Multi-Beam Discrete Lens Arrays with Amplitude-Controlled Steering

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Abstract **— This paper presents a multi-beam antenna array with amplitude-controlled continuous beam steering of each beam. The principle is demonstrated on a Ka-band full-duplex dual-polarized array with an uplink frequency of 24.7GHz and a down-link frequency of 26.7GHz. The array is designed as a discrete lens, and the antenna elements are dual-frequency patches integrated in a 5-layer structure with delay lines that enable multiple beams. The array is spatially fed with a feed corresponding to each beam. Amplitude control at the feed results in continuous beam steering. Theoretical and experimental results for the multi-beam patterns and the beam steering are presented.**

I. INTRODUCTION

Many antenna systems can benefit from simultaneous multiple beams, one example being satellites flying in fixed formation [1], as well as base-station antennas for wireless communications. This paper addresses the development of a multi-beam lens array antenna for cross-link communications between satellites in tight formation, intended to collect diverse scientific mission data [2]. The application considered requires several simultaneous dual-frequency dual-polarization beams at different angles. The pointing angle of each beam needs to be fine-tuned continuously by about half of the half-power beamwidth to allow pointing corrections with satellites slightly out of formation. A standard way to perform beam forming and steering is with phased array antennas. A multibeam phased array would require a multi-layer feed structure such as a Butler matrix [3]. The feed network includes phase shifters that are very lossy, typically above 10dB at millimeter wavelengths [4], and has limited bandwidth.

In this paper, we use a McGrath lens [5], analogous to a Rotmann lens, which we refer to as a Discrete Lens Array (DLA), Fig.1. A DLA consists of two arrays of antennas with transmission lines connecting each non-feed element between the two sides. One side is referred to as the *non-feed side*, and the other as the *feed side*. The feed side antennas face the feed antennas positioned along a focal surface. Each antenna of the feed side is connected with transmission lines to its pair on the non-feed side. The transmission lines are of different electrical length for each element: the larger delay at the central element with respect to the external ones mimics an optical lens, thicker in the center and thinner in the periphery.

The far-field radiation pattern of the DLA is defined by the lattice and the radiation patterns of the elements on the non-feed side, together with the spatial combining network. The latter consists of the feed-side antenna array and the feeds positioned on the focal arc.

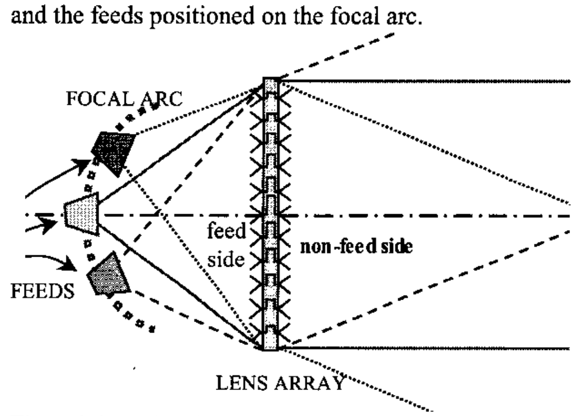

Fig.1. Schematic of a planar discrete lens array with several independent feeds on its focal arc. Each feed controls a radiation pattern with the main beam pointing at a different angle off boresite.

This type of true-time delay beam-forming system has been demonstrated first in [5], and subsequently applied to a number of systems, including adaptive antennas with front-end analog pre-processing [6-9].
Discrete lenses allow the presence of several simultaneous beams at different angles with a single spatial feed structure. The two degrees of freedom in planar DLA

design are the positions of the elements on the feed side (relative to the corresponding elements on the non-feed side) and the electrical lengths of the transmission lines connecting the two sides. Proper choice of delay and positions allows for a cone of best focus, which optimizes for a number of beams with possibly large scan angles (up to ±30 degrees) [6]. In another DLA with two focal points, a ±45 degree scan angle was demonstrated [7].

II. DESIGN OF KA-BAND FULL-DUPLEX DLA

The lens array presented in this paper is a two-degree of freedom design for a cone of best focus of ±30 degrees. The antenna elements are rectangular patch antennas fed from the radiating edges for crossed polarization at 24.7 and 26.7GHz. The simultaneous radiation of two different frequencies requires a two-section quarter-wave transformer between the radiating edges of the patch and each of the 50-ohm feed lines, as shown in Fig.2a. The element bandwidth is measured to be 3% for both frequencies. To satisfy the beam requirement of a 10-degree half-power beamwidth, we used 64 elements on triangular lattice with 0.6λ and λ in the horizontal and vertical directions, respectively.

Fig.2b shows the cross-section of each unit element of the DLA. The patch pair is connected with slot couplers in the antenna ground planes to a common buried delay-line sptripline layer. The delay line lengths range from 0.11λ to 1.05λ with the longest corresponding to the central array element.

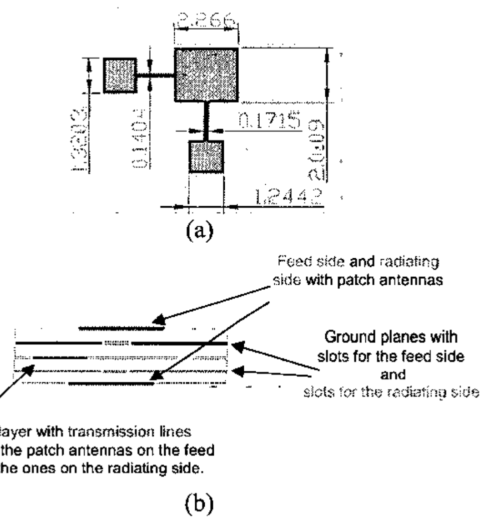

Fig.2. (a) Dual-frequency dual-polarized patch element layout, showing the two-section quarter-wave transformer between the radiating edges and the 50-ohm feed lines (not shown); (b) Sketch of the cross-section of the 5-layer lens unit cell. Notice the buried layer with the delay lines coupled to the antenna elements through resonant slots in the ground planes.

The photograph of the fabricated lens is shown in Fig.3. All substrates are TMM6 Rogers substrates with a permittivity of 6 and a thickness of 0.38mm.

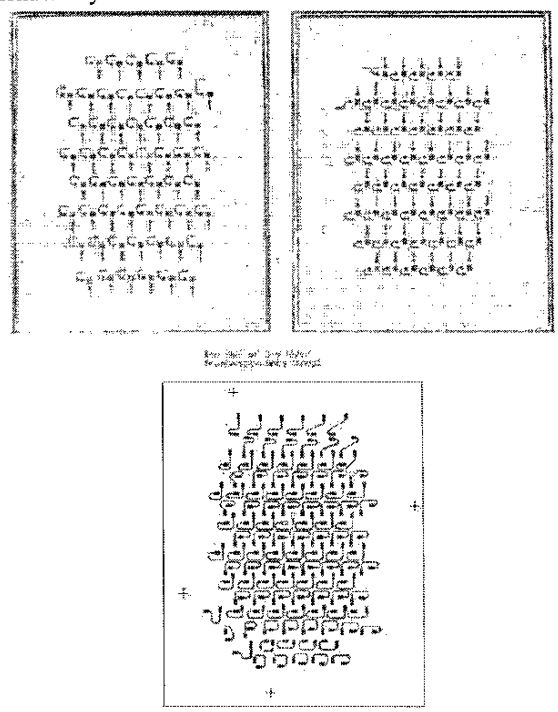

Fig.3. Photographs of the feed (top left) and non-feed (top right) sides of the DLA and layout of the strip-line delay line buried layer (bottom). The dimensions of the lens are 120mm (vertical) and 96mm (horizontal).

III. CHARACTERIZATION OF A DUAL-BEAM KA-BAND FULL-DUPLEX DLA

The antenna array radiation patterns have been measured in a computer-controlled anechoic chamber at the Univ. of Colorado at Boulder and at the NASA Glenn Research Center (GRC), for both the up-link and down-link frequencies.

In Fig.4 are shown the radiation patterns measured at 24.7GHz at University of Colorado for five different positions of a waveguide feed along the focal arc.

The measurements performed at the NASA GRC were part of a characterization of the prototype complete with the custom designed feeds used to implement the amplitude-controlled beam steering. Each of the feeds is placed at an angle of ±30°off boresite on the DLA focal arc.

The radiation patterns measured at NASA GRC at 26.7GHz for two dual-polarized dual-patch antenna feeds are shown in Fig.5. These measurements were performed to verify the measurements at the Univ. of Colorado lab.

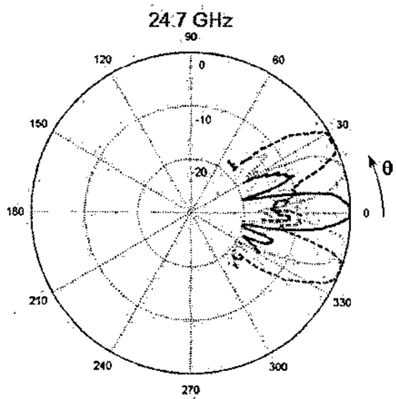

Fig.4. Measured multibeam radiation patterns at 24.7GHz with a waveguide feed placed at 5 different positions along the focal arc. The measurements were performed in the anechoic chamber at University of Colorado. The 26.7GHz patterns are similar and are not included due to limited space.

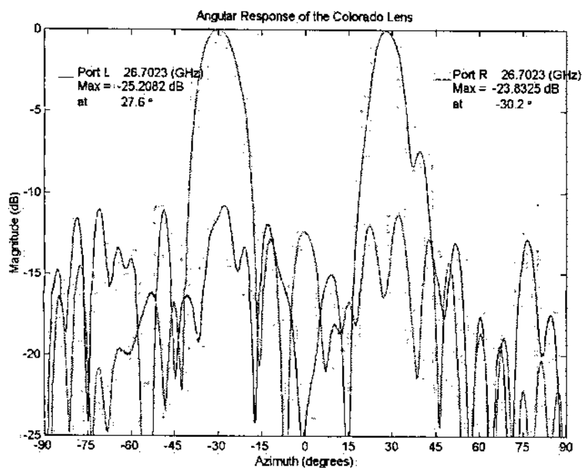

Fig.5. Measured dual-beam pattern for the 26.7GHz frequency of operation. The two lines correspond to power received at two dual-polarized patch antenna feeds for the same polarization placed at ±30° on the DLA focal arc. This measurement was performed at NASA GRC.

As part of the characterization performed at NASA GRC, the frequency response for both polarizations has been measured. In Fig. 6 is shown the upper-frequency response for both feeds placed at ±30° on the lens focal arc.

IV. AMPLITUDE-CONTROLLED BEAM STEERING

The lens array performs a discrete Fourier transform, in analogy to an optical dielectric lens performing a Fourier transform. Because of this property of DLAs, amplitude variations at the feed on the focal surface correspond to phase shifts at the non-feed side, which in turn correspond to a steering of the beam.

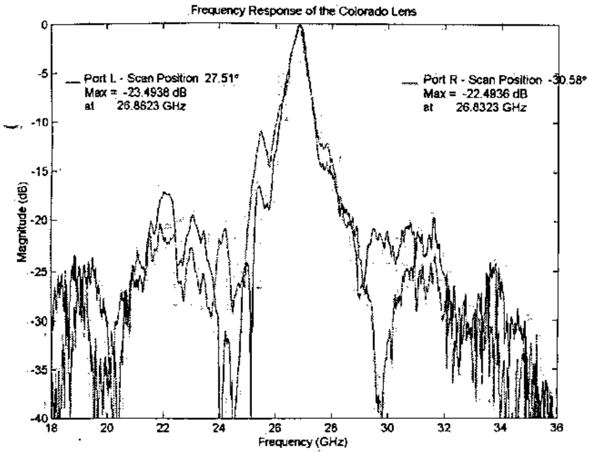

Fig.6. Measured frequency response for the upper frequency (26.7GHz): the two lines correspond to each of the two feeds placed at ±30° on the DLA focal arc. This measurement was performed at NASA GRC.

In order to demonstrate this principle, each feed of the dual-beam array was implemented with a 2-element array of patch antennas, spaced λ apart.

The power radiated/received by each element is controlled with variable-gain attenuators or amplifiers so that the ratio between them can be varied to steer the beam, as illustrated in Fig.7.

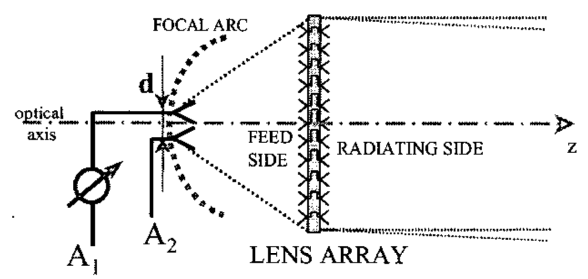

Fig.7 Schematic of a dual-element DLA feed with variable relative amplitude between the two feed elements. The amplitude variation generates a phase shift on the non-feed side of the DLA allowing steering of the beam.

The measured and simulated small-angle steering of the beam around its fixed position at +30 degrees, are shown in Fig.8. The calculations were performed in Matlab [10], taking into account the lens configuration, positions of the feeds and simulated radiation patterns for the antenna elements.

The boundaries for small-angle steering are set by the angular positions of the 2 elements of the feed, but depend also on the half-power beamwidth of the DLA.

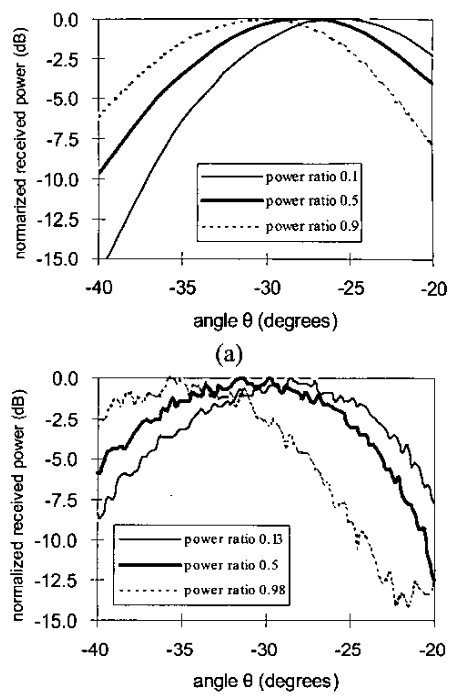

Fig.8. Calculated (top) and measured (bottom) radiation patterns of a fine-steered beam pointing at +30 degrees off optical axis, corresponding to a power ratio of 0.13 to 0.98.

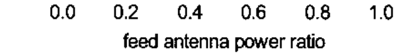

Fig.9. Measured amplitude-controlled beam steering versus power ratio for the two elements of the feed. The red dashed line represents symmetric ±3-degree beam steering around 30 degrees.

The measured continuous beam steering for the up and down link is shown in Fig.9, with the red dashed line indicating what we would expect from a perfectly symmetrical lens with a perfect control at the feed. While the power at one of the two elements of the feed array is kept constant, the other is varied from a ratio of 0.1 to 1.

ACKNOWLEDGEMENT

This work was funded by NASA through contract NAG3-2587. We thank Dr. Kevin Lambert at NASA GRC who performed array measurements to verify the ones done at the University of Colorado, Figs.5 and 6.

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