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RESEARCH-ARTICLE

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A novel broadband and high-gain microstrip reflectarray antenna with variable polarization

Abstract This article proposes a new kind of microstrip reflectarray antenna, of which the polarization could be reconfigured among all the polarization states instead of some fixed states in a dual- or multi-polarized antenna. The mechanism for polarized variability is so simple that only mechanical rotation is needed. Theoretical analysis shows that the reflected polarization covers all states and that the dual- or multi-layered unit structure sandwiched with air-gaps can broaden the bandwidth efficiently. Moreover, it is demonstrated that adopting more elements can enhance antenna gain. With these advantageous features, this kind of antenna has the potential significance for engineering applications in radar, communication, etc. In this article, a complete theoretical analysis as well as a specific design sample is given to verify this method.

Keywords reflectarray, variable polarization, polarization reconfigurable antenna, wideband, high-gain

1 Introduction

Polarization characteristics of electromagnetic waves have been utilized extensively in modern communication systems for functional diversification, such as identifying a target through the polarized response of a radar cross-section (RCS) of cloud, rain, etc., in weather radar systems; enhancing communication reliability by adopting circular polarization (CP) in satellite communications [1]; eliminating multi-path effects by using polarization diversity in mobile communication systems, etc. For radars and electronic warfare applications, it is always necessary to vary the real-time polarized state of the antenna for electric countermeasures and camouflaging. Such antenna, whose polarization is reconfigurable, is denoted as a polarization variable antenna. The polarization variable antenna (PVA) differs from dual- or multi-polarized antenna because its polarized state is continually tunable among all polarization states, while the latter can only switch its polarization among some definite states. The traditional PVA is usually realized by tuning the amplitude ratio and phase difference between two orthogonal feed branches to radiate arbitrarily polarized wave [2].

The microstrip reflectarray (RA) [3], used as an alternative for the traditional parabolic reflector, can be extensively applied in satellite communication, radar, direct broadcast satellite (DBS) system, etc., due to its advantages: low-profile or conformable structure, flexible design without a complex feed-network, easy deployment, easy fabrication by printed technology and low cost. The microstrip RA has been one of the hot topics in the antenna industry in the past decade. Many types of configurations have been developed for different applications, such as square or circular patches loaded with variable length of stubs [4], square patches with variable sizes [5], aperture-coupled patches [6], CP patches with variable rotation angles [7], annular patches with variable sizes [8], ground-slotted patches [9], multi-layered square patches [10], and so on. Usually, research on microstrip RA on polarization focuses on the realization and applications of dual linearly-polarized (LP) or circularly-polarized (CP) reflectarray.

With reference to the polarization twist by rectangular patches [11] and the bandwidth broadening by stacked patches [10], the authors proposed a novel RA with polarization-transform (PT) [12], which changes the polarization state of the reflected wave from that of the illuminated wave. Thus, the phase compensation and PT can be realized simultaneously by means of the proper design of the sizes of double-layered rectangular patch elements. This RA-PT has a number of advantages compared with the traditional RA: to reflect the CP wave by illumination of an LP feed as an LP to CP transform [13]; reduces the feed-blockage effect on the reflected

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wave by orthogonal PT as a LP to X-LP transform [14] and also to match arbitrarily polarized wave radiated from or received by RA with a proper PT as a polarization variable antenna.

It should be possible to tune the polarization variability over all of the polarization states: the horizontal or vertical LP, the left-handed (LH) or right-handed (RH) CP, the LH or RH elliptic polarization (EP) with arbitrary axial ratio (AR) and also axial direction. As demonstrated in Fig. 1, polarization variability is realized by simply rotating the feed and/or RA. This RA consists of an array of stacked rectangular patch elements with different sizes and also a sheet of tapered slot-line radiator as the primary feed. A prototype with 37 elements has been designed, fabricated and tested, which exhibits 17.3 dB gain corresponding to ~40% antenna aperture efficiency. In the case of CP radiation, the cross-polar level is less than −15 dB within 8% bandwidth, and approaches to −26 dB at minimum.

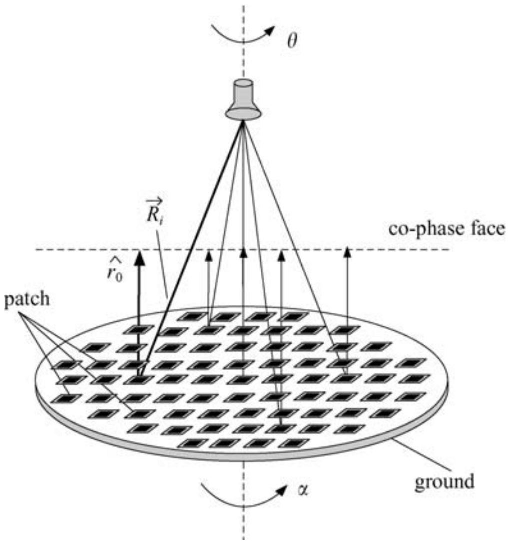


Fig. 1 Demonstration of reflectarray antenna with variable polarization

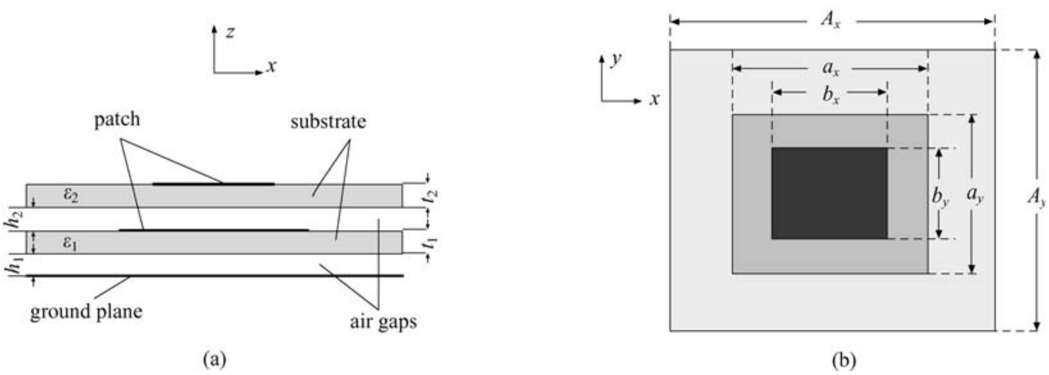
2 Principle

Figure 1 demonstrates the reflectarray, consisting of a planar array of metallic patches etched on a dielectric substrate backed ground-plate, and illuminated by an LP feed located at a defined focus point on the symmetric axis of the aperture. The feature of this reflectarray differs from traditional one in that, not only the wide-angle illumination beam from the feed can be concentrated into a phase-coherent beam, but also the polarization of the reflected beam can be changed, by means of rotating the feed and/or array around the symmetric axis. Denote θ as the angle of the feed relative to the array, and α as the rotating angle of the whole antenna including both the feed and array. Both θ and α may be adjusted independently in structure.

The key technique of designing such a reflectarray is employing the double-layered rectangular patch shown in Fig. 2 as the elements of the array instead of the traditional square patch elements. For a rectangular element with different side-lengths in x and y direction, the reflected phases, which are denoted as ϕ_x for x-component and ϕ_y for y-component respectively, must be different. For a given element, properly design its side-lengths to get a specific phase ϕ_x to compensate for the phase error due to the length difference of the ray-path coming from the feed, and keep the phase difference $\sigma = (\phi_y - \phi_x)$ always being $(N \cdot 360^\circ + 90^\circ)$ for each element.

How to perform the polarization variability of this reflectarray? It can be demonstrated in Fig. 3. When the incident wave E_{in} decomposes into x and y components, those phases are coherent but the amplitude ratio $\gamma = E_y/E_x = \tan\theta$ changes with the varying of θ. Thus, the components of reflected wave E_x^r and E_y^r meet the following relation

$$\begin{cases} E_x^r = E\sin(\omega t - \beta z) \\ E_y^r = E\tan\theta\sin(\omega t - \beta z + 90^\circ) \end{cases}. \tag{1}$$



(a) (b)

Fig. 2 Geometry of dual-layered rectangular element. (a) Side view; (b) top view

After a manual operation, it yields

$$\left(\frac{E_x^r}{E}\right)^2+\left(\frac{E_y^r}{E\tan\theta}\right)^2=1. \qquad (2)$$

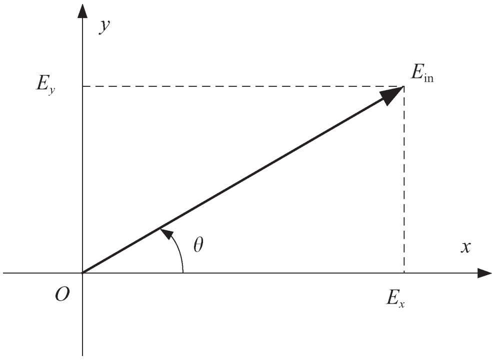


Fig. 3 Components amplitude ratio versus feed rotation angle

Obviously, the resulting polarization of the reflected wave depends on the angle θ, as shown in Fig. 4, where $\theta=0°$ corresponds to x-LP; $\theta=45°$ to LHCP; $\theta=90°$ to y-LP; $\theta=135°$ to RHCP; otherwise, it corresponds to EP with various AR. On the Poincare sphere, an initial x-LP point moves 2θ along the longitude circle orthogonal to the equator. However, all polarization states obtained by adjusting θ have the same polarization tilt-angle. To perform an arbitrary polarization covering the Poincare sphere, the tilt-angle should be also changeable. Fortunately, it can be achieved by simultaneously rotating both the array and feed. Figure 4 shows that when the antenna is rotated a physical angle α, the axis orientation in polarized ellipse of the reflected wave rotates 2α along a latitude circle parallel to the equator. In conclusion, when θ and α are adjusted from 0° to 180° respectively, the initial horizontal LP can be varied into arbitrary polarization.

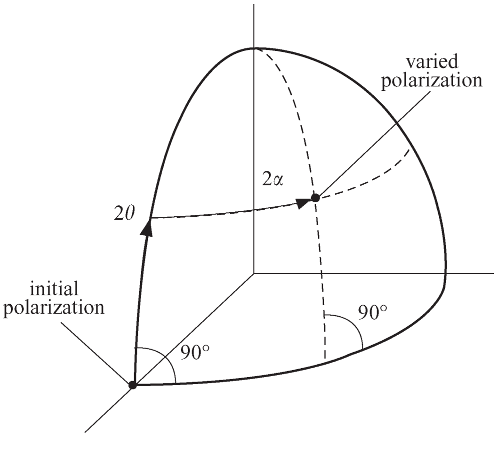


Fig. 4 Representation of polarized variability on Poincare sphere

3 Design sample and results

To verify the above principle, a 37-element reflectarray was designed as a practical sample for test. The central frequency is specified to be $f_0=10$ GHz and two substrates with a permittivity $\varepsilon_1=\varepsilon_2=2.2$ are chosen. The thickness $t_1=t_2=0.5$ mm, the height of air gaps $h_1=h_2=2$ mm and the size of a square period $A_x=A_y=18$ mm. For simplicity, the structural sizes of the patches in the upper- and lower-layers are the same. Thus, the similarity ratio of patches as $s=b_x/a_x=b_y/a_y$ and an aspect ratio of rectangular patch as $\tau=a_y/a_x=b_y/b_x$, where s is always given within 0.6–0.8, and $s=0.7$ is set for all elements in this design. Thus, a_x and τ become two independent variables to specify the size of element. Summarize a great number of simulation data by using the Microwave Studio CST-Coder, a set of recommended (a_x in mm, τ) for elements by the distance from the array centre in order are: (14.00, 0.91),(13.66, 0.91),(13.36, 0.91),(12.84, 0.90),(12.61, 0.89),(11.78, 0.85), (11.40, 0.83),(11.03, 0.82). An exponentially tapered slot-line antenna is employed as the LP-feed, which is located at the focus, about 84.4 mm away from the surface of the array.

The key performance of a reflectarray with variable polarization is the cross-polar level that can be characterized by CP reflection when $\theta=\pm45°$. While two orthogonal components of the incident wave have equal magnitude and co-phase, the two reflected components should keep an equal magnitude, but with ± 90° phase fluctuation provided by rectangular patches in principle. In practice, unfortunately, because of the existence of errors in the magnitude of the reflection coefficients between components in design and also in fabrication, the resultant CP is not pure, corresponding to a finite cross-polar level.

The simulated and measured radiation patterns are shown in Fig. 5. For the designed sample, the measured results of −26 dB cross-polar level, −13 dB side-lobe level, ~13.5° half-power beamwidth, and 17.3 dB gain corresponding to ~40% aperture efficiency are obtained. The bandwidth for cross-polar level less than −15 dB exceeds 8%. Hence, the precise polarized variability by adjusting θ and α in a relative broad band can be expected.

4 Conclusions

In this paper, a novel broadband reflectarray antenna with variable polarization is proposed. The principle of polarized variability is analyzed in detail, which is also verified by simulation and experiment. The mechanism of polarized variability is much simpler than a traditional antenna with complex feed network, for only the

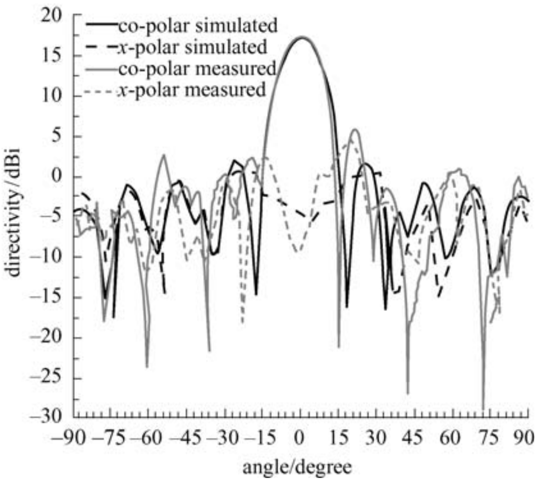


Fig. 5 Simulated and measured pattern incase of CP wave reflection

operation of mechanical rotation is needed. This antenna presents good features of broadband and higher gain (with a great number of elements), so it has potential significance for engineering applications.

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