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Analysis of a Microstrip Reflectarray Antenna for Microspacecraft Applications

J. Huang
Spacecraft Telecommunications Equipment Section

A microstrip reflectarray is a flat reflector antenna that can be mounted conformally onto a spacecraft's outside structure without consuming a significant amount of spacecraft volume and mass. For large apertures (2 m or larger), the antenna's reflecting surface, being flat, can be more easily and reliably deployed than a curved parabolic reflector. This article presents the study results on a microstrip reflectarray with circular polarization. Its efficiency and bandwidth characteristics are analyzed. Numerous advantages of this antenna system are discussed. Three new concepts using this microstrip reflectarray are also proposed.

I. Introduction

JPL is currently developing microspacecraft technologies for future deep space missions in order to meet NASA's goal of having small, efficient, and inexpensive spacecraft. The microspacecraft, having sizes on the order of one-half meter, will certainly require components that are small both in size and mass. High-gain antennas are one part of the telecommunications equipment that warrants attention since they generally require a significant amount of real estate and mass. The conventional high-gain antennas most often used are parabolic reflectors. Although they are efficient radiators, parabolic reflectors are generally bulky in size and large in mass, due to their curved reflecting surfaces. As a result, a flat reflector called a microstrip reflectarray [1,2] is being proposed as a future candidate high-gain antenna. It is well known that when a required antenna gain is given at a particular frequency, the antenna aperture size is more or less fixed. The only significant size reduction that may be achieved for an antenna is its profile thickness. The flat-plate microstrip reflectarray offers such an advantage of profile size reduction as compared to a conventional parabolic reflector.

The reflectarray antenna as shown in Fig. 1 represents World War II technology [3]. However, the low-profile printed reflectarray is a fairly new concept. The microstrip reflectarray, being one of the printed low-profile antenna technologies, consists of a very thin, flat reflecting surface and an illuminating feed, as shown in Fig. 2. On the reflecting surface, there are many isolated microstrip patch elements without any power division network. To each patch element is attached a short segment of phase-adjusting transmission line to compensate for the phase delay over the path from the illuminating feed. Because of the phase adjustment capability of the patch elements, the reflecting surface can be flat or conformal to its mounting structure and still maintain a constant phase aperture field. A detailed description of this antenna concept, as well as its advantages, is given in the following sections. Theoretical analysis of the antenna performance parameters, such as radiation pattern, efficiency, and bandwidth, is also presented.

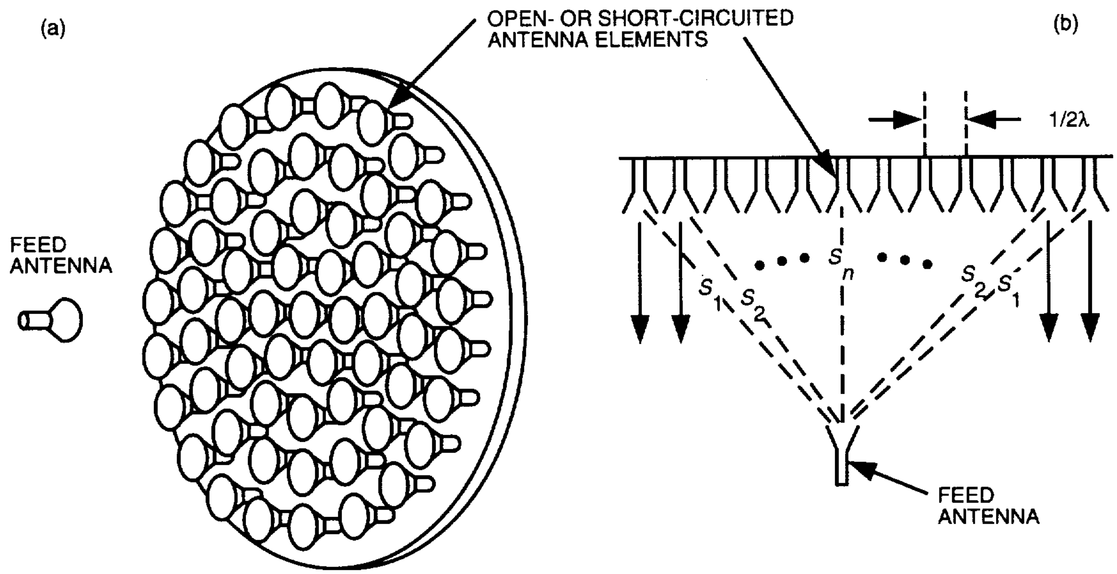

Fig. 1. Reflectarray configuration: (a) three-dimensional view and (b) two-dimensional view.

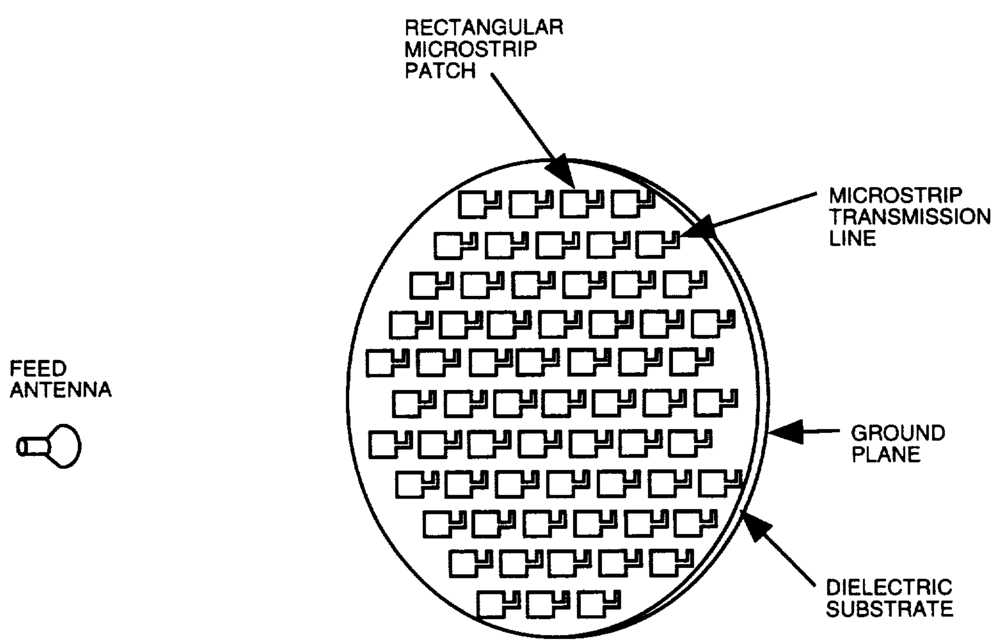

Fig 2. Flat-plate microstrip reflectarray with identical patches but different-length microstrip transmission lines.

II. Description of the Microstrip Reflectarray

When many antenna elements with open- or short-circuited terminations are arranged in a planar aperture and are illuminated by a feed antenna, as shown in Fig. 1, these elements will reradiate their illuminated energy into space. The total reradiated energy will be noncophasal if all the elements and their terminations are identical. This is because the fields that propagate to the elements from the feed have different path lengths, $S_1, S_2, \cdots, S_N$, as shown in Fig. 1(b), and thus form different phases. However, if each element's phase is adjusted to compensate for these different path lengths, the total reradiated field can be made cophasal and concentrated toward a specific direction. The array antenna formed by the above concept is named the reflectarray and was introduced [3] many decades ago using a horn, dipole, open-ended waveguide, etc., for the element. Since these elements are large in size at lower microwave frequencies and many elements are needed in a reflectarray in order for it to be efficient, the earlier reflectarray antennas were bulky in size and heavy in weight. Due to the recent advancement of the lightweight and low-profile printed antennas, such as the microstrip patch, the printed reflectarray becomes physically more realizable and attractive. Several different versions of the printed reflectarray have recently been developed. One version, shown in Fig. 2, has all identical microstrip patch elements but with different-length microstrip transmission lines. This microstrip reflectarray was first patented by Munson and Haddad [4] and then openly published and analyzed by Huang [2] and Metzler [5]. Litva, Zhuang, and Wu [6], as well as Chang and Huang [7], have demonstrated the concept via hardware development. Malibu Research Center developed a different reflectarray [8] with printed dipoles having different sizes and no phase delay lines. The required path delay-compensating phases from the elements are achieved primarily via the differing lengths of the dipoles. Different lengths yield different input impedances (complex quantity) at a particular frequency, which in turn give different phases. Targonski and Pozar [9] developed a microstrip reflectarray with patches having different sizes and no delay lines. It is expected that the reflectarray with printed dipoles or patches having different sizes will not radiate as efficiently as the identical-patch reflectarray with different-length delay lines. This is because, for a particular frequency, there is only one optimal size of the resonant structure (dipole or patch) to reflect or reradiate energy; other sizes will result in lower amplitudes. This is similar to the phenomenon observed with frequency selective surfaces (FSS), where only a narrow spectrum will yield total reflection.

By reason of its expected higher efficiency, the microstrip reflectarray with patches having identical sizes and different phase-delay lines is proposed and studied here. This flat reflector antenna, as shown in Fig. 2, is composed of a thin (≤ 0.03 wavelength) slab of dielectric material having one side completely covered with a thin layer of metal (serving as a ground plane) and the other side etched with many identical metallic microstrip patches. A feed antenna, located at an optimally designed distance from the array elements, will effectively illuminate all the patches. The size of each patch, which can be rectangular, square, or circular, is designed to resonate at the frequency of the feed antenna. A short transmission line is connected to each patch at one end with the other end of the line either open or short circuited. To generate circular polarization, two equal-length transmission lines are needed to be orthogonally connected to each square or circular patch, as shown in Fig. 3. In this case, the feed has to be circularly polarized. The short transmission line connected to each patch can be either a microstrip line etched on the same side of the patch or a stripline sandwiched in an additional layered structure placed behind the patch's ground plane. The advantage of the microstrip line is ease of fabrication, while that of the stripline is minimum interference to the patch's radiation. When the radiation field of the feed antenna (in transmit mode) strikes each patch, the received resonant field of the patch will travel through its connected transmission line and be reflected by its open- or short-circuited termination and then reradiated by the patch into space. Thus, all the microstrip patches behave as reradiators, while the short transmission lines serve as phase delay lines. The lengths of these transmission lines are intentionally made different for differently located patches to compensate for the path delay differences from the feed antenna. With proper design and calibration of these line lengths, the reradiated fields from all the patches can be made cophasal in the broadside direction. Also, by redesigning the line lengths, the main beam can be directed toward other directions at large angles (up to more than 50 deg) from the broadside direction. Since the required phase changes for all the elements are between 0 and 360 deg, the maximum length needed for the transmission line is only one-half wavelength. Consequently, the insertion loss associated with these short lines will be insignificantly small. The transmission line should be impedance matched to the patch radiator, which can be done using a quarter-wave-long impedance matching section. Because this is a phase-delay approach and not a time delay, as frequency changes, a phase excursive error will occur, especially for the outer elements of the array (assuming the feed is located at the center axis of the array). In other words, the phase will accumulate more error for the outer elements as the frequency changes, and this limits the bandwidth performance of the reflectarray. This accumulated phase error can be reduced by using longer transmission lines for the center elements (time delay approach) or by using a larger f/D ratio, where f is the distance between the feed and the array center and D is the array diameter.

Since the microstrip reflectarray does not require any power divider, its efficiency in a large array system is much higher than a conventional array having the same aperture size. One possible drawback is that, in addition to the reradiated fields from the patches, there will also be scattered field from the patches, reflected field from the ground plane (especially away from the resonant frequency of the patch), scattered field from the phase delay lines, and diffracted field from the edge of the reflectarray. These backscattered fields may increase the sidelobe level and possibly distort the main beam shape. However, because most of these scattered fields are noncophasal, and as long as the aperture directivity of the reflectarray is sufficiently higher (20 dB or more) than the feed directivity, the backscattered energy is generally small relative to the desired main beam. In other words, the microstrip reflectarray can be an efficient antenna system only if it has a large number of array elements (500 or more).

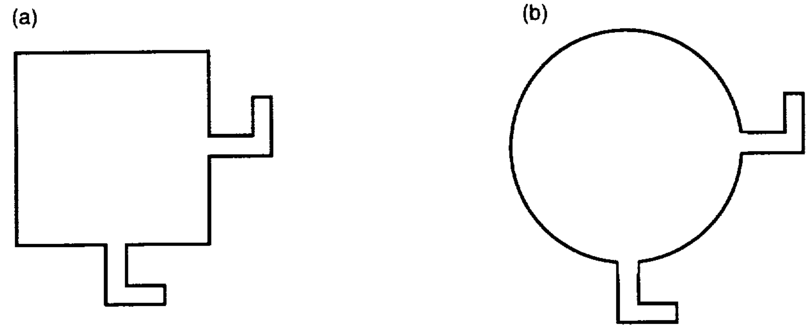

Fig. 3. Reflectarray (a) square and (b) circular microstrip elements, for circular polarization.

III. Radiation Analysis of the Microstrip Reflectarray

When a rectangular planar array with $M \times N$ microstrip patch elements is nonuniformly illuminated by a low-gain feed at r_f, as shown in Fig. 4, the reradiated field from the patches in an arbitrary direction, $\hat{u}$, will be of the form

$$E(\hat{u}) = \sum_{m=1}^{M} \sum_{n=1}^{N} F\left(\vec{r}_{mn} \cdot \vec{r}_f\right) A\left(\vec{r}_{mn} \cdot \hat{u}_o\right) A\left(\hat{u} \cdot \hat{u}_o\right) \exp\left\{-jk_o\left[\left|\vec{r}_{mn} - \vec{r}_f\right| + \vec{r}_{mn} \cdot \hat{u}\right] + j\alpha_{mn}\right\} \tag{1}$$

where F is the feed pattern function, A is the pattern function of the microstrip patch, r_{mn} is the position vector of the mnth patch, $\hat{u}_o$ is the desired main-beam pointing direction, and α_{mn} is the required transmission-line phase delay of the mnth element. The condition for the aperture distribution to be cophasal in the desired direction $\hat{u}_o$ is

$$\alpha_{mn} - k_o\left[\left|\vec{r}_{mn} - \vec{r}_f\right| + \vec{r}_{mn} \cdot \hat{u}_o\right] = 2n\pi, \qquad n = 0, 1, 2, \cdots \tag{2}$$

For a circular aperture, which is desirable for better aperture efficiency as compared with a rectangular aperture, the summation signs in Eq. (1) can be truncated to 0 (no calculation) for patches located outside of the circular aperture.

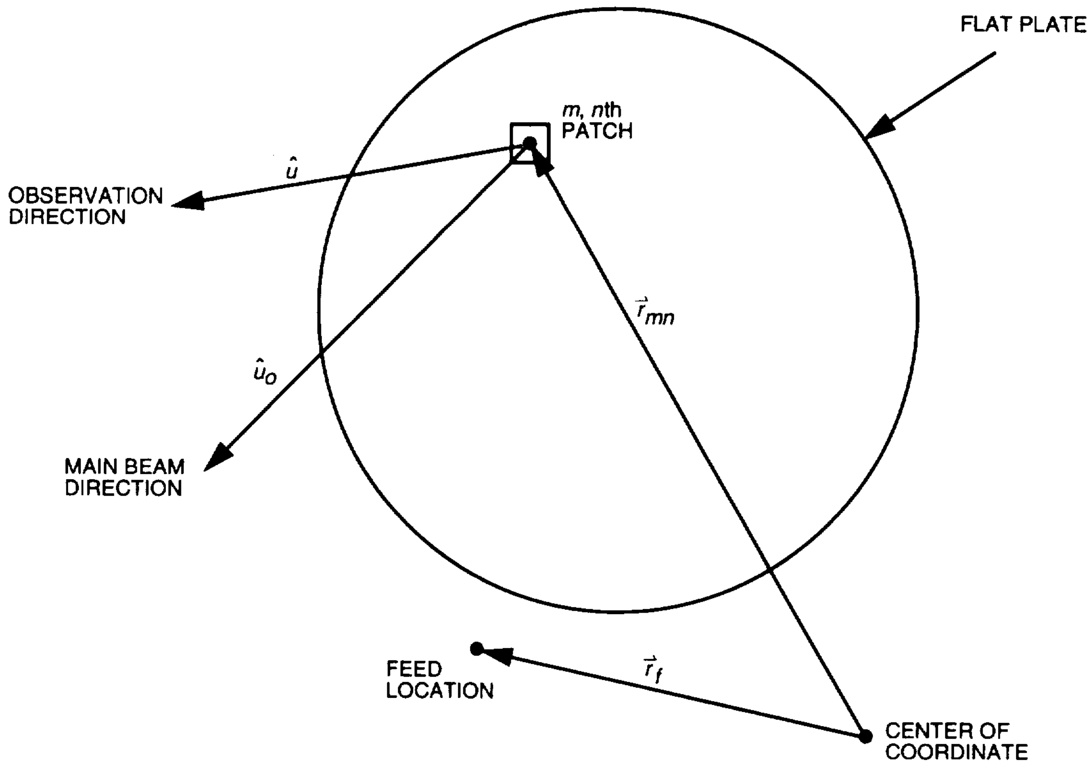

Fig. 4. Coordinate system for reflectarray pattern analysis.

Equation (1) gives a nonpolarized (scalar) field. For circularly polarized radiation, the field of Eq. (1) can be separated into θ and ϕ components:

$$E_\theta = E(\hat{u})\left[\left(\hat{f}_1 \cdot \hat{p}_1\right)\hat{p}_1 \cdot \hat{\theta} + \left(\hat{f}_2 \cdot \hat{p}_2\right)\hat{p}_2 \cdot \hat{\theta}\right] \tag{3a}$$

$$E_\phi = E(\hat{u})\left[\left(\hat{f}_1 \cdot \hat{p}_1\right)\hat{p}_1 \cdot \hat{\phi} + \left(\hat{f}_2 \cdot \hat{p}_2\right)\hat{p}_2 \cdot \hat{\phi}\right] \tag{3b}$$

where $\hat{f}_1$ and $\hat{f}_2$ are the two orthogonal polarization vectors of the feed horn at the patch location, $\hat{p}_1$ and $\hat{p}_2$ are the two orthogonal patch polarization vectors, and $\hat{\theta}$ and $\hat{\phi}$ are the orthogonal far-field spherical coordinate unit vectors. For a right-hand circularly polarized feed, the far-field copolarized radiation from the reflectarray is

$$E_{co-pol} = \frac{1}{\sqrt{2}}\left(E_\theta + jE_\phi\right) \tag{4a}$$

and the cross-polarized radiation is

$$E_{x-pol} = \frac{1}{\sqrt{2}}\left(E_\theta - jE_\phi\right) \tag{4b}$$

In Eq. (1), the feed pattern function F is modeled by a $\cos^q \Psi$ function. For the pattern function A of the single microstrip patch, a simple closed-form model using the dual-slot theory [1] is employed. This simple model, which is accurate enough for large array prediction, allows the computation time of many thousands of patch elements to become more realistic as compared with other more rigorous techniques. Consequently, mutual coupling effects between patches are not included. For a substrate thickness of less than 0.03 free-space wavelength, beam scan angles of less than 45 deg, and no extremely low sidelobe requirement, the mutual coupling effects can generally be neglected for the microstrip array. Experimental reports [10] demonstrated that, due to the low-profile nature of the microstrip antenna, mutual coupling has not been found to be a serious problem in most of the array applications.

In addition to the reradiated field given in Eq. (1), there is a certain amount of backscattered field, such as the scattered field from the phase delay transmission lines, the patches, the ground plane, and the ground plane edges. However, as long as the reflectarray is designed with proper element spacing (avoiding the grating lobe condition) and the patch element is designed to resonate at the correct frequency, the backscattered fields can be minimized. Furthermore, if the directivity of the feed antenna is significantly lower (by at least 20 dB) than the directivity of the reflectarray aperture, the effect of the noncophasal backscattered field will generally be insignificant [1] when compared with the cophasal reradiated fields from the patches. To summarize, with proper design and large enough array size, Eq. (1) is an excellent approximation with which to efficiently calculate the far-field radiation pattern of the reflectarray. It should be able to predict the main beam and the first few sidelobes with good accuracy.

IV. Antenna Efficiency Analysis

The two primary factors that govern the efficiency of the microstrip reflectarray are very similar to those for the parabolic reflector. These are the aperture illumination efficiency and the feed spillover efficiency [11]. Other minor factors that contribute to the reflectarray efficiency are the patch element loss and the back scattered field loss. The aperture illumination efficiency is caused by the unequal illumination of the array aperture due to the feed's tapered pattern. A uniformly illuminated aperture is defined as having 100-percent illumination efficiency. The spillover efficiency is the ratio of the amount of feed energy that illuminates the entire array to the total amount of energy that is radiated by the feed, which includes the amount that spills outside the array aperture. It is clear that the illumination and the spillover efficiencies are complementary to each other. In other words, if one increases, the other will decrease, and vice versa.

Let us define the total aperture efficiency (η) as the product of the illumination (η_{ill}) and spillover (η_s) efficiencies:

$$\eta = \eta_{ill} \cdot \eta_s \tag{5}$$

From Silver [12] and Fig. 5,

$$\eta_{ill} = \frac{\left| \int_{\theta=o}^{\theta e} \int_{\phi=o}^{2\pi} \vec{E} \cdot P\hat{x} ds \right|^2}{s \int_{\theta=o}^{\theta e} \int_{\phi=o}^{2\pi} |\vec{E}|^2 ds} = \frac{|I|^2}{sII} \tag{6}$$

where $s = \pi \rho_e^2 = \pi f^2 \tan^2 \theta_e$, and

$$\eta_s = \frac{\int_{\theta=o}^{\theta e} \int_{\phi=o}^{2\pi} |\vec{E}|^2 ds}{\int_{\theta=o}^{\pi/2} \int_{\phi=o}^{2\pi} |\vec{E}|^2 ds} = \frac{II}{III} \tag{7}$$

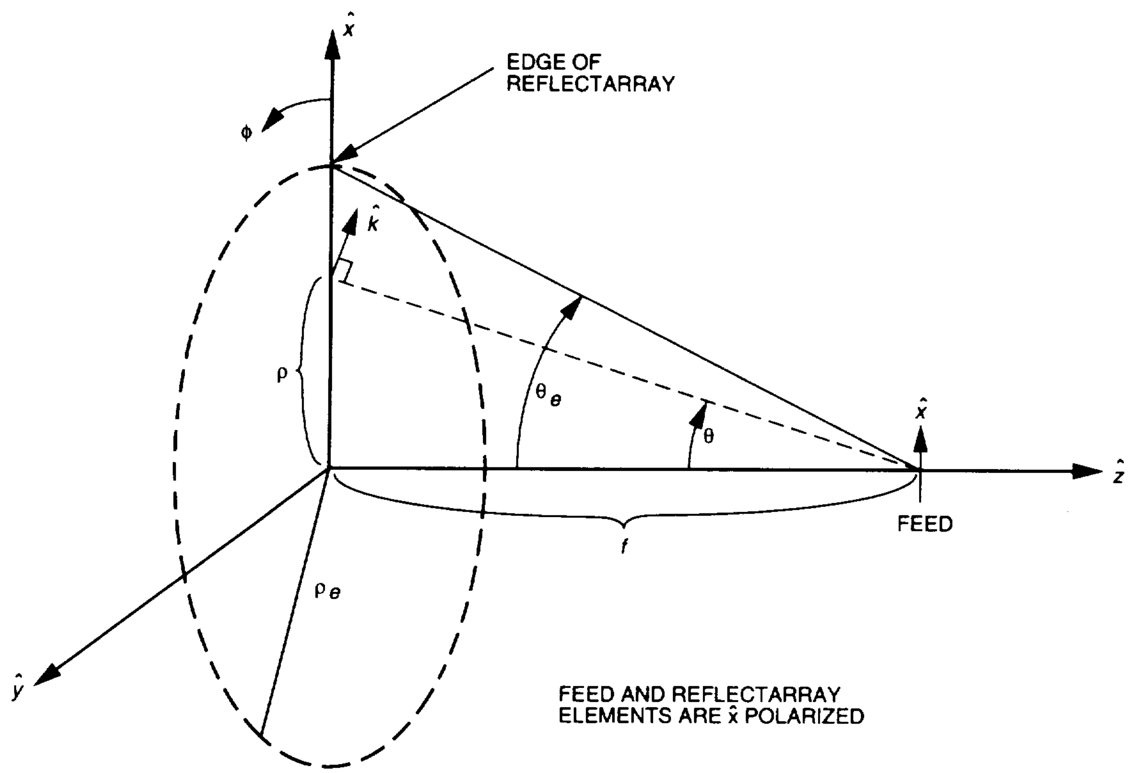

Fig. 5. Coordinate system for reflectarray efficiency analysis.

where $|I|^2$ is the power distributed across the reflectarray aperture, II is the total power radiated by the feed within the reflectarray aperture, and III is the total power radiated by the feed to its front hemisphere. The analysis here assumes the feed has a $\cos^q \theta$ pattern and is polarized in the $\hat{x}$ direction. All the patch elements are also polarized in the $\hat{x}$ direction. The $\hat{E}$ vector in both Eqs. (6) and (7) is the feed far-field function and is given by

$$\vec{E} = |E|\hat{k} = C_o \frac{\cos^q \theta}{r} \left(\cos\phi\hat{\theta} - \sin\phi\hat{\phi} \right) \tag{8a}$$

where the phase term e^{-jkr} is suppressed since phase does not play a role here for the efficiency calculation. The function P in Eq. (6) is the far-field pattern function of the patch element in the reflectarray and is assumed to be $\cos\theta$.

$$\vec{E} \cdot P\hat{x} = C_o \frac{\cos^q \theta}{r} \left(\cos\theta \cdot \cos^2\phi + \sin^2\phi \right) \cos\theta \tag{8b}$$

The last term, $\cos\theta$, in Eq. (8b) is the patch element pattern effect on the incoming wave from the feed.

$$I = \int_o^{\theta e} \int_o^{2\pi} \frac{c_o \left(\cos^{q+2}\theta \cos^2\phi + \cos^{q+1}\theta \sin^2\phi \right)}{r} ds$$

Because $ds = \rho \, d\rho \, d\phi, \rho = r\sin\theta, r = f/\cos\theta$, and $d\rho = (f/\cos^2\theta)d\theta$,

$$I=\int_o^{\theta e}\int_o^{2\pi} c_o\left(\cos^{q+2}\theta\cos^2\phi+\cos^{q+1}\theta\sin^2\phi\right)\sin\theta\frac{f}{\cos^2\theta}d\phi d\theta=c_o f\pi\left[\frac{1-\cos^{q+1}\theta_e}{q+1}+\frac{1-\cos^q\theta_e}{q}\right] \tag{9}$$

$$II=\int_o^{\theta e}\int_o^{2\pi}\frac{c_o^2\cos^{2q}\theta}{r^2}rd\theta\cdot\rho d\phi$$

Because $\rho = r\sin\theta$,

$$II=2\pi c_o^2\frac{1-\cos^{2q+1}\theta_e}{2q+1} \tag{10}$$

$$III=\int_o^{\pi/2}\int_o^{2\pi}\frac{c_o^2\cos^{2q}\theta}{r^2}rd\theta\cdot\rho d\phi=2\pi c_o^2\frac{\left[1-\cos^{2q+1}(\pi/2)\right]}{2q+1}=\frac{2\pi c_o^2}{2q+1} \tag{11}$$

By using Eqs. (6), (7), (9), (10), and (11),

$$\eta_{ill}=\frac{|I|^2}{sII}=\frac{\left[\left((1-\cos^{q+1}\theta_e)/(q+1)\right)+\left((1-\cos^q\theta_e)/q\right)\right]^2}{2\tan^2\theta_e\left[(1-\cos^{2q+1}\theta_e)/(2q+1)\right]} \tag{12}$$

and

$$\eta_s=\frac{II}{III}=1-\cos^{2q+1}\theta_e \tag{13}$$

By using Eqs. (12) and (13), the efficiencies are plotted against the feed pattern shapes in Fig. 6 with a given reflectarray diameter of 0.5 m at 32 GHz (Ka-band) and a f/D ratio of 1.0. The element spacing is half of the free-space wavelength, and the total number of patch elements is 8,937. These curves clearly indicate that the illumination and the spillover efficiencies are complementary to each other. The optimal aperture efficiency can be designed with a feed q factor equal to 10.3. Another curve (Fig. 7) gives the optimum f/D ratio when an arbitrarily selected feed pattern is given ($q = 8$). Equations (12) and (13) are very important tools that aid in the design of an optimal reflectarray configuration.

As mentioned previously, there are other efficiency factors, in addition to aperture efficiency, in the complete characterization of the reflectarray antenna system. The various contributors to the overall efficiency factor are estimated and listed in Table 1 for a Ka-band 0.5-m reflectarray with $f/D = 1.0$ and feed q factor $= 10.3$.

It should be noted that the above feed loss does not include loss in the transmission line between the feed and the transceiver.

V. Bandwidth Study

Bandwidth is often an important quantity for satellite communication, especially with the increasing demand for higher data rates. At 32 GHz, 1 GHz of bandwidth (3 percent) is anticipated. In addition, it is expected that, for Ka-band deep space satellite communication, 32 GHz will be used for downlink

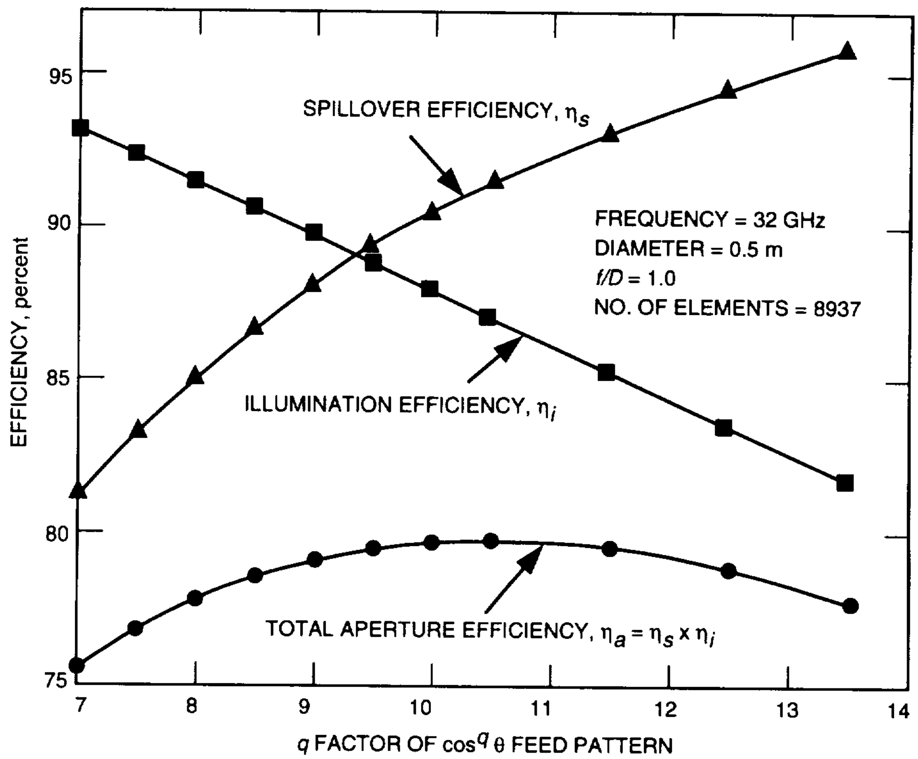

Fig. 6. Microstrip reflectarray spillover and illumination efficiencies versus feed pattern shape.

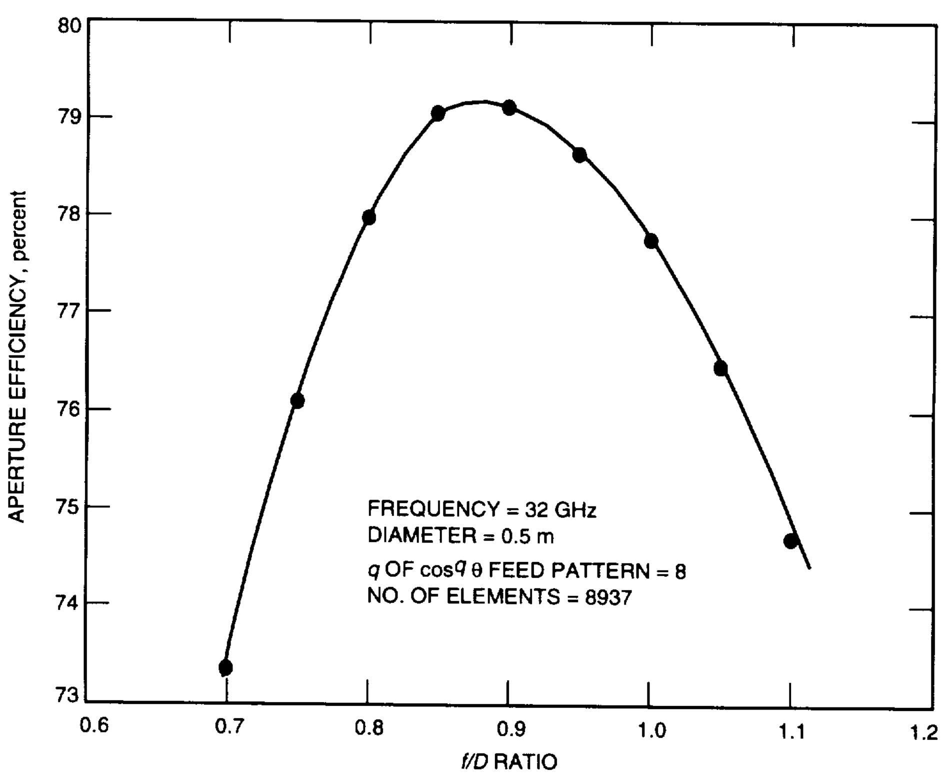

Fig. 7. Microstrip reflectarray aperture efficiency versus *f/D* ratio.

Table 1. Estimated efficiency of the microstrip reflectarray.

Type of efficiency	Efficiency, percent	Loss, dB
Illumination	87	0.60
Spillover	91	0.41
Patch loss	97	0.13
Delay line loss	95	0.22
Feed loss	95	0.22
Cross-pol loss	95	0.22
Total	66	1.80

and 34 GHz for uplink. If a reflectarray antenna needs to cover both uplink and downlink frequencies, a bandwidth of more than 6 percent is required. Certainly, the bandwidth performance of the reflectarray is no match to the parabolic reflector, which has, theoretically, an infinite bandwidth. It is the intention of this section to study the bandwidth characteristics of the microstrip reflectarray and to optimize it for a given application.

The bandwidth performance of a microstrip reflectarray can be limited by four factors: (1) the microstrip patch element, (2) the array element spacing, (3) the feed antenna bandwidth, and (4) the differential spatial phase delay. Due to its thin cavity, the microstrip patch element can generally achieve a bandwidth of only 3 percent. To achieve a bandwidth larger than 3 percent, techniques such as the stacked dual patch or the patch with a thicker substrate can be employed. Ten- to fifteen-percent bandwidths for microstrip antennas have been reported. The array element spacing limits the reflectarray performance such that, as frequency is decreased, the electrical element spacing becomes small, and excessive mutual coupling effects start to degrade the array performance. As the frequency is increased, the electrical element spacing becomes large, and undesirable grating lobes begin to appear. Fortunately, previous calculations and experiences have shown that the element spacing effect will not be detrimental until the frequency variation is more than 30 percent ($\pm$15 percent around center frequency). The third bandwidth limiting factor is the feed antenna, which can be designed to operate over a bandwidth of at least 10 percent while maintaining a relatively constant beam shape and input impedance. Waveguide horns and cavity-backed dipoles are good candidates. If desired, an Archimedean spiral can be used to achieve more than 100 percent of bandwidth. The fourth limiting factor, differential spatial phase delay, has not been well understood and is separately detailed in the following paragraph.

The differential spatial phase delay can best be explained by referring to Fig. 8, where the differential spatial phase delay, Δs, is the difference between the electrical paths S_1 and S_2. This Δs can be many multiples of the wavelength at the center operating frequency, such as $\Delta s = N.d\lambda_o$, where N is an integer and $.d$ represents the fractional number of a free-space wavelength λ_o. At each patch location on the reflectarray, $N.d$ could be different numbers. In order to achieve constant aperture phase for the reradiated waves, the $.d$ at each patch location is compensated for by the appropriate length of the phase delay line attached to the patch. However, as frequency changes, the $N.d$ will change accordingly. Since the phase delay lines are fixed, a frequency excursion error will occur in the reradiated phase front. The old $N.d\lambda_o$ now becomes $N.d(\lambda_o + \Delta\lambda_o)$, where $\Delta\lambda_o$ is directly proportional to the frequency change. The amount of phase change is, therefore, $N.d\Delta\lambda_o$, which can be a significant portion of a wavelength (360 deg). To reduce the amount of frequency excursion error, the integer number N must be reduced. There are two ways to reduce N. One is to design the reflectarray with a larger f/D ratio, and the other is simply to use a reflectarray with a small electrical diameter. With a fixed f/D ratio, the larger the electrical diameter, the larger the N will be. The effects of the f/D ratio and the diameter on bandwidth performance are calculated by using Eq. (1) and are plotted in Figs. 9 and 10, where beam directivity versus frequency change is shown. The bandwidth effects of the patch element and the feed

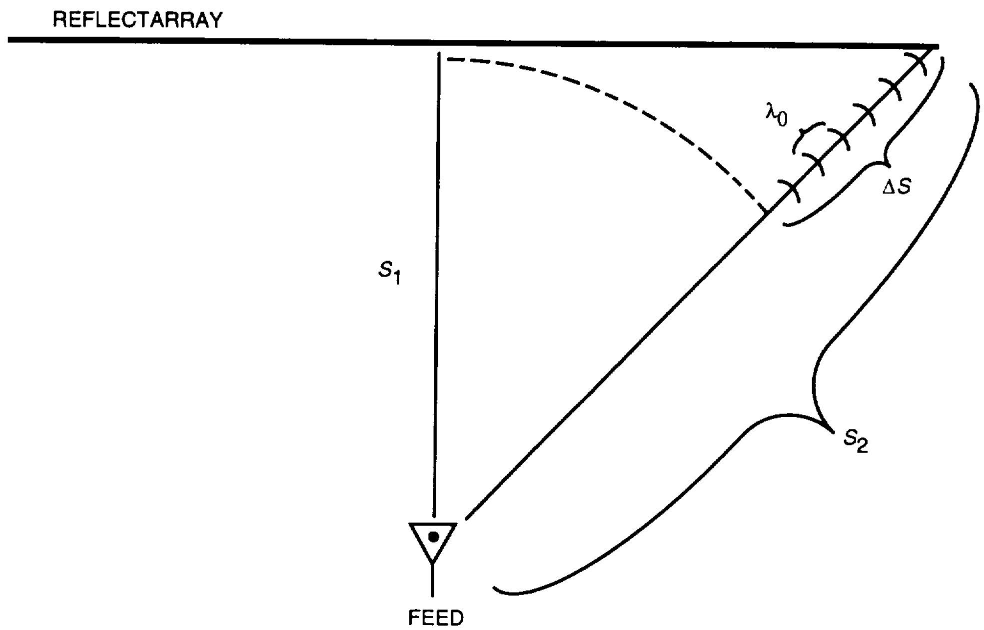

Fig. 8. Spatial phase delay of the reflectarray.

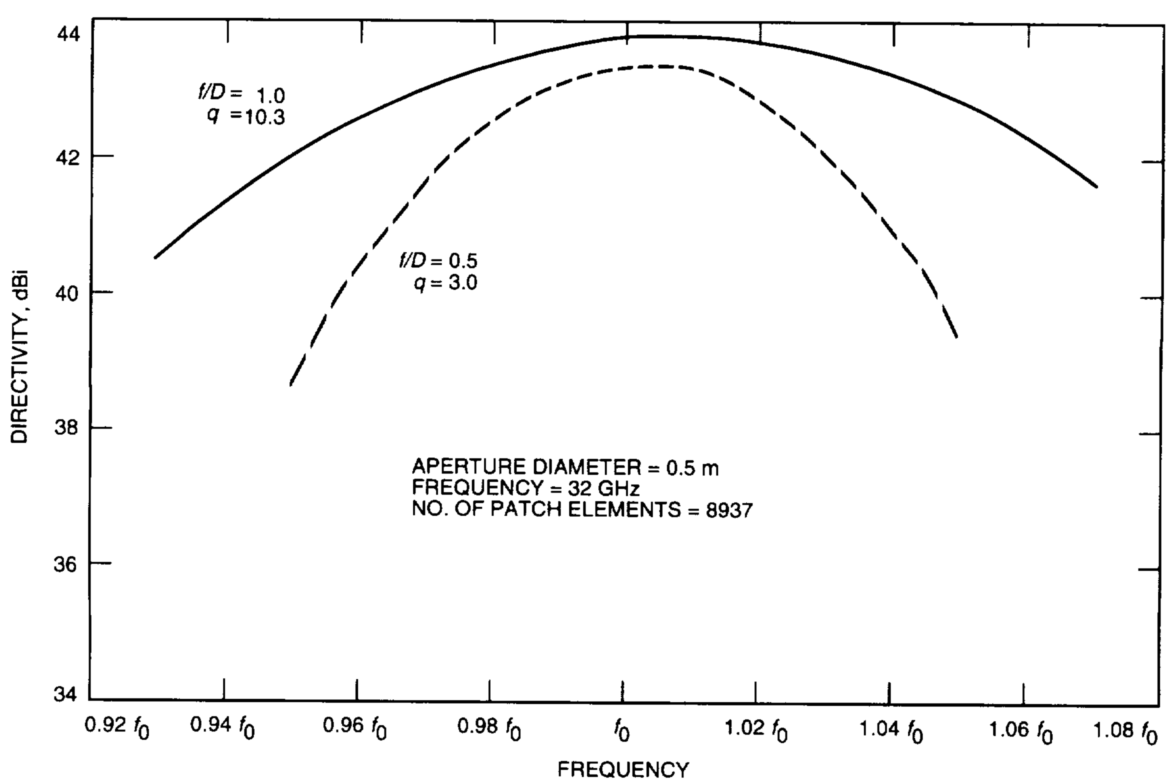

Fig. 9. Antenna directivity versus frequency for a 0.5-m Ka-band microstrip reflectarray.

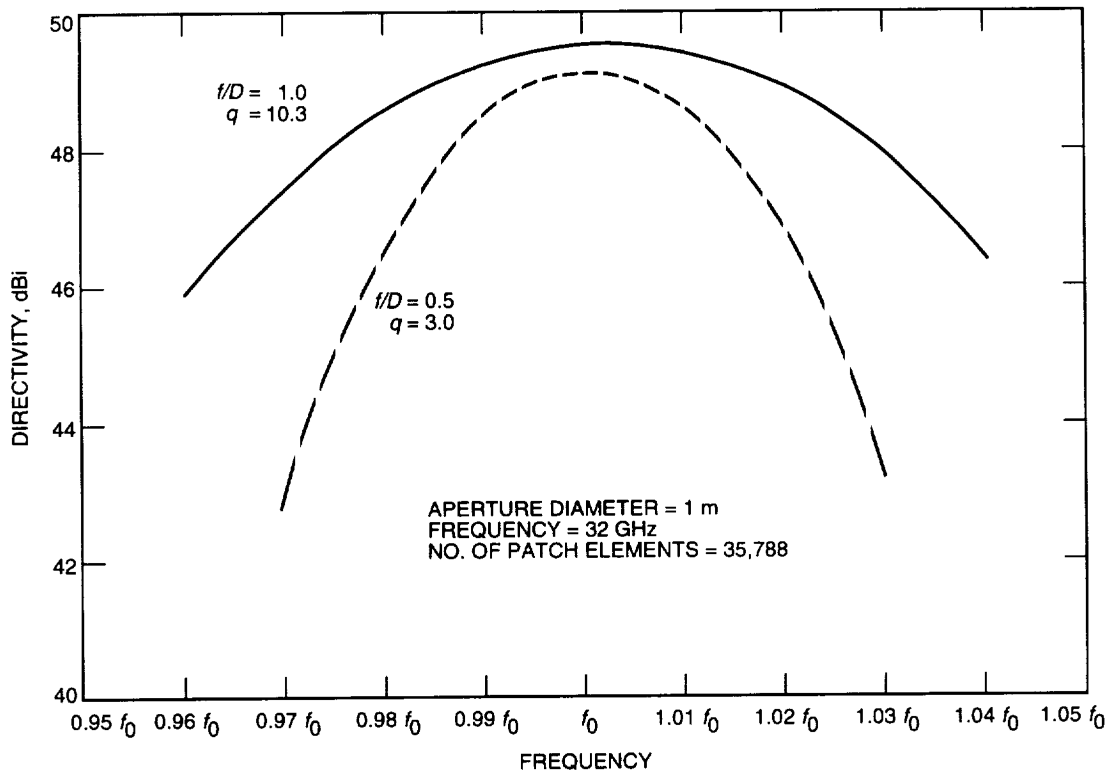

Fig. 10. Antenna directivity versus frequency for a 1.0-m Ka-band microstrip reflectarray.

antenna are not included in these figures. Figure 9 is plotted for a 32-GHz reflectarray having a diameter of 0.5 m and a total of 8,937 patch elements. Two f/D ratios of 0.5 and 1.0 are plotted in this figure. It is obvious that an f/D of 1.0 gives better bandwidth performance. Similar curves are plotted in Fig. 10 for a 1-m-diameter reflectarray at 32 GHz. The number of patch elements in this case is 35,788. By comparing Figs. 9 and 10, the 1-m reflectarray with the same f/D gives less bandwidth than the 0.5-m one. This implies that, with the same f/D ratio, the larger the reflectarray, the smaller the bandwidth it will provide. The bandwidth performances of Figs. 9 and 10 are summarized in Table 2.

Table 2. Bandwidth performance of the 32-GHz reflectarray.

f/D	0.5-m diameter, percent	1.0-m diameter, percent
	−1-dB gain-drop bandwidth	
0.5	4.8	2.6
1.0	8.5	4.5
	−3-dB gain-drop bandwidth	
0.5	8.4	4.3
1.0	14.0	7.5

The radiation patterns of the reflectarray will change as frequency changes. These differences are illustrated in Figs. 11 and 12 for two different f/D ratios. The pattern defocusing effect as frequency deviates from the center (design) frequency is clearly demonstrated in these figures.

From the above results, it can be concluded that, among the four bandwidth limiting factors, the element spacing and the feed antenna are not serious concerns in designing the reflectarray if the bandwidth requirement is 15 percent or less. It also can be concluded that a 3-percent bandwidth (1-GHz bandwidth at 32 GHz) for the reflectarray is fairly easy to achieve. An 8-percent bandwidth to cover both the uplink frequency (34 GHz) and the downlink frequency (32 GHz) may require an f/D ratio close to 1.0 and a specially designed patch element.

VI. Advantages of the Microstrip Reflectarray

The microstrip reflectarray antenna takes the best characteristics and eliminates the poor features of the parabolic reflector, the array, and the microstrip patch. This contributes to the microstrip reflectarray's six significant advantages, which are separately discussed below.

A. Surface Mountable With Lower Mass and Volume

Since the antenna's reflecting surface is a thin, flat structure, it can be flush mounted onto the surface of a structure, such as a spacecraft's main body or a building, with less supporting structure mass and volume as compared with the curved parabolic reflector. One possible application is shown in Fig. 13, where the reflectarray is surface mounted onto one side panel of a pentagonally shaped microspacecraft. Another application is given in Fig. 14, where the reflectarray is surface mounted onto a house wall for direct broadcast satellite (DBS) television service. In addition to the capability of surface mounting onto a flat structure, the reflectarray can also be mounted conformally onto a slightly curved structure (either concave or convex). The phase deviation of the curved structure can be compensated for in the design of the set of phase delay lines.

B. Easily Deployable

When a deployment mechanism is needed for a large aperture antenna, the flat structure of the reflectarray can be folded or unfolded by a simple hinge type of mechanism. A single or a double folding mechanism for a flat structure is significantly simpler (approximately an order of magnitude simpler) than that for a curved parabolic structure and is also more reliable.[1] The flat panel folding technique has been commonly used in the deployment of solar panels and has shown excellent reliability.

C. Lower Manufacturing Cost

The reflectarray, being in the form of a printed microstrip antenna, can be fabricated with a simple and low-cost etching process, especially when it is produced in large quantities. The antenna also can be cost effective just because of its flat structure. For example, the special molding process that is generally required for fabricating a curved paraboloid is not needed for a flat structure.

D. Scannable Beam

The main beam of the microstrip reflectarray can be designed to point at a large fixed angle (up to 60 deg) from the broadside direction, while a parabolic reflector can only have a very limited beam tilt (several beamwidths). If cost permits, phase shifters can be placed in the phase delay transmission lines for electronic beam scanning.

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[1] Personal communication with R. Freeland, Mechanical Engineer, Applied Mechanics Technologies Section, Jet Propulsion Laboratory, Pasadena, California, 1994.

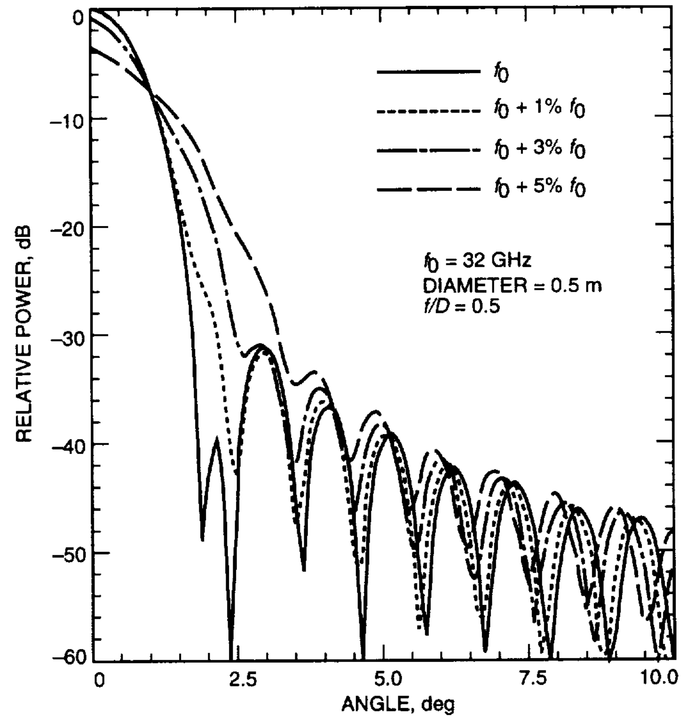

Fig. 11. Change of radiation patterns as frequency deviates from its center frequency for a reflectarray with an f/D ratio of 0.5.

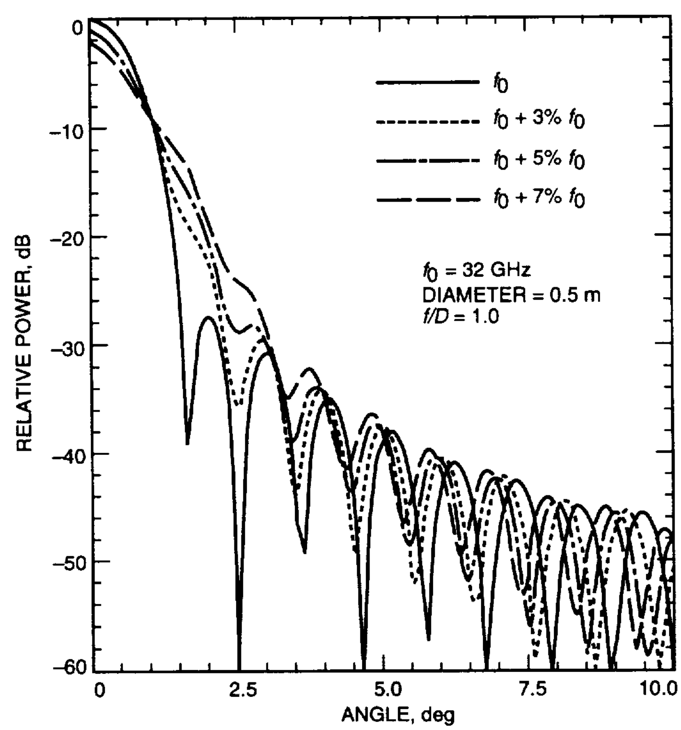

Fig. 12. Change of radiation patterns as frequency deviates from its center frequency for a reflectarray with an f/D ratio of 1.0.

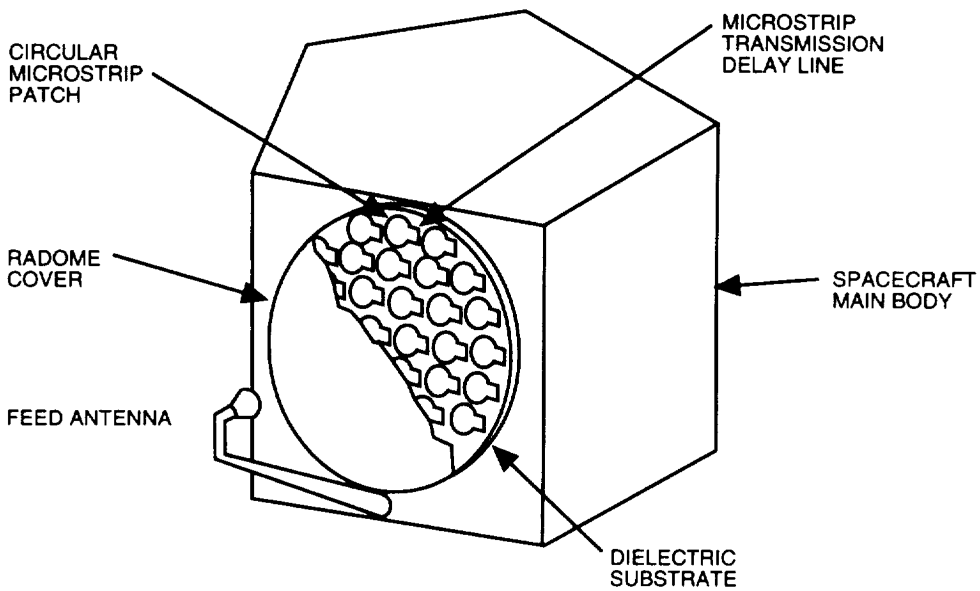

Fig. 13. Surface mounting of a microstrip reflectarray onto the side panel of a microspacecraft.

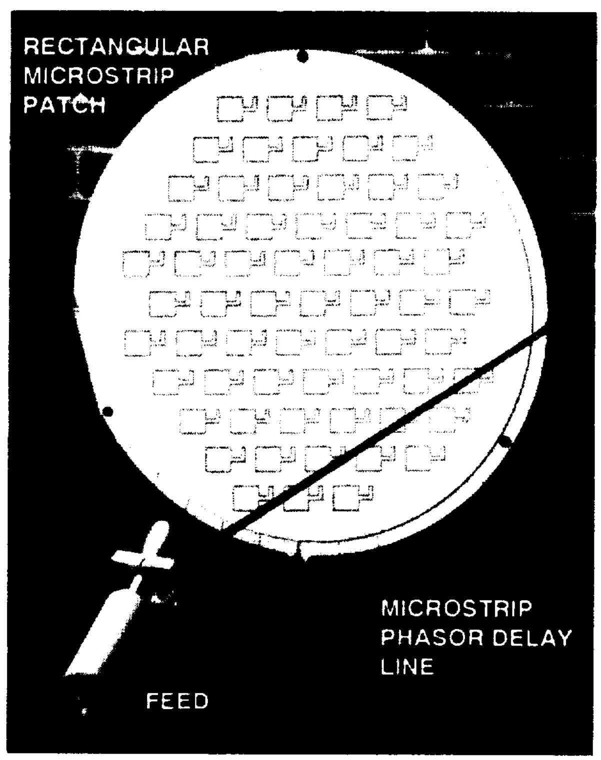

Fig. 14. Surface mounting of a microstrip reflectarray onto a house wall for a DBS application.

E. Integratable With a Solar Array

Since both the solar array and the reflectarray antenna are in the form of large, flat panels, they have the possibility of being integrated together to save space and mass. There are two possible configurations for the integration. One is for a lower-frequency application (below 5 GHz) where the patch radiator is large enough to place solar cells on top of it. This is shown in Fig. 15, where the RF energy radiates from the perimeter of the patch and is not affected by the solar cells. The other configuration, proposed by Malibu Research [8], is to use thin wire dipoles as reflectarray radiators. This is illustrated in Fig. 16, where the thin dipoles are suspended on thin wires and placed in front of the solar panel. A metallic wire-mesh ground plane is placed between the dipoles and the solar cells. This ground plane is needed for the dipoles to reradiate effectively. This concept should be feasible for frequencies below 15 GHz. For frequencies higher than 15 GHz, the dipoles and the mesh ground plane may become too dense for significant amounts of sunlight to penetrate, and the mechanical support structure for the dipoles (with mesh ground plane) may be difficult to implement. Even for frequencies lower than 15 GHz, because the dipoles are placed in front of a wire mesh and not a continuous perfect ground plane, the RF efficiency will be impaired. In addition, because the dipoles and the wire mesh ground plane will partially block the sunlight, the solar cell efficiency will also be reduced. The degrees of impairment of RF and solar cell efficiencies remain to be studied.

F. Very Large Aperture Array

Due to the fact that no power divider is needed, the insertion loss of thousands of microstrip patches in the reflectarray is the same as that of a few patch elements. Thus, the reflectarray can achieve as good an efficiency as a large array antenna system. As a possible application, a very large, flat reflectarray can be constructed on flat land (array aperture parallel to the land) with its feed mounted on top of a high tower. The size of the antenna is only limited by the tower height. A feed height of 300 m with an f/D ratio of 0.5 will result in an array with a diameter of 600 m. At 10 GHz, this antenna size can produce a pencil beam 0.0035 deg in beamwidth and 95 dBi of directivity. Such an antenna can be used in astrophysics applications.

VII. Proposed New Configurations of the Microstrip Reflectarray

To improve the performance of the microstrip reflectarray, three novel concepts are introduced here. They are separately presented below.

A. The Cassegrain Feed Reflectarray

As mentioned previously, in order to achieve a wider bandwidth, a large f/D ratio is generally needed for the reflectarray. A large f/D implies that the focal feed has to protrude far from the array aperture, which will result in larger volume and larger mass. The proposed Cassegrain configuration, shown in Fig. 17, will reduce the feed height while maintaining the same or a higher effective f/D ratio. In addition, the transmission line loss between the feed and the transceiver is significantly reduced, which is especially important at higher frequencies, such as Ka-band.

B. Bandwidth Enhancement by Subarray Arrangement Techniques

The second concept uses specially arranged subarrays in the entire array aperture to improve the bandwidth performance. Figure 18 shows that, for linear polarization, each two-patch subarray uses the antiphase method [13] and, for circular polarization, each four-patch subarray uses the sequential rotation method [14] to improve the bandwidth. For conventional microstrip arrays, these subarraying techniques have been successfully demonstrated to increase bandwidth from 3 percent to more than 8 percent. For a single patch, as frequency changes away from its resonant frequency, higher order modes start to form in the patch's cavity, and these will impair the input impedance match and polarization quality. By using the antiphase and sequential rotation methods, these high-order modes can be canceled, causing the desired fundamental mode to continue to dominate as the frequency changes.

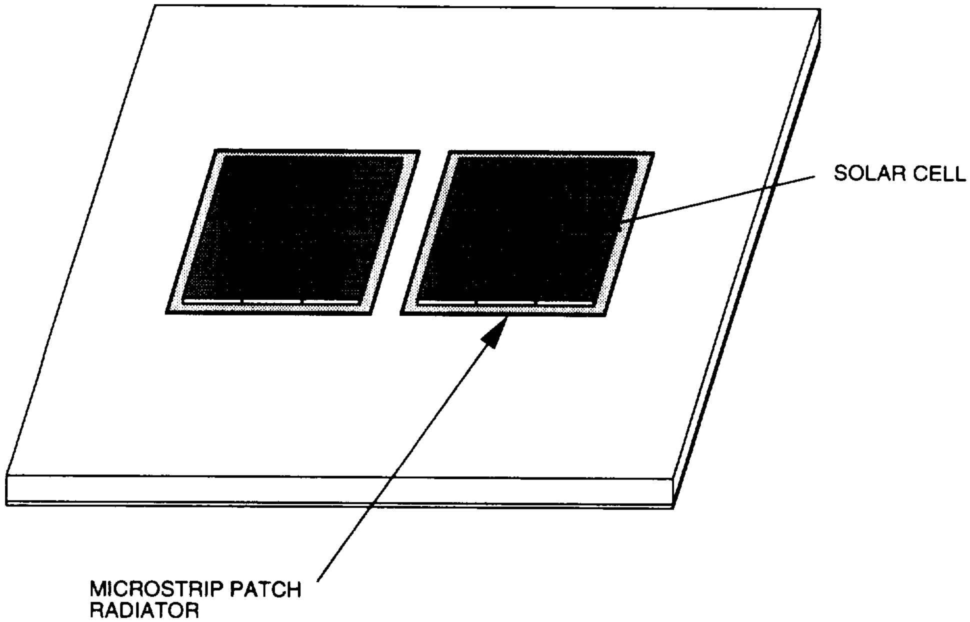

Fig. 15. Integration of solar cells and microstrip radiators for low-frequency reflectarray applications.

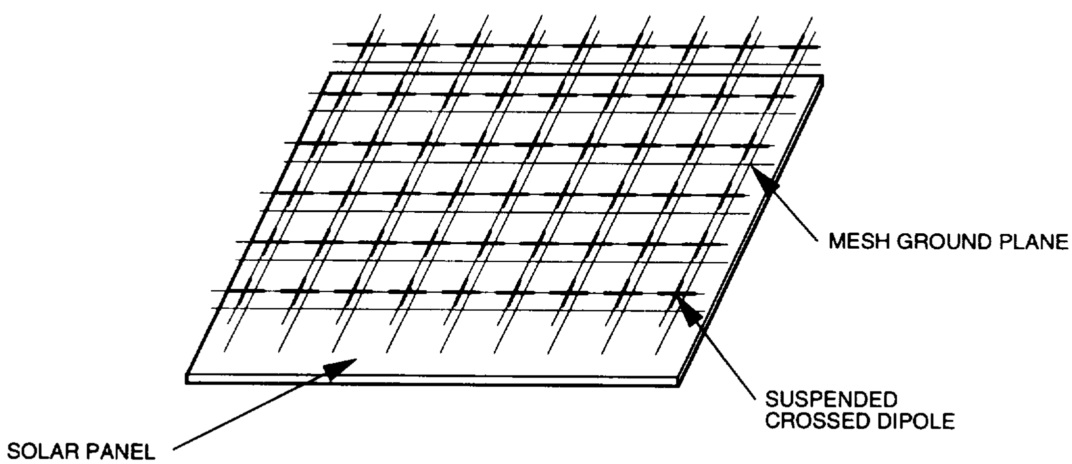

Fig. 16. Integration of a solar panel with a thin-wire reflectarray antenna.

C. Phase-Delay Compensation by Rotation of Identical Elements

In a circularly polarized microstrip reflectarray, the circular polarization can be achieved by having two equal-length delay lines orthogonally attached to each patch (see Fig. 3). The length of these delay lines varies from element to element to compensate for the different spatial phase delays of the feed antenna. In this newly proposed technique, the required different phase-delay compensations for each of the elements are achieved by different angular rotations of the elements, as shown in Fig. 19. All elements, except for rotations, are identical with identical delay lines. The delay lines, in this case, only serve as the angular references for rotations and not for phase-delay compensations. Especially for a circular patch, without some kind of angular reference, the rotations between different patches cannot be differentiated. The required amount of rotation in degrees is half of that required for the phase delay in degrees. This technique of rotating the circularly polarized element to achieve the required phase has been demonstrated [15] previously in a conventional array.

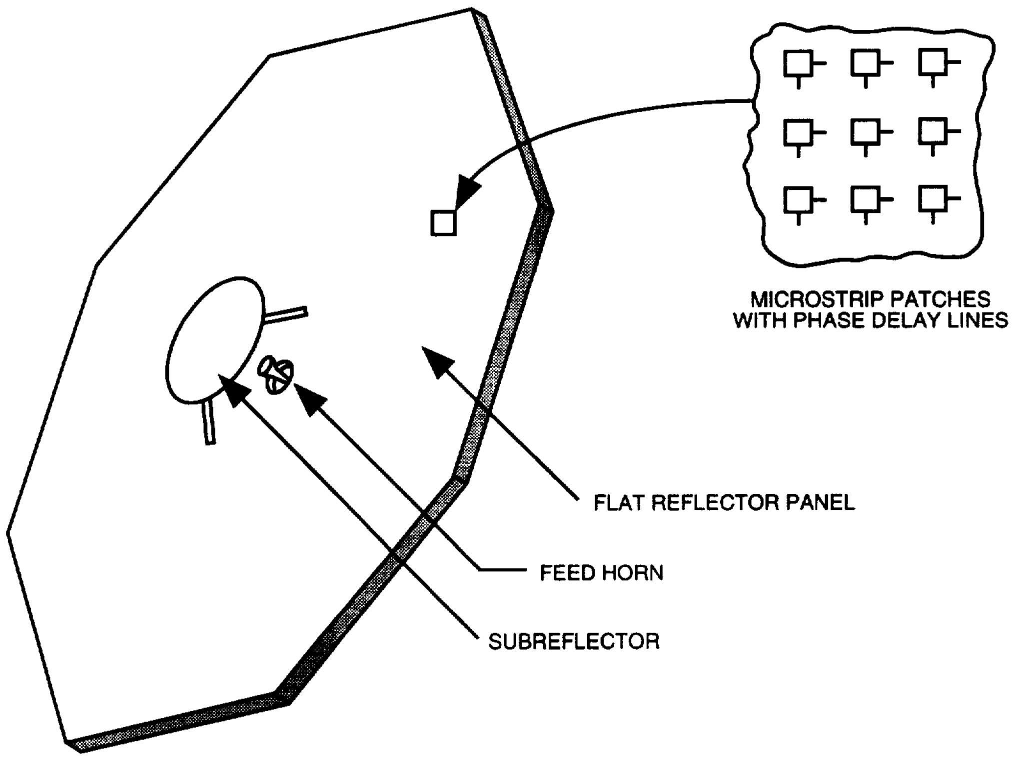

Fig. 17. Cassegrain reflectarray configuration.

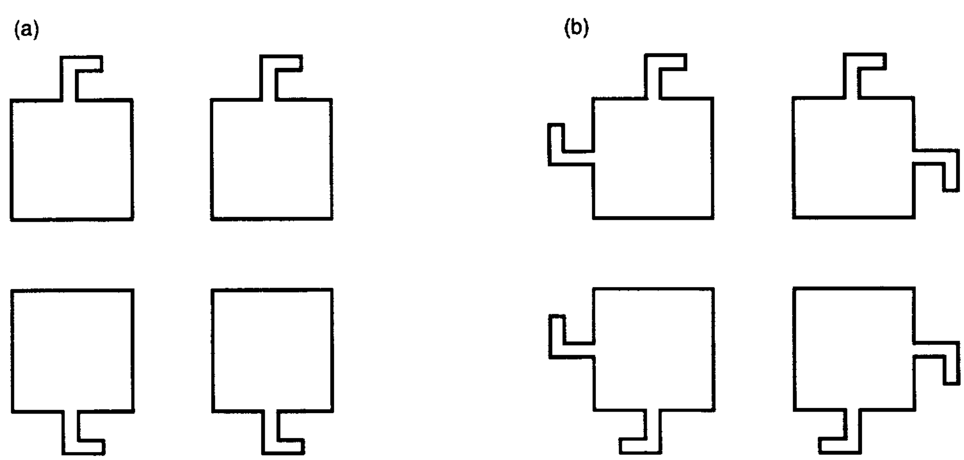

Fig. 18. Reflectarray bandwidth enhancement by subarray arrangement techniques: (a) linear polarization and (b) circular polarization.

By combining the "rotation" technique with miniature motors, the main beam of the microstrip reflectarray can be made to scan. In other words, as shown in Fig. 20, a miniature motor can be placed under each patch element to mechanically rotate the patch to achieve the required phase for beam scanning. Since all the elements in a reflectarray are isolated from each other with no need for a power divider, no rotary joint is required, which will reduce cost and enhance reliability. By using the miniature motors, high-cost phase shifters are not needed for beam scanning. Consequently, a very large, phased array antenna system with relatively low cost may be realizable.

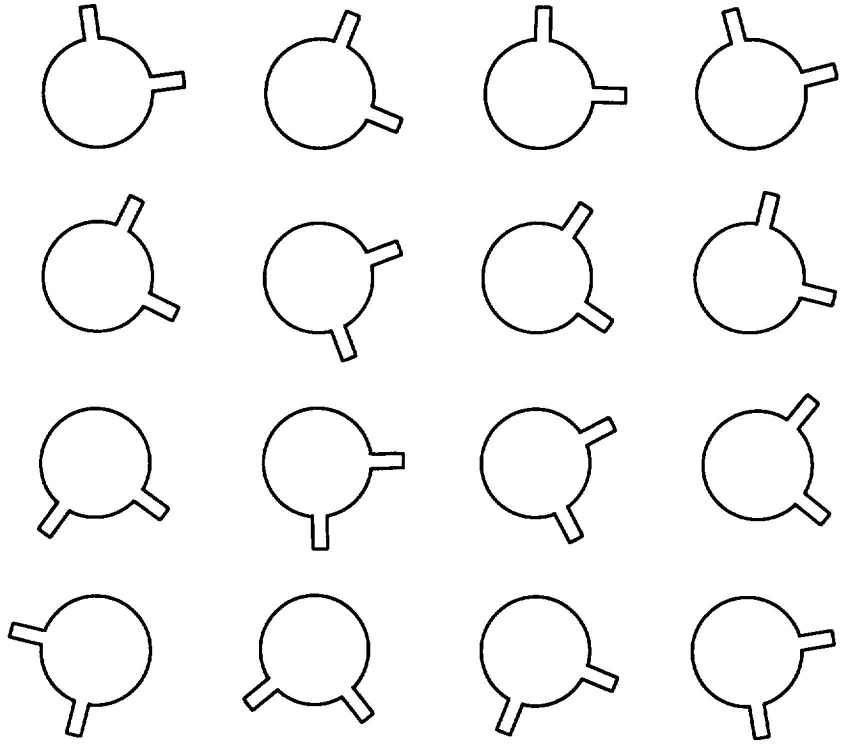

Fig. 19. Reflectarray phase-delay compensation by rotation of identical elements.

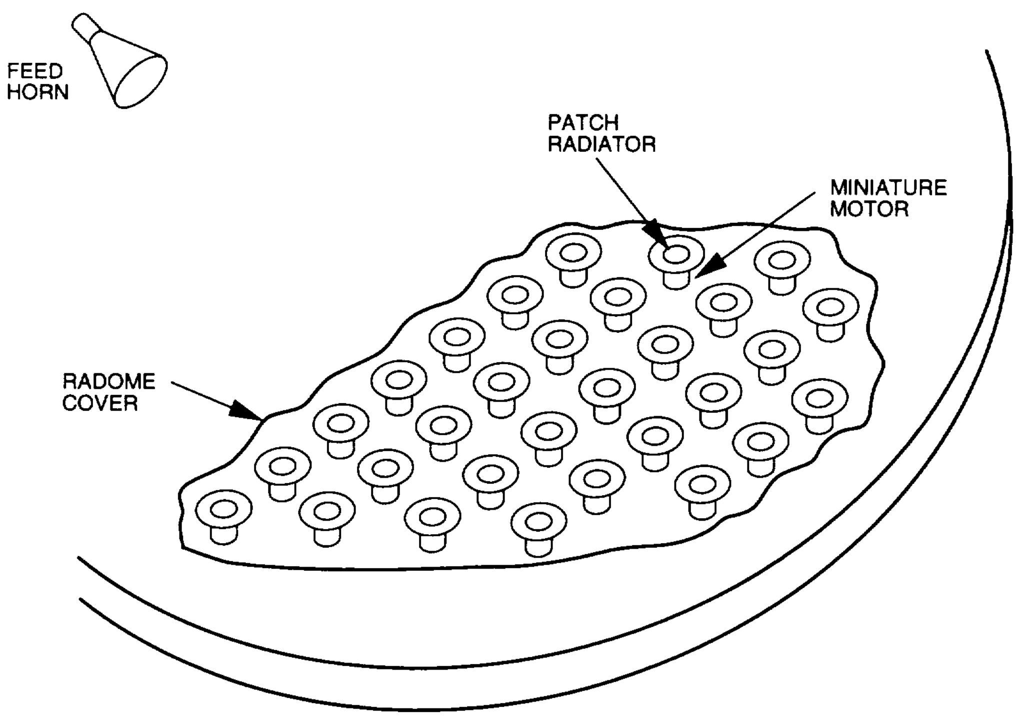

Fig. 20. Mechanically phased reflectarray—beam scan by mechanical rotation of elements.

VIII. Conclusion

The circularly polarized microstrip reflectarray has been analyzed using conventional array theory. Antenna performance parameters, such as radiation pattern quality, directivity, efficiency, bandwidth, etc., are calculated for a 0.5-m Ka-band reflectarray with 8,937 patch elements. It is found that an 8-percent bandwidth is achievable for this antenna and that bandwidth performance improves for a larger f/D ratio. An f/D ratio close to 1.0 is recommended for the 0.5-m Ka-band antenna. Overall antenna efficiency in the range of 50 to 70 percent is possible. Numerous advantages of this flat-plate reflector antenna have been discussed. Three novel configurations of the microstrip reflectarray are proposed for future studies.

References

[1] J. Huang, *Microstrip Reflectarray Antenna for the SCANSCAT Radar Application*, JPL Publication 90-45, Jet Propulsion Laboratory, Pasadena, California, November 15, 1990.

[2] J. Huang, "Microstrip Reflectarray," *IEEE AP-S/URSI Symposium*, London, Ontario, Canada, pp. 612–615, June 1991.

[3] R. C. Hansen, *Microwave Scanning Antennas*, vol. 1, New York: Academic Press, pp. 251–252, 1964.

[4] R. E. Munson and H. Haddad, *Microstrip Reflectarray for Satellite Communication and RCS Enhancement or Reduction*, U.S. Patent 4,684,952, Washington, D.C., August 1987.

[5] T. A. Metzler, *Design and Analysis of a Microstrip Reflectarray*, Ph.D. Dissertation, University of Massachusetts, Amherst, February 1993.

[6] Y. Zhuang, K. L. Wu, C. Wu, and J. Litva, "Microstrip Reflectarrays: Full-Wave Analysis and Design Scheme," *IEEE AP-S/URSI Symposium*, Ann Arbor, Michigan, pp. 1386–1389, June 1993.

[7] D. C. Chang and M. C. Huang, "Microstrip Reflectarray Antenna With Offset Feed," *Electronics Letters*, pp. 1489–1491, July 1992.

[8] A. Kelkar, "FLAPS: Conformal Phased Reflecting Surfaces," *Proceedings of the IEEE National Radar Conference*, pp. 58–62, March 12–13, 1991.

[9] S. D. Targonski and D. M. Pozar, "Analysis and Design of a Microstrip Reflectarray Using Patches of Variable Size," *IEEE AP-S/URSI Symposium*, Seattle, Washington, pp. 1820–1823, June 1994.

[10] R. J. Mailloux, J. F. McIlvenna, and N. P. Kernweis, "Microstrip Array Technology," *IEEE Transactions on Antennas and Propagation*, pp. 25–37, January 1981.

[11] A. W. Rudge, K. Milne, A. D. Olver, and P. Knight, *The Handbook of Antenna Design*, vol. 1, London, England: Peter Peregrinus Ltd., pp. 169–172, 1982.

[12] S. Silver, *Microwave Antenna Theory and Design*, New York: McGraw-Hill, Inc., pp. 177–179, 1949.

[13] J. Huang, "Dual-Polarized Microstrip Array With High Isolation and Low Cross-Polarization," *Microwave Optics Technology Letters*, pp. 99–103, February 1991.

[14] T. Teshirogi, M. Tanaka, and W. Chujo, "Wideband Circularly Polarized Array Antenna With Sequential Rotations and Phase Shift of Elements," *Proceedings of ISAP*, Japan, pp. 117–120, 1985.

[15] M. L. Oberhart and Y. T. Lo, "Simple Method of Experimentally Investigating Scanning Microstrip Antenna Arrays Without Phase-Shifting Devices," *Electronics Letters*, vol. 25, no. 16, pp. 1042–1043, August 1989.