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An Overview of Novel Tuning Techniques for Realizing Programmable Beam-Scanning Metasurfaces

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Abstract

Programmable metasurfaces are two-dimensional artificial subwavelength thin-layer structures with programmable electromagnetic properties that can operate over a wide frequency range. Controlling the tunable components of these subwavelength structures enables the electromagnetic parameters of the incident wave, such as phase and amplitude, to be modified in a programmable fashion. Several tuning procedures are employed to generate programmable metasurfaces, ranging from global tuning at the metasurface level to local tuning at the unit cell level. In this paper, we give a comparison of our proposed unique programmable beam-scanning metasurfaces.

1 Introduction

Aside from the exciting discovery of unique metasurfaces, the engineering advances of reconfigurable metasurfaces are becoming pressing tasks as there are promising useful real-world applications. Reconfigurable metasurfaces may adjust the amplitude, phase[1], polarization [2], and other properties of an electromagnetic wave as needed, allowing for the development of a variety of planar functional devices with unique functionalities across a wide range of frequencies. Electronic control [3], mechanical control [4], and fluidic control [5] are examples of methodologies for programmable metasurfaces that have been documented in recent years. The electromagnetic response characteristics of metasurfaces loaded with varactor/PIN diodes [6], MEMS-switches [7], graphene, and liquid crystals [8] can be dynamically controlled by adjusting the applied bias voltage on the materials/components in those metasurfaces. The mechanically adjustable metasurface offers a viable technique for controlling electromagnetic waves in real-time [4], [9]. The form of the elastic/flexible substrate material may be mechanically altered when the metasurface is created on it. As a result, the electromagnetic response of the metasurface unit may be altered, allowing for the creation of a mechanically adjustable metasurface. Microfluidic technology has been used to create programmable metasurfaces that don't need electrical devices or time-consuming fabrication procedures [5], [10]. Fluid can flow through the channels as a conductive element or as a loading element using the needed pressure, hence adjusting the electromagnetic response.

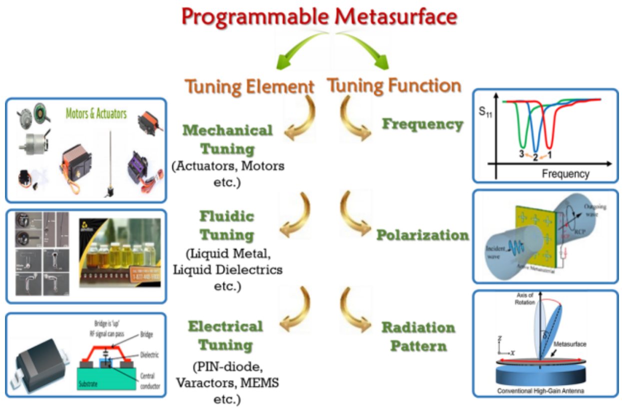


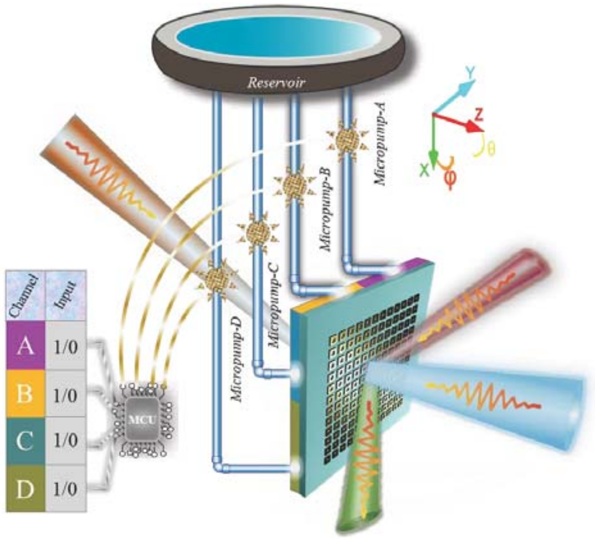
Figure 1. Illustration of several programmable metasurface tuning techniques and functionalities.

Certainly, a few obstacles might hinder the development of the envisioned programmable metasurfaces. Tuning speed, communication losses, and feeding technology are only a few of the primary concerns that significantly impact the radiation efficiency and accuracy at microwave and millimeter-wave frequencies. Due to manufacturing constraints, developing programmable metamaterials at higher frequencies can be substantially more difficult.

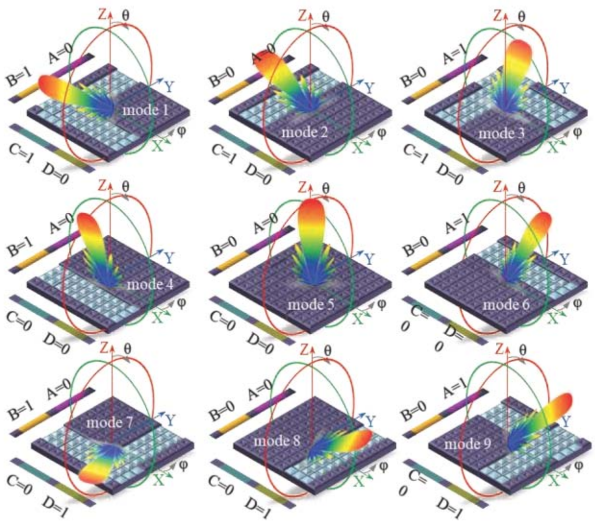
In the remainder of this paper, we'll look at three separately proposed novel programmable metasurfaces.

2 Globally Tunable Fluidically Programmable Beam-scanning Metasurface

The design configuration of the globally tunable fluidically programmable beam-scanning metasurface (FPMS) is illustrated in Fig. 2(a) [11], [12]. FPMS is composed of two layers i.e., a conductive top layer and a bottom channel layer for fluid flow. The top layer of the FPMS is made up of 4×4 conductive square element array on top side of a thin Rogers3003 dielectric substrate with a thickness of 0.5 mm. Fluidic channels were created using 3D printing on a polylactic acid (PLA) substrate with dielectric constant = 2.5 and dielectric loss tangent = 0.02. EM wave phase variation can be realized fluidically using water flow inside the fluidic channels controlled by programable electronic pumping.



(a)



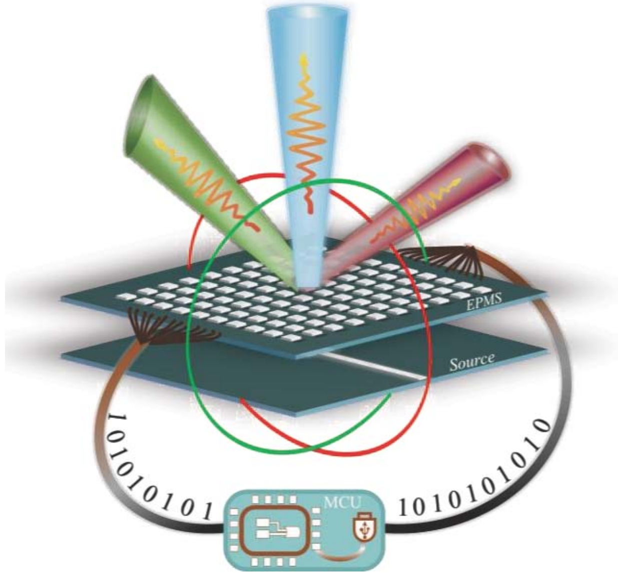
(b)

Figure 2. (a) Proposed FPMS concept and design. (b) An FPMS illustration demonstrating the beam scanning capabilities for modes 1 through 9 with the four microfluidic channels A, B, C, and D.

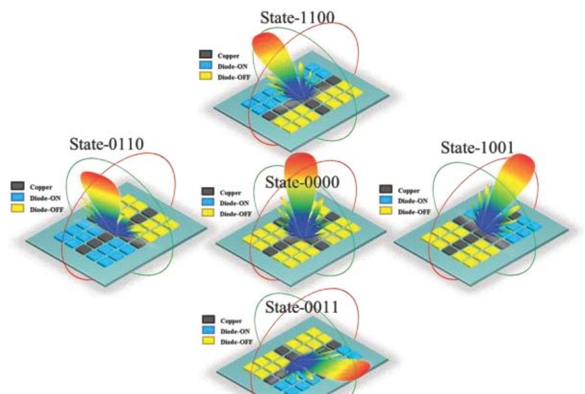
The proposed FPMS offers a low-profile, cost-effective method for programming EM waves in the microwave domain using water, as illustrated in Fig. 2(b). For Mode-1 to Mode-9, the simulated and measured 10-dB impedance bandwidth (IMBW) ranged from 2.41 to 2.60 GHz and 2.41 to 2.65 GHz, respectively. The fabrication process' accuracy and how well microfluidics is used for tuning are what mostly defines the precision and accuracy of beam-scanning. The effective permittivity of the FPMS may change as a result of slight fabrication errors, poor sealing, and a fluidic injection/extraction process, which could reduce the precision of beam-scanning.

3 Globally Tunable Electronically Programmable Beam-scanning Metasurface

Figure 3(a) depicts the design configuration of globally tunable electronically programmable beam-scanning metasurface (EPMS) for Ka-band applications with a significantly low profile ($0.44\lambda_o$) and low cost [13]. EPMS assembly comprises a radiating source, tunable single-layered metasurface comprising hybrid meta-cells, dedicated microcontroller unit (MCU) hardware system, and power source. To create a passive meta-cell, a square metallic patch with periodicity *d* was printed on the top side of a Rogers 5880 substrate with a dielectric constant and dielectric loss equal to 2.2 and 0.0009, respectively. Using PIN-diodes, the passive meta-cell was changed into an active meta-cell to induce reflection phase inconsistencies.



(a)



(b)

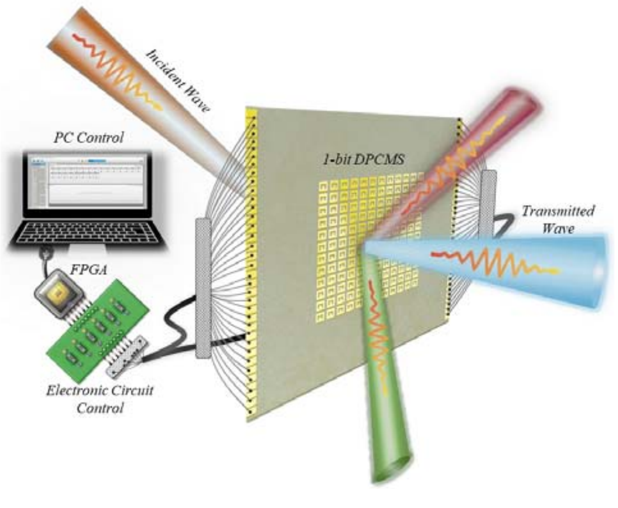
Figure 3. (a) Proposed EPMS concept and design. (b) Operating principle of proposed EPMS with the four subarrays A, B, C, and D.

Controlling diodes on different metasurface subarrays can generate reflection phase inconsistencies. The proposed configuration generates a boresight beam at θ = 0° when all the subarrays operate at the same state, i.e., all ON or all OFF, or steer the beam at θ = ±10° in the φ = 0° and 90° planes with tunable reflection phase distribution, as shown in Fig 3(b). Simulated 10-dB IMBW = 27.4–28.9 GHz and measured common 10-dB IMBW = 27.8–28.2 GHz show excellent agreement.

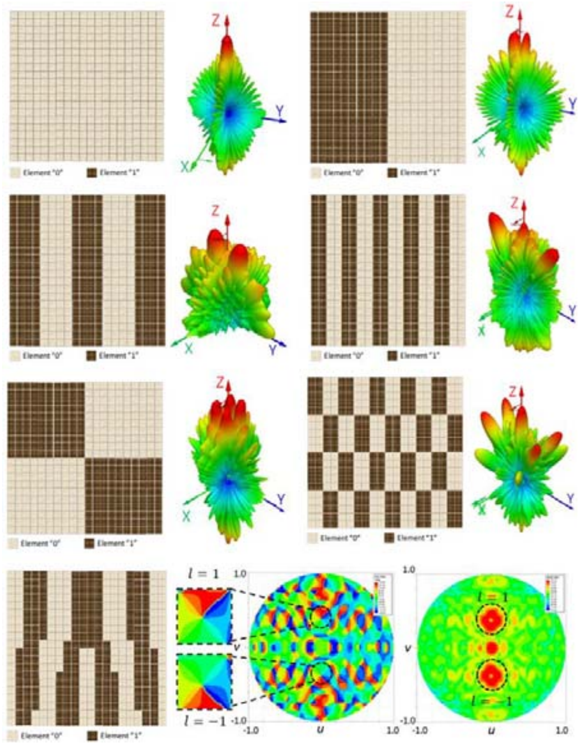
4 Locally Tunable 1-bit Digitally Programmable Coding Metasurface

The design configuration of the locally tunable 1-bit digitally programmable coding metasurface (DPCMS) is illustrated in Fig. 4(a). The proposed structure was constructed completely using the low-cost substrate FR-4, which significantly enhances the cost-effectiveness of the design. Two PIN diodes MA4GP907 were integrated on each unit cell and switched to control signal flow, thus creating transmission phases of 0° and 180°. Various real-time beam-shaping functions were realized using a field-programmable gate array (FPGA) to execute different coding sequences.

At the design frequency of 28 GHz, the simulated S-parameters show minimum insertion losses of 2.9 and 3.3 dB for the 0-bit and 1-bit states, respectively, whereas the measured S-parameters show minimum insertion losses of 3.4 and 4.5 dB for the 0-bit and 1-bit states, respectively. The proposed design effectively performs multiple dynamic beam-shaping functionalities, including dual-beam steering, multiple-beam shaping, and vortex beams with orbital-angular-momentum (OAM) generation. Three main functions were investigated, including dual-beam steering, multi-beam shaping, and OAM-mode dual-vortex-beam generation, as depicted in Fig. 4(b).



(a)



(b)

Figure 4. (a) Proposed 1-bit DPCMS concept and design. (b) Multiple function coding and radiation patterns using the proposed DPCM.

5 Conclusion

In this contribution, we have discussed novel possibilities and the evolution of metasurfaces using various tuning strategies. We investigated the possibility of expanding the metasurface functionality by introducing local tuning based on our past expertise in creating globally tunable metasurfaces for polarization converters and beam-scanning. The operating principles of these programmable metasurfaces for accomplishing such unusual capabilities have been briefly addressed, and their configurations have been published. In the context of intelligent systems for next-generation wireless communications, these findings indicate the viability of covering metasurfaces as a promising method for constructing reconfigurable systems.

Acknowledgements

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