Recent Advances in Near-Field Meta-Steering

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***Abstract* — This paper reviews the recent advances in *Near-Field Meta-Steering (NFMS)*. In this relatively new low-profile tilt-free antenna beam-steering method, beam steering is achieved by independently rotating a pair of metasurfaces that are placed in very close proximity to a high-gain antenna aperture, obviously very much in the near-field region. Many advantages of this low-cost method have been identified and independently verified by different groups. Recent advances since its seminal paper published in 2017 include methods to minimize grating lobes that may occur during beam steering, realization of high-power microwave systems with beam steering, demonstration of the steering of dual-polarized beams for satellite communications and development of an accurate phase method to substantially reduce the error in analytically predicting the beam direction (azimuth and elevation angles) when metasurfaces are rotated independently, especially at large elevation angles.**

Keywords— beam steering, COTM, near-field, meta-material, metasurface, phase shifting surface, phase transformation, phase gradient metasurfaces, SOTM, SATCOM, 5G, 6G, satellite communication, satellite TV, SOTM, transmitarray, reflectarray, lens antenna, CP, LP, RHCP, LHCP

I. INTRODUCTION

The evolution of existing wireless services and emergence of new services such as the Internet of Things (IoT) have provided the impetus to research in the fields related to wireless communication. Among others, emphasis is on the development of efficient, low-cost and low-profile front-end beam-steering antennas. The traditional mechanical and electronic beam steering methods have some limitations and unconventional methods such as those based on liquid crystals, planar metasurfaces and optical beamformers are being investigated [1].

One of these relatively new unconventional beam-steering methods, first presented by the authors in 2017, has a pair of rotating near-field metasurfaces positioned very close to the aperture of a high-gain base antenna, which has a fixed beam [2]. This method, subsequently developed by the authors and a few other research groups independently, is now called *Near-Field Meta-Steering (NFMS)* [3]. It was found to have several advantages over competing antenna beam-steering technologies. They include (i) the lack of tilting parts, (ii) planar low profile, due to small gap between the base antenna and the metasurface and lack of tilting; (iii) requires very low power to operate (only a few watts for the two motors when steering, nothing when locked); (iv) polarization flexibility – any polarization (LP/CP) and dual (LP/CP) polarization can be achieved natively without polarizer plates by designing appropriate base antennas; (v) high aperture efficiency – often determined by the base antenna; (vi) very high overall efficiency even up to 30 GHz – again determined by the base antenna; (vii) relatively low cost of fabrication and low bill of materials – depending on the base antenna; (viii) no active non-linearly, intermodulation, etc. due to the lack of active electronics; (ix) no thermal management challenges due to low RF losses overall; (x) high power handling capability; (xi) no fundamental limit on maximum gain or maximum bandwidth or gain-bandwidth-product; (xii) lack of mechanical translation; (xiii) in many cases, base antenna is totally stationary so does not require powerful motors or rotary joints etc.; (xiv) does work with already designed or manufactured base antennas with fixed beams. In contrast to some electronically steered antennas, NFMS method does not require any active radio frequency (RF) components such as PIN diodes or phase shifters thus have high antenna efficiency and high power handling capabilities.

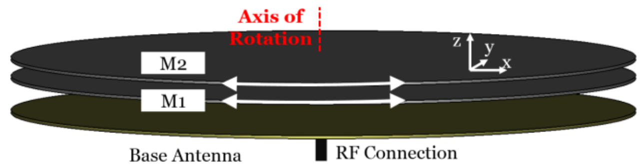

Fig. 1: A perspective of classic Near-Field Meta-Steering (NFMS) based antenna system. The base antenna is fixed while two metasurfaces M1 and M2 are physically rotated to steer the beam.

A classic NFMS antenna system comprises a fixed high-gain base antenna and a pair of thin and flat rotatable phase-gradient metasurfaces positioned very close to the base antenna, as shown in Fig. 1. Ideally the base antenna has a uniform near-field phase distribution. When its near-field phase is not uniform but has approximate rotational symmetry, it can be "corrected" to at the same time by incorporating radial phase correction to the lower phase-gradient metasurface [2]. The rotatable metasurfaces provide the dynamic near-field phase transformation required to steer the beam. Thus the antenna beam can be dynamically steered to any azimuth and elevation angle within a large cone by appropriately orienting the two metasurfaces. Beam steering up to 51^0 in elevation has been experimentally demonstrated with less than 3dB drop in antenna gain [2].

II. NEAR-FIELD META-STEERING METHOD

The NFMS was inspired by the optical beam-scanning method used in Risely prisms. The method has been long used in the field of optics where a pair of glass prisms are used with an optical beam. The two prisms are rotated to scan the beam of light. The concept was later extended to microwaves where a pair of dielectric wedges were placed several wavelengths away from a horn antenna [4]. The dielectric wedges were later replaced with thin flat printed phase-shifting surfaces (PSSs), again placed several wavelengths away from a horn antenna [5]. Such large gaps between the horn antenna and metasurfaces allowed the application of ray optics methods and approximations when designing such antenna systems but for the same reason these antenna systems are not low-profile.

In contrast, in NFMS and other near-field phase transformation methods, the metasurfaces or other types of phase transformers are placed very close to the base antenna, thus dramatically reducing the total system height. However, ray methods are out of the question and the physical aperture area of a preferred base antenna is almost the same as that of circular metasurfaces used for steering its beam. Thus, much higher aperture efficiencies are achievable using base antennas with high aperture efficiency. The metasurfaces can be designed to be polarization independent, and hence, steerable beams of linear, circular or dual (linear or circular) polarization can be produced with appropriate base antennas.

III. Recent Developments

Since the publication of first paper [2], the concept is being extended in various forms by several groups. A few are outlined here. A high-power microwave (HPW) system has been developed using rotatable totally-metal cross-slot type phase gradient metasurfaces and a metal horn antenna [6, 7]. These polarization-conversion type metasurfaces do not have any dielectric and are instead made of thin metal sheets separated by a 2D array of metal waveguides [6].

A dual-polarized beam-steering antenna system has been demonstrated [8]. It uses two orthogonally placed CST arrays as the base antenna for dual polarizations and a pair of linear phase progression phase-shifting surfaces for beam-steering. The measured results confirms that the antenna beam can be steered up to 40^o in elevation for all azimuth angles. The overall height of the antenna system is only $1.17\lambda_0$, which is extremely small when compared with beam-steering antenna systems with tilting antennas.

More recently, a pair of metasurfaces have been optimised to reduce undersirable grating lobes, which may be inherently generated due to the periodic nature of the metasurfaces [3]. It has been demonstrated through intensive numerical simulations that the use of steeper phase gradient for the pair of near-field metaurfaces can produce a given 2D beam steering range with less number of grating lobes and higher directivity.

Most of the applied research related to NFMS method has so far focused on increasing the capabilities of the systems. The common analytical technique used to predict the beam direction is based on first order paraxial approximation reported in [2], which generates unacceptable error for larger elevation angles. A recently developed more accurate method based on phase calculations has reduced the error in predicted beam direction from 5^o of paraxial method to only 1.2^o for elevation steering angles as large as 56^o [9].

For a wideband millimeter-wave system, two 3D printed dielectric phase transformer blocks have been developed instead of planar metasurfaces for near-field phase transformation and near-field phase correction. They have been placed almost at a touching distance from the aperture of a horn antenna and rotated using low-cost stepper motors and a massive beam-steering bandwidth of 40.5% has been demonstrated experimentally [10].

IV. Conclusion

The Near-Field Meta-Steering (NFMS) method or its close variants is being pursued by several groups and their efforts have already produced remarkable results in less than three years from the seminal publication [2]. Nevertheless there exits many opportunities and room to further improve the method and its capabilities and its full potential in wireless communication in general and mobile satellite communication in particular is yet to be reached.

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