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Development of Passive and Reconfigurable Reflectarray Antennas

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Abstract This report outlines the research activities conducted by our research group over the past decade in the development of reflectarray antennas. Our focus has been on both passive reflectarray antennas and reconfigurable reflectarray antennas, also known as reconfigurable intelligent surfaces (RIS) or intelligent reflecting surfaces (IRS). For passive reflectarray antennas, our research has tackled major challenges such as achieving wideband, multiband, and multifunctional capabilities, while maintaining low losses and high aperture efficiency. On the other hand, for reconfigurable reflectarrays, our efforts have been concentrated on addressing issues related to complexity, aperture efficiency, and reflection loss.

Key words RIS; reconfigurable intelligent surfaces; beam steering; liquid crystal; reconfigurable intelligent surface; reflectarray; antennas; wireless communications.

In urban areas characterized by high-density buildings, a significant issue arises wherein radio waves emitted by cellular mobile communication base stations are obstructed, particularly within narrow streets flanked by buildings. These areas are commonly referred to as "blind spots." In such areas, the signal-to-noise ratio (SNR) diminishes significantly, leading to degraded communication quality, particularly concerning next-generation wireless communication systems operating at ultra-high speeds and frequencies. The blockage of a propagation channel in a blind spot may also greatly decrease the channel capacity for a multi-input multi-output (MIMO) system. Many efforts have been made to address this problem, which dramatically degrades the efficiency of data transmission between mobile users and base stations. However, in most of the cases where a direct microwave path cannot be established (i.e., None-Line-of-Sight, NLOS) between two points, it is possible to re-establish a propagation path by using the help of reflectarray.

The original reflectarray (RA) comprises a low-profile planar array of microstrip elements which were printed on a grounded substrate and illuminated by a primary feed source [1]. The planar reflectarray combines the advantages of reflectors and phased arrays, and rapidly becomes an attractive alternative to the conventional parabolic reflector antenna. Since the 1980s, reflectarray has been developed for several decades and achieved wide range of applications for its advantages, such as surface-mountable, low mass and volume and easy deployment, etc [1], [2]. Planar reflectarray antennas with non-specular reflection performance can be embedded into the top part of the vertical building walls or integrated into firmly settled advertisement boards on the top of buildings to reflect wave beams covering different areas, especially blind spots for the primary source.

A unit cell of the reflectarray which has a capability of covering a more than 360-degree reflection phase at a wide frequency range is required to make a wideband reflectarray with high aperture efficiency. How to design the unit cell of good performance is a challenging work in development of reflectarray. A novel reflectarray element using an interdigital gap loading structure was proposed [3]. A wide reflection phase range of more than 1000° was obtained, which could support a sufficient phase range for a large scattering angle. The unit cell had a feature of equal element size for equal amplitude of reflection, because the reflection phase was adjusted by controlling the finger length of the interdigital gap. Thus, abrupt geometry variations for consecutive cells in the traditional reflectarray were avoided. A Ku-band reflectarray using the unit cell was fabricated and measured for demonstration of the design.

The bandwidth of reflectarray is dependent on the array configuration and the bandwidth of unit cells. A log-periodic dipole array (LPDA) is one of the wideband antennas. A wideband scattering performance of a reflectarray composed of the LPDA was designed and studied numerically and experimentally [4]. The reflectarray was designed using method of moments. Numerical simulation demonstrated that a reflectarray composed of the LPDA is wideband because the LPDA operated as a wideband reflectarray element due to its self-complementary structure. A reflectarray could be fabricated using a three-dimensional printing technology, and its scattering performance was experimentally confirmed. It was shown that the 1-dB and 3-dB bandwidths of the designed reflectarray are 45% and 64%, respectively. Scattering performance of a reflectarray using the LPDA element was also demonstrated numerically and experimentally [5]. A bistatic radar cross section (BRCS) of the designed reflectarray was measured and the measured BRCS was in good agreement with that obtained using the MoM and the effect of near-field. According to so-called self-complementary structure of the LPDA element, 1-dB bandwidth over 40

The possibility of using a passive reflectarray to improve outdoor radio channel in none-line-of-sight (NLOS) environment was demonstrated in [8], [9]. The reflectarray composed of the unit cell design in [3] has a capability of a up-to 58-

degree scattering angle. It was installed on the roof of a building to eliminate blind spots on the road in front of the building, and enhance MIMO performance of the mobile users on the road. The performance and effectiveness in improvement of the receiving signal noise ratio (SNR) and channel quality were experimental investigated. It was found that the received power level and channel capacity for 8×8 MIMO were improved by more than 10 dB and 4 bps/Hz compared to those without the reflectarray in NLOS environment, respectively. An experiment champagne was performed at 11 GHz in the island of Ishigaki-jima.

In the mobile communications, the wireless environment of a mobile user varies from moment to moment. The reflectarray should be reconfigurable, and is adaptively controlled to scatter the incident wave to the desired direction every moment with the information of propagation channel. One of the early research on the reconfigurable reflectarray was punblished in [10]. The reconfigurable reflectarray is usually composed of the unit cells including tunable devices which are either electrically controlled, or mechanically controlled. Reduction of power loss, response time, and accurate control of both the reflection amplitude and reflection phase, are the particularly challenging work for us to develop a reconfigurable reflectarray of high performance in applications of wireless communications. The reconfigurable reflectarray is also called metasurface, metamaterial surface, intelligent reflecting surface (IRS), or reconfigurable intelligent surfaces (RIS), in the different societies.

A reflectarray based dual-beam gain-reconfigurable structure was proposed for dynamically controlling the gain of each beam [11]. By modulating the excitation conditions for each phased-array feed and compensation phase distribution on the aperture, dual beams with different gains can be realized simultaneously. A novel wideband, multifunctional space-fed planar array antenna was proposed to independently control forward/backward beams [12]. A novel four-layer polarization-dependent unit cell was introduced as the phasing element. A generalized-scattering-matrix (GSM)-based network model was developed to evaluate the element performance and optimize the element structure. A system-level analysis in terms of source feed performance, antenna configuration, and efficiency factors were demonstrated. A wideband transmitarray antenna exploiting 1-bit polarization-rotation unit cell was proposed in [13]. In order to obtain wideband performance, a novel three-layer polarization-rotation 1-bit unit cell was developed to introduce phase errors over the aperture, which act as one kind of degree-of-freedom during the system design.

Development of reconfigurable reflectarray based on liquid crystal (LC) technology attract attention in recent years, because the LC is linear medium and its permittivity is tunable by bias voltage. The LC is different from those tunable components like varactor tuning diodes and PIN diodes which are non-linear, and easily generate high-order harmonic wave. A bias network for the LC based reflectarray to control the beam scanning in both E-plane and H-plane was proposed in [14]. A 12×12 LC reflectarray composed of individually controlled LC unit cells was studied. The further study on the LC based reflectarray was conducted to characterize the performance of beam steering by experiment in [15]. Beam steering at E-plane from 0° to 35°, and beam steering at H-plane from 0°, to 40°, were demonstrated. But the high-power loss of the LC based reflectarray is a big problem. In [16], a structure to reduce the reflection loss of the LC based reflectarray was proposed. The numerical simulation indicated that the large electric field in the LC layer caused the high-power loss. To address this issue, a loss suppression structure was presented. Theoretical analysis indicated the reflection loss was reduced, and a 15 ×15 prototype LC based reflectarray was fabricated and measured. Simulated and measurement results demonstrated a loss reduction of 11.3 dB, while keeping reflection phase at a range of 204°.

In the 1-bit reflectarray design, the design of unit cell which can show two status of reflection phase is considered to be the highest priority. However, the consideration of accurately controlling the reflection amplitude is not often, because it is difficult to control both the amplitude and phase of the reflection coefficient of unit cell simultaneously. A 1-bit time-modulated RA (1-bit TMRA) was designed based on a conventional 1-bit RA and TM technology in [17]. The fabricated 1-bit TMRA was evaluated by measuring the direction of beam scanning, and sidelobe level as well. The results show that the proposed 1-bit TMRA could realize the TM characteristics without significantly increasing the system complexity of the 1-bit RA. The proposed 1-bit TMRA operated at the center frequency, making it suitable for applications in the existing wireless communication systems.

Owing to simple structure, low cost and high performance, NRD waveguide has attracted much attention for millimeter wave applications [18]. A wideband reflectarray antenna was proposed which was composed of the NRD waveguide as the unit cells [19]. Because of the NRD waveguid is not a resonant radiator, wideband reflectarray was expected. In contrast to conventional rectangular waveguide-based RA, the proposed design simplified the unit cell structure by eliminating a pair of conductor walls and the metal ground used for reflecting the incident electromagnetic wave. In addition, the proposed design achieved a compact unit cell size of 0.43 $\lambda\times$ 0.44 λ, whereλ represents the free-space wavelength at the center frequency (10 GHz). The single-layer dielectric was employed for the RA design instead of previously reported multilayer or stacked layers to achieve the comparable performance. The prototype was made of 16×16 unit cells, with the dielectric components fabricated by 3-D printing technology. The measurements showed that the 1 dB and 3 dB gain bandwidth of 18% and 27% was realized, respectively, with a peak aperture efficiency of 45%. Both the simulations and measurements demonstrated that the proposed design enables wideband and improved efficiency using a low-cost compact structure.

Besides the electrically controlling approach for the reconfigurable reflectarray, the mechanically controlling approach is also one the interesting topics. A novel mechanically reconfigurable reflectarray element actuated by an electromagnet working in C-band was proposed [20]. The 1-bit phase shift of reflecting wave was achieved by bending a half-wavelength dipole with magnetostatic force. Due to the isolation between element and RF phase shifter, the proposed reflectarray element was free from insertion loss. This was the first article demonstrating the performance of a reconfigurable reflectarray with the element totally isolated from the RF phase shifter. Due to the contactless reconfigurable system, the mechanical connection between the electromagnet and the reflectarray element was physically unnecessary. A 25×8 1-bit reconfigurable reflectarray using the proposed elements was fabricated and its scattering performance was demonstrated via field measurement. The measured gain and aperture efficiency of the fabricated 1-bit reconfigurable reflectarray were 22.7 dBi and 34.0% at specular direction, respectively.

In practical use, the reflectarray should be covered by a so-called radome. The EM effect of dielectric radome on the performance of reflectarray should be investigated. Effect of a dielectric superstrate on scattering performance of reflectarray elements was studied in [21]. Results and theories demonstrated in this article showed quantitative guidelines on designing the reflectarray elements covered by the superstrate from the viewpoints of angle dependence, geometry, and permittivity of the superstrate.

Numerical analysis of the reflectarray is necessary in the reflectarray development. Because the reflectarray is usually composed of a large scale of unequal array elements, a full wave electromagnetic simulation costs huge CPU time. Efficient and accurate numerical analysis method is required in development of reflectarray. A design method of reflectarray by the induced electromotive force (EMF) method was proposed in [22]. The effect of oblique incidence from a primary source to a reflectarray element was included in the design process of the reflectarray by the proposed method. The CPU time by the proposed method was reduced because mutual coupling between reflectarray elements was ignored. A fast design method of the finite FSS-backed reflectarray was also presented in [23]. In the design method, induced electromotive force method was again used for calculating self/mutual impedance between linear elements. Resultant matrix equation was solved by a block diagonal preconditioned-conjugate gradient (BDP-CG) method. The total CPU time of the BDP-CG method became much small compared with that of the conventional direct solver. As a result, total CPU time was saved for designing the reflectarray backed by finite FSS.

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