Applications of Near-Field Meta-Steering Antenna Systems

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***Abstract*—The near-field meta-steering (NFMS) method, a beam-steering technique using pair of near-field metasurfaces, has several unique attributes, including planar profile, lack of active components, and high efficiency. The NFMS uses a thin planar high-gain antenna and stacked pair of near-field metasurfaces that are rotated around the antenna aperture with a pair of stepping motors to steer the beam in a large conical region. The NFMS systems are suitable for a broad spectrum of applications, including communication-on-the-move in providing data connectivity in remote places and moving platforms such as trains, buses, ambulances, and fire trucks. Some specialized all-metal metasurfaces are designed to make the NFMS system suitable for high-power microwave applications. Stepped dielectric metasurfaces are used to realize wideband beam-steering antenna systems used in sensing applications.**

***Index Terms*—near-field meta-steering, metasurfaces, beam-steering, communication-on-the-move, high power microwave**

I. Introduction

High-gain antennas with the ability to dynamically steer their beam are used to maintain secure data connectivity irrespective of the location of the two communicating nodes. The relevance of beam-steering antennas has seen unprecedented growth due to existing and upcoming wireless applications such as on-the-move connectivity. Apart from classic mechanically rotated reflector dishes and electronically steered phased arrays, researchers from academia and industry have been working on unconventional beam steering methods. This includes use of liquid crystals [1], digitally controlled transmit arrays [2], [3], in-plane translation of lenses with fix antenna feed [4], and leaky-wave antennas to name a few [5], [6].

One of the promising solutions among the unconventional beam-steering solution is that based on a pair of near-field metasurfaces referred to as near-field meta-steering (NFMS) [7]–[10]. NFMS is a low-profile wide-angle continuous beam-steering solution for high-gain antennas. The classic NFMS systems comprise a high-gain base antenna and a pair of near-field phase-gradient metasurfaces (PGMs) placed in the near-field antenna region. The antenna beam is fixed in the broadside direction and is steered in a large conical region by rotating the two metasurfaces. Unlike mechanically tilting dishes and flat panel arrays, the NFMS systems occupy fixed volumes. The ability to steer beam while keeping antenna fix means these systems do not need radio frequency (RF) rotary joints, unlike dish-based communication-on-the-move(COTM) terminals. On the other hand, when compared with electronically steered arrays, NFMS systems have low RF losses and no intermodulation distortions. These systems also do not need thermal management mechanisms due to the lack of active components and only need nominal power to rotate the two PGMs with stepping motors.

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The NFMS systems were envisaged to provide COTM services. However, the unique attributes associated with NFMS systems make them suitable in the range of applications and platforms where conventional mechanical and electronic beam-steering antennas fail to meet constraints. Since the first design reported in 2017 [7], the technology has been explored for various applications, including connectivity and wireless sensing, by multiple groups around the world. This paper summarizes the critical development and applications of the NFMS systems and focuses on the potential end-user applications that can benefit from these developments.

The rest of the paper is arranged such that first, we briefly describe the method in Section II. Potential end-user applications needing beam-steering antennas are discussed in Section III. The development of NFMS for diverse applications is summarized in Section IV. Section V provides an evaluative conclusion to this article.

II. Near-Field Meta-Steering Method

The configuration of a classic NFMS system is shown in Fig. 1. The beam steering is based on creating a dynamic aperture phase distribution. In NFMS systems, this dynamic

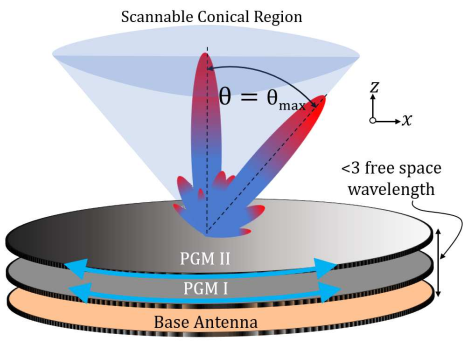

Fig. 1. Configuration of near-field meta-steering system with scannable conical region.

aperture phase distribution is achieved by physically rotating the two PGMs. The PGMs are thin metasurfaces designed to create a linear phase progression with a fixed gradient in the propagating electric field. In classic NFMS systems, both PGMs are designed to create identical gradients in the electric field propagating through the PGM. The effective phase transformation through the PGM pair depends on their orientations. The effective gradient in the phase of the field through PGM is maximum when they are aligned in a direction that moves the beam to a maximum elevation angle. When the PGMs are pointing in opposite directions, the effective phase gradient is zero, and the beam points in the boresight direction. The idea of introducing phase in the radiated electric field is different from phased arrays, where phase shifters are inserted in the antenna feed network.

III. Applications of Near-Field Meta-Steering

NFMS systems can be used in several diverse end-user applications needing beam steering. One of the most highly anticipated applications is to provide high-speed internet connectivity across the globe through low-earth-orbit(LEO) satellite constellations. Unlike geostationary satellites that are fixed relative to a position on earth, the LEO satellites are visible on the horizon for a few minutes, and even stationary ground stations require antennas to track satellites as they move over the horizon. Similarly, COTM applications where data link is needed on moving platforms such as buses, trains, and airplanes can be served through existing geostationary satellites can also make use of NFMS systems. These antennas can provide secure point-to-point connectivity through microwave links in back-haul networks, which often use dishes that need manual adjustment in severe weather conditions. Some of the prominent areas where NFMS technology has been investigated as a front-end antenna solution with a brief context are discussed in the following subsections.

A. High-Power Microwave Application

A high-power system such as radars with beam scanning capability has long been a topic of interest due to its ability to image and identify benign and enemy targets at a distance [11], [12]. The direct energy active denial system is another example of a high-power microwave system that uses a non-lethal beam of high power directed towards a potential threat approaching an area of concern. Some other high-power systems can be used to neutralize drones or vehicles operating in unauthorized areas permanently. All such systems use hundreds of Gigawatt or even higher power in a narrow beam created through a high-gain antenna or an array [13].

In these systems, the radio-frequency front-end, including antenna and any active components, needs to handle high-power levels. It is desirable to make these systems low profile to be concealed in mobile platforms or within cavities on a wall. The conventional flat-panel antenna technology that uses dielectric laminates suffers serious challenges because of their breakdown and power handling capability. Some systems use large diameter reflectors typically used on rooftops of stationary or mobile platforms such as a custom-built truck to address this issue. Reflector-based antennas have been used for decades and are a mature technology capable of handling high-power energy and excellent performance for steering applications. However, reflectors are bulky, heavy, and need a costly mechanism to physically rotate them for beam-steering applications. Planar phased arrays because of electronic components are not ideal either in replacing dishes due to low efficiency, RF losses, and thermal management challenges.

The NFMS technology with specialized components can be used to built systems capable of handling the high power needed in these applications. In [**?**], [14], NFMS inspired beam-steering solution based on the horn and waveguide-based multilayer metallic metasurface was successfully demonstrated. The system can handle up to 4 GW of power of level and steer the beam around $\pm 18^o$ in the elevation plane with full azimuth. The use of waveguides adds to the weight and cost of the system. Alternatively, a new class of fully metallic metasurfaces is designed without using dielectrics [15], [16]. These metasurfaces are mechanically robust and can build an all-metal beam steering system for high-power applications.

B. Low Profile Antenna Systems for Mobile Applications

Connectivity solution on mobile platforms particularly those operating in rural areas or areas with poor connectivity through satellites has gathered impetus in recent years due to the availability of high bandwidth and interest from technology giants. A compatible ground-based receiving terminal can be fitted to a land vehicle, aircraft, or ship [17], [18] and can provide connectivity through satellites in such situations. In rural areas with no mobile coverage, the ground terminal can be a fixed installation. In either case, cellular connectivity for users is provided using a hybrid solution of microcells or picocells connected to 5G core network via a broadband satellite link [19]. Satellite-based internet technology for communication on the move finds applications in commercial motor vehicles, high-speed trains, ships and buses to facilitate web-based services for business and infotainment, first responders (emergency vehicles) and news-gathering vehicles to provide either a one way (TV and radio program) or a two way (real-time video, internet, and data transfers) connectivity [20], to provide internet access on long haul flights, and to provide up-to-the-minute tactical and logistical information to the battlefield [21].

A satellite-based network draws demand for unconventional antenna architecture with dynamic beam-steering capability and exceptionally high performance. Mobile units require real-time agile communication systems for voice, data, images, and videos as they travel rapidly over a large area. Ground station antennas should be meeting demanding regulatory requirements during vehicle maneuvers and should be unaffected by the type of terrain [22]. Some desirable attributes in the antenna include high gain, high efficiency, low-cost, low-profile steerable antennas with a small footprint, and a minimum visual signature that is aesthetically pleasing and does not unnecessarily detract from the architecture of the structure. Installations on small business jets and unmanned aerial vehicles (UAVs), commercial and military aircraft, and a wide range of land vehicles, including High Mobility Multipurpose Wheeled Vehicles (HMMWVs) and

Sport Utility Vehicles (SUVs), have to be very low profile to meet requirements of low drag to increase flight time, easy transportation, and small visual signature [23], [24].

It is because of their low profile, NFMS can be concealed in flat areas such as roof-tops of building and facade. They can be easily mounted on moving land-based vehicles, airborne vessels, and ships. Due to their compact size, they are aesthetically pleasing with less visible signature, and low drag and, hence are favorable for UAVs and other low-profile mobile applications. Here the PGMs are the only moving component. The dynamic electromagnetic wave control ability of PGMs has been explored to optimize the radiation pattern and avoid excessive signal leakage due to spurious sidelobes and grating lobes [9], [25], [26]. The use of NFMS for high-capacity wireless communication is explored using dual polarization in [27]. The NFMS systems can be remotely operated using a pair of stepper motors which may be solar-powered [28], [29]. Unlike electronic beam steering antenna systems, the NFMS systems are entirely passive and do not suffer from RF losses, and it also mitigates the problem of heating and thermal instability [30], [31].

C. Spectral Monitoring and Beam Scanning

Recent years have witnessed a significant advancement in satellite-based technologies. Satellite technology has an enormous range of applications in military and civilian domains, e.g., navigation, weather forecasting, radio, TV broadcasting, global mobile communications, etc. With the growth in the use of wireless spectrum in the range of applications, there is a need to ensure compliance through continuous spectral monitoring. Beam-steering antennas can be effectively used in monitoring large areas with a single platform. However, most flat-panel steering antennas typically operate in a narrow frequency band. The wideband beam-steering antennas are also needed for LEO constellations such as OneWeb that use a series of multifrequency beams to serve the ground stations as the satellite pass over the field of view. The ground terminal needs to switch the frequency and align beams every few seconds to maintain the connectivity. Therefore antenna system needs to reorient the beam dynamically. The NFMS technique makes it possible to have about 10% or more bandwidth depending on the channel bandwidth used for uplink and downlink in these constellations. For much wider bandwidth needed in spectral monitoring, stepped dielectric beam-steering antennas have been developed and demonstrated that could have more than 40% fractional bandwidth around center operating frequency [32]. This level of bandwidth is extremely difficult to achieve with conventional phased-array technology.

Spectrum sensing and direction of arrival estimation are crucial in Electronic Warfare and Electronic Support in defense applications. Spectrum sensing imposes wideband requirements, and direction of arrival requires directional antennas. Some legacy systems use rotational disks to determine the direction of arrival, similar to radars but again have the disadvantages of size and weight. It is essential to operate undetected in reconnaissance, thus require low-profile antenna systems. The NFMS based wideband antennas are therefore very suitable candidates for such applications. The fast beam scanning capability provides the ability to scan signals from multiple directions in a short time.

IV. Conclusion

The NFMS technique presents a wide range of benefits compared to conventional beam steering technologies such as mechanically rotated dishes and electronically steered arrays. As a result, the variants based on the NFMS technique are used as an alternative antenna technology to these legacy systems. The high-power handling capable variants based on complete metal metasurfaces are used for high-power microwave applications such as radars. The lightweight, low profile, low power variants are suitable as terminals for COTM applications. The wideband variants are ideal for electronic sensing and spectral monitoring applications.

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