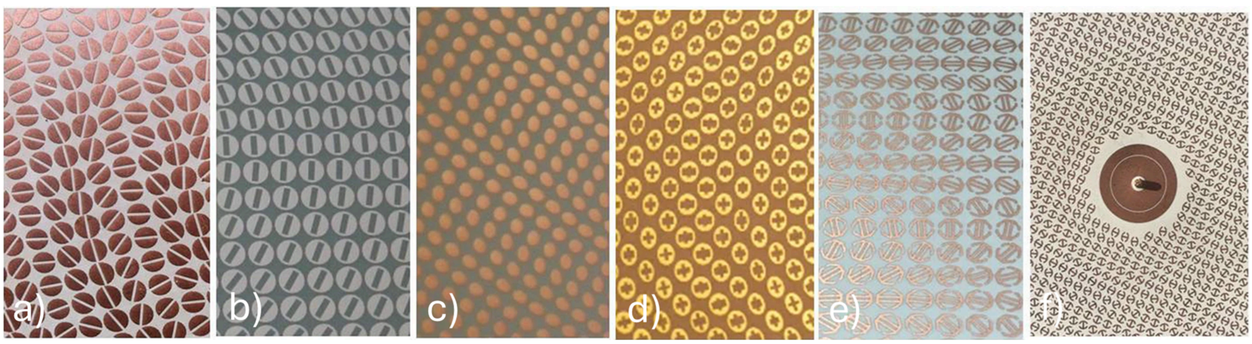

Fig. 1 Examples of metasurface patterns like a) coffee bean, b) patch with slot, c) grain of rice, d) patch with cross slot, e) double π, and f) double anchor from [9] licensed under CC BY 4.0.

IV. Space Antenna Systems

In communications, antennas operate with the purpose of radiating and receiving electromagnetic waves containing modulated data. Based on the mission and needs of the system, a variety of antennas with diverse capabilities are designed to optimize specific performance parameters.

A. Conventional Antennas

Dipole antennas serve as the simplest antennas found in the field of telecommunications. These antennas radiate in nearly all directions, with their energy focused radially outward along the plane perpendicular to the antenna elements. These omnidirectional antennas have the advantage of maintaining communication in almost every direction at nearly any spacecraft orientation, but efficiency suffers as a result. The size of these antennas is directly proportional to their operating frequency, which in some cases can make them quite large. Miniaturization of these antennas can be achieved by printing them on a dielectric substrate. However, this can reduce their omni-directionality and operational bandwidth - the range of frequencies in which performance requirements are satisfied.

Patch antennas are planar antennas offering directionality outward from one of its faces, providing nearly 180 degrees of coverage. These antennas are often used on spacecraft and satellites in LEO, where an earthward orientation is maintained and coverage areas are large. These antennas can operate independently or be used in conjunction with others to form what is called a phased array. Phased array antennas typically use small patch antennas connected to phase shifters to achieve beam forming - the ability to orient one or more energy lobes in specific directions. This capability enhances connectivity and signal quality by focusing more energy toward ground stations and smaller geographic coverage areas as it passes overhead, typically for only about 10 minutes at a time. While dynamic control over directivity is a great benefit, these antennas tend to be less power efficient and larger due to bulky phase shifters [8].

Parabolic dish antennas are also common in space applications due to their high directivity, which is the ability to focus energy in a concentrated, narrow direction. This characteristic is important for spacecraft farther from Earth, such as those in geostationary orbit (GEO) or in deep space. Parabolic dishes achieve high directionality due to this dish, which redirects incoming waves to a central feed point. Oftentimes, this feed point is a horn antenna, which has its own advantages of high bandwidth and directionality. Due to reciprocity, these characteristics apply to both transmission and reception. Some downsides of these dishes are their size, shape, and difficult fabrication process [10]. Although deployable dish options are available, such as modular solid pieces or mesh systems, this increases antenna complexity and adds questions about reliability. These antennas also lack an electrical beam steering capability, driving the need for mechanical devices to accomplish this task. Mechanical beam steering devices also add complexity, and mass, and can require additional bulky parts.

B. Metasurface Antennas

The designable electromagnetic properties of metasurfaces make them excellent candidates for antenna applications. Whether incorporated as part of an antenna or even replacing the antenna entirely, metasurfaces can enhance wave propagation while alleviating pitfalls of conventional antenna systems. In the case of commonly used phased array antennas, metasurfaces possess the same beam steering capability [8] (Fig. 2) in a smaller, lighter package. By taking advantage of passive elements rather than active ones, such as phase shifters, metasurfaces are less lossy and more energy efficient. In the case of highly directional antennas, metasurfaces alone cannot overcome the directivity achieved by the parabolic dish. However, the size, mass, and complexity involved in this design, due to its large dish reflector and bulky mechanical beam steering components, make these highly capable antennas less than ideal. Instead of replacing the antenna, research shows similar performance when replacing the parabolic reflector with a flat metasurface. By tailoring the meta-atoms to produce a greater phase shift radially outward from the center, Yao. M et.al.[10] were able to mimic the electromagnetic effects of the curved dish (Fig. 3).

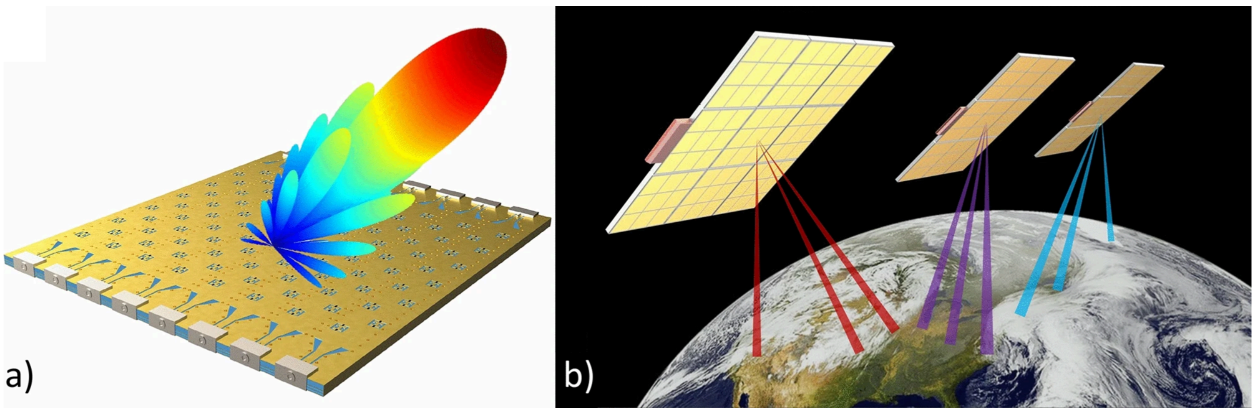

Fig. 2 Metasurface a) with beam steering and b) applications in LEO from [8] licensed under CC BY 4.0.

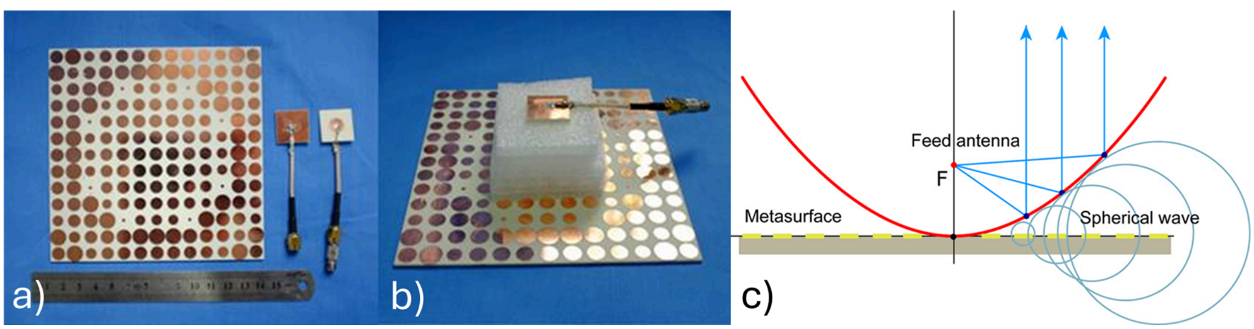

Fig. 3 A 10GHz metasurface a) prototype with unmounted feed antenna, b) prototype with mounted feed antenna on styrofoam spacer, and c) graphical side view depicting theoretical parabolic dish (red line) reflection compared to phase-shifted metasurface emissions (blue circles) from [10] licensed under CC BY 4.0.

Metasurfaces are not, however, without their limitations - at least not without further research and development. While significant advancements have been made in developing metasurfaces with comparable performance characteristics to traditional antennas, there remain drawbacks in some areas of their optimization. To name a few, electrically reconfigurable metasurfaces, such as those designed for electronic beam steering, can face increased losses and bandwidth limitations resulting from necessary, but complex circuitry [3]. In terms of manufacturing, limitations were found in the minimum distance within and surrounding the meta-atoms that make up the structure in Ref. [11], which can be challenging as frequency increases with this design. Lastly, a major hurdle to overcome will be the testing and evaluation of these new systems in space, likely to last a significant amount of time prior to widespread development and manufacturing.

V. Benefits of Space-Based Metasurface Antennas

Metasurface antennas can transform space-based systems through an efficient, reliable, and low-cost method of obtaining spacecraft communications. Free of mechanical beam steering and bulky phased arrays, these antennas reduce structural complexity, lowering the cost of manufacturing and operations, as well as the cost of increasing reliability and mission durations. The compactness and power efficiency of these metasurface antennas demonstrates the potential to preserve already-limited space and resources for additional scientific payloads and experiments. With the growing need for high-rate data links, satellite constellations, and reconfigurable communication systems, metasurface antennas can also provide a cutting-edge solution that provides optimum performance and scientific payback to government and commercial space agencies.

A. Cost, Efficiency, and Reliability

Metasurface antennas offer a cost-effective solution for space missions by addressing two of the industry's largest expenses: launch and manufacturing costs. Phased array antennas conventionally consist of numerous active elements with power-hungry phase shifters, resulting in high operating costs. Metasurface antennas leverage passive or semi-passive wavefront control, which reduces energy consumption and enables operational cost savings. A conventional electronically steered phased array operating in the Ku-band (12 - 18GHz) requires approximately 200–300W for a 1-meter aperture, while an equivalent metasurface antenna requires only 50–100W, allowing power to be redirected to other critical spacecraft systems [12, 13].

Launch costs are directly related to payload mass, making mass reduction a key financial advantage. Traditional mechanically steered antenna systems can exceed 100kg, whereas metasurface antennas provide similar functionality at a fraction of that mass. With Falcon 9 rideshare missions costing between $50,000 and $80,000 per kilogram [14, 15], replacing a 100kg parabolic dish with a 20kg metasurface antenna - using 20kg as an arbitrary example - would save $480,000 per satellite. Multiplied across satellite constellations of hundreds or thousands of units, such savings are critical for commercial and government space missions.

Manufacturing costs are another area where metasurface antennas considerably cut expenses. Traditional antennas require precision-machined reflectors, complex RF feed networks, and mechanical steering mechanisms—all of which are expensive to produce. Metasurface antennas, however, can be produced using cost-effective techniques such as lithographic printing and roll-to-roll production [16], making them a more economical option for both commercial and research applications.

Aside from launch and production cost savings, metasurface antennas also lower long-term mission costs through enhanced reliability and longer operating life. Unlike traditional antennas, which rely on mechanical components that degrade over time, metasurface antennas are entirely solid-state, eliminating failure points from moving parts. This reduces mechanical wear and extends mission longevity, ensuring a higher return on investment. Additionally, since active, tunable metasurfaces are software-defined, they allow satellites to adapt in orbit. Depending on the design, a satellite manufactured for Earth observation could theoretically be reprogrammed for telecommunications by adjusting its antenna configuration, maximizing operational flexibility and mission value.

B. Expanding Space Capabilities and Future Implications for the Aerospace Industry

The impacts metasurface antennas have on the aerospace industry go beyond improving efficiency and reducing costs; they can enable satellite miniaturization, high-frequency operations, and autonomous beam control. CubeSats and microsatellites - extremely limited by size and power constraints - could especially benefit from this as they require creativity and ingenuity to house traditional antennas. Metasurface antennas, being thin and flexible, could integrate seamlessly into compact satellites, allowing them to maintain high-bandwidth communications [17]. In large-scale LEO constellations, these antennas could enable satellites to adjust beams to optimize coverage based on demand, reduce signal congestion by steering away from interference zones, and enable seamless satellite networking for autonomous data relay. Additionally, the advantages of metasurface antennas could extend to deep-space probes and military applications. For instance, future Mars missions could one day leverage metasurface antennas to establish high-speed laser communication links, overcoming the bandwidth limitations of current radio-based systems [18]. For deep-space and interstellar probes, metasurface antennas can be used to facilitate ultra-high-gain, reconfigurable beamforming at THz and optical frequencies [19]. This will significantly mitigate the power and mass constraints for long-range communications. The European Space Agency (ESA) is already researching optical beam steering with metasurfaces, showing promise for interplanetary networking [20]. The aerospace industry could highly benefit from such applications, as this could allow for high-rate data transmission from exoplanetary missions with high-resolution imaging, and could even introduce the possibility of live broadcasts of scientific experiments from beyond Earth's orbit.

VI. Conclusion

The space industry has always been constrained by the trade-offs between performance, size, and cost, limiting advancements in space-based communications. As the demand for high-speed and reliable connections grows, traditional antenna systems struggle to keep up with the pace of the evolving communication needs in space. Metasurface antennas show promise in many applications of space communications, featuring characteristics that outshine those of traditional antenna systems while maintaining or improving performance. After further research and testing, metasurfaces will completely reshape the antenna systems of the space industry.

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