MULTIBEAM PLANAR DISCRETE MILLIMETER-WAVE LENS

FOR FIXED-FORMATION SATELLITES*.

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ABSTRACT

A planar discrete millimeter-wave lens [1] is proposed for use as a multibeam Ka-band array antenna for fixed-formation satellites. The application considered in this paper requires several simultaneous beams at different angles, each carrying two frequencies with different polarizations. The angle of each beam can be fine-tuned with a small scanning angle around the fixed positions. In this paper a prototype radiating two Ka-band frequencies with two different linear polarizations is described and experimentally characterized. As a peculiar feature of discrete lens arrays, amplitude control (in place of phase control) of each of the two feed elements allows a small scan angle of about 5 degrees.

BACKGROUND

Communications between satellites in a fixed formation require the use of multibeam arrays. Discrete lenses allow the presence of several simultaneous beams at different angles with simpler feed structure than phased arrays.

A discrete lens consists of two arrays of antennas with transmission lines connecting each radiating element between the two sides. One side is called the *radiating side* and generates the far-field pattern of the lens, while the other side, called the *feed side*, faces the feeds. 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. Together with the electrical lengths of the lines, the positions of the array elements on the feed side also determine the focusing properties of the lens. This allows for a design with up to two perfect focal points lying on a focal arc or with a cone of best focus [1]. The two degrees of freedom are the positions of the elements on the feed side and the electrical lengths of the transmission lines connecting the two sides. The main design constraint is the equality of the path length from the feed to each element on the radiating side of the lens.

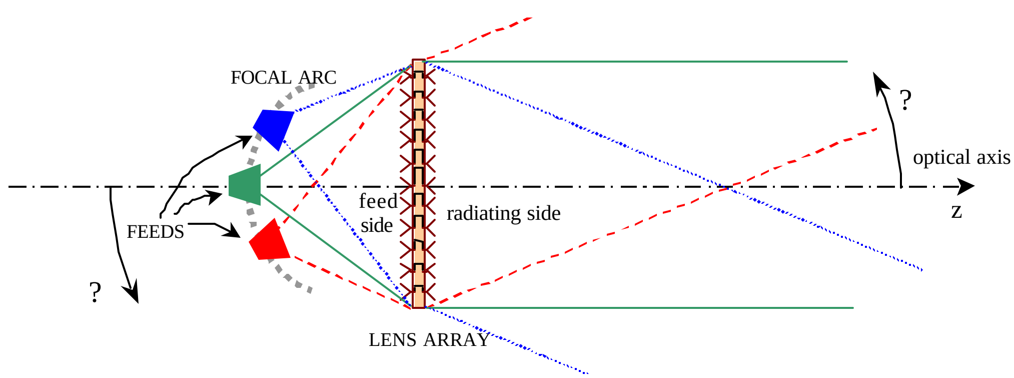

Fig. 1. Schematic of a planar discrete lens array with several independent feeds on its focal arc. Each feed controls a radiation pattern with the main beam pointing at a different angle off boresite.

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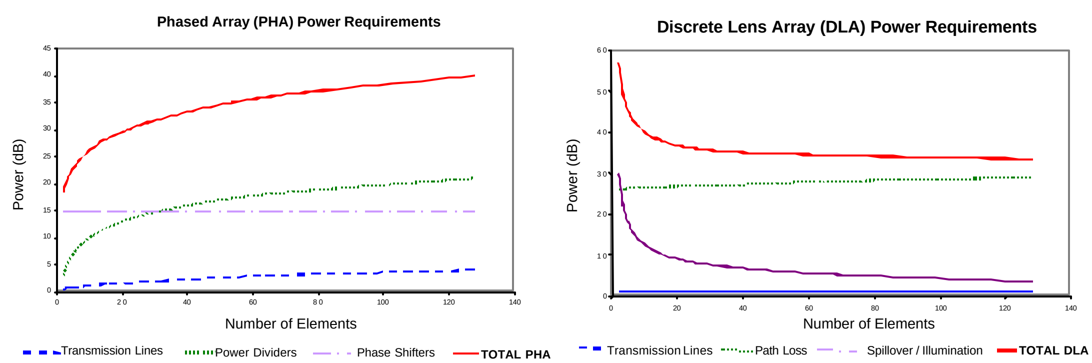
The position of the elements on the radiating side sets the features of the far field radiation pattern as with a traditional array: the spacing and type of elements is chosen to satisfy the radiation specifications such as grating lobes, sidelobes and beamwidth.
Several feed antennas placed on this focal arc spatially feed the lens generating a beam in each different direction. Such feature inherently allows the presence of several independently controlled simultaneous beams. Fig. 1 shows a schematic of a planar lens with several feeds at different angles with respect to the "optical axis" of the system. The feed positioned on the focal arc at an angle ? generates a radiation pattern with the main beam at an angle ? ?(with ? ? ?) in the far field of the planar lens.

A COMPARISON BETWEEN PHASED ARRAYS AND PLANAR DISCRETE LENSES

The use of a lens array in place of a phased array in multibeam applications presents several advantages arising from the spatial feed concept. The spatial feed allows a multibeam configuration with only minor modifications in the system design, avoiding the high complexity of a feed network. A phased array, in this application, would require a multi-layer feed structure such as a Butler matrix [2]. Phased array feed networks also have bandwidth limitations due to the phase shifters and the impedance matching requirements, while the bandwidth of a lens array is limited only by the antenna elements. Additionally, unlike phased arrays where feed loss scales with array size, feed loss in a lens array with more than 50 elements is nearly independent of the number of elements. In Fig. 2 are shown the input power requirements for a phased array with corporate feed network (PHA) and for a discrete planar lens array (DLA), assuming the same power radiated in the far field.



(a) (b)

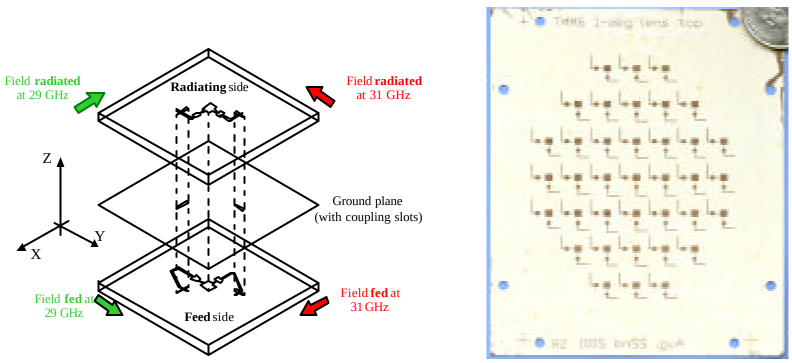
Fig. 2. Power requirements as a function of number of elements for (a) phased arrays (PHA) and (b) discrete planar lenses (DLA). Together with the total amount of power required to give equivalent performance, individual contributions to both systems are also illustrated.

In particular, the main loss in a phased array is due to the power dividers used in the corporate feed network, resulting to be dependent on the number of element, while the main loss in a discrete lens is due to path losses in free space that increases only negligibly with the lens size.
Moreover, a planar lens accomplishes the same functions as a dielectric lens in principle, but presents some advantages. Planar lenses are fabricated using standard PCB technology, making them lightweight, easy to manufacture, and easy to optimize for large scan angles [3]. Unlike a dielectric lens, input and output polarizations are a design parameter for planar discrete lenses, allowing different polarizations on the feed and radiating side of the array.

DESIGN OF THE LENS

The planar lens described in this paper is a 1-degree-of-freedom lens, designed for one perfect focal point on the optical axis. The position of the elements on the feed side is the same as for the radiating side, leaving the length of the transmission lines connecting the elements as the only design parameter for the focusing properties. The lens has dual-polarization, dual-frequency patch antenna elements on both sides on a rectangular lattice, with one free-space wavelength spacing in the vertical, and ¾ of a free-space wavelength spacing in the horizontal dimension. The expected 3-dB beamwidth is about 9 degrees.

The coupling between the transmission lines on the two sides is accomplished through resonant slots in the common ground plane. A drawing of one element of the lens is shown in Fig. 3. The two different frequencies are radiated using two orthogonal linear polarizations. The orientation of the patches allows isolation between the two sides of the lens: each frequency is received on the feed side with one polarization, and radiated from the other side of the lens in the orthogonal polarization.



(a) (b)

Fig. 3. (a) An exploded three-dimensional drawing of one element of the planar lens. The coupling between the transmission lines on the two sides of the lens is accomplished with slots in the common ground plane. (b) Photograph of the radiating side of the planar lens compared with a US quarter coin. Two different frequencies (29 and 31 GHz in the prototype) are radiated using two different linear polarizations.

CHARACTERIZATION OF THE PROTOTYPE

A 37-element array prototype was designed and fabricated on a 0.38mm (15mil) ceramic substrate with ?$_r$=6 (Rogers TMM6?): a photograph of its radiating side is shown in Fig. 3b.
Far field radiation pattern measurements show a 3dB-beamwidth of 11 degrees in the E-plane for the lower frequency (29GHz) and 6 degrees in the H-plane for the higher frequency (31.9GHz). The measured bandwidth is about 3% for both frequencies, limited by the dual-frequency dual-polarization rectangular patch antenna used in the unit cell of the array. The transmitted and received frequencies are measured at 29 and 31.9 GHz.

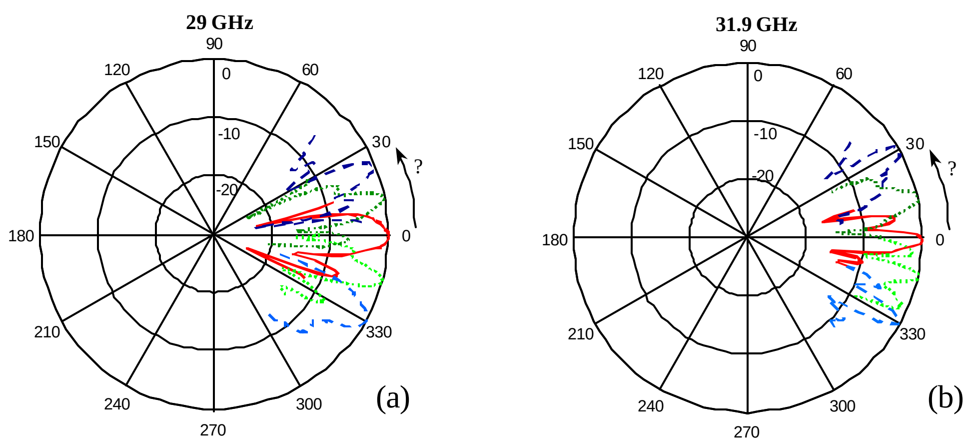
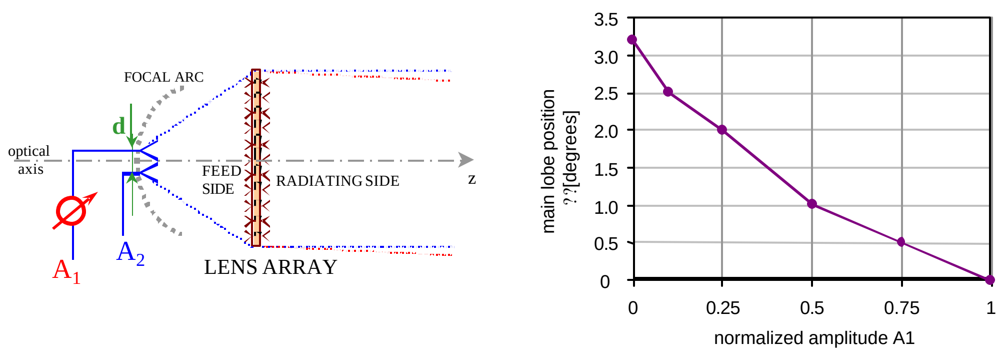


Fig. 4. Measured radiation patterns demonstrating the multibeam capabilities of a planar lens for (a) 29GHz, with the feed vertically polarized, and (b) 31.9 GHz, with the feed horizontally polarized. The plotted radiation pattern are generated by a feed positioned on axis (solid), at an angle ?? =±15° (dotted) and at an angle ? =±30° (dashed)

A demonstration of the multibeam performance of the planar lens is shown in the polar plots in Fig. 4, where the measured radiation patterns are generated by different positions of the feed on the focal arc. For example, the radiation pattern with the main beam at ?=30° is obtained placing the feed on the focal arc at an angle ?=30° (see Fig. 1).

AMPLITUDE-CONTROLLED SMALL ANGLE SCANNING

In order to have the possibility of fine variation of the angular position of the main beam, each feed antenna has been designed as a two-element array. The two patch antenna are identical to the ones used for the discrete lens array and they are placed in a row, as showed in Fig. 5a. By changing the amplitude of the excitation of each of the two elements, the illumination of the feed side of the lens become asymmetric, allowing a small angle steering of the main beam in the far field of the lens. In the simulation results in Fig. 5b the power delivered to one element of the feed array is kept constant, while the other is varied. In particular, with amplitude variations between 0.1 and 1 (normalized), which correspond to a 20-dB variation in the power delivered to the element, it is possible to steer the main beam of about 2.5 degrees.



(a) (b)

Fig. 5. (a) Schematic of the amplitude-controlled small scan angle configuration used in the simulations. (b) Simulation results showing the small angle scanning of the main beam by amplitude variations across the feed two-element array. A variation from 0.1 to 1 of the normalized amplitude of the excitation to one element of the feed array produces a steering of the main beam of about 2.5 degrees.

SUMMARY

Planar discrete lens array have been presented as a valid solution for multibeam antennas as required in satellite applications. The advantage of the planar technology is added to the simpler feed structure and lower loss of such a system with respect to a traditional phased antenna array. Measurement results illustrating the multibeam characteristics have been presented. Moreover, it is described the possibility to steer the main beam for small angles simply with amplitude variations across a feed array, avoiding the use of phase shifters in the entire system.

REFERENCES

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