ON THE BANDWIDTH OF MICROSTRIP REFLECTARRAYS

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Abstract - In this article, several factors that govern the bandwidth performance of the microstrip reflectarray are discussed. One that has not been studied in detail and has a significant impact on the overall bandwidth performance is the differential spatial phase delay. With proper designs, the bandwidth limitation caused by this differential spatial phase delay and other factors can be minimized, and an overall -3dB bandwidth of 10 percent is achievable.

I. INTRODUCTION

The microstrip reflectarray consists of a very thin, flat reflecting surface and an illuminating feed, as shown in Figure 1. On the reflecting surface, there are many microstrip patch elements. However, there is no power division network so these elements are isolated from each other. When these elements are illuminated with electromagnetic energy by the feed antenna, they will reradiate the 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, $S_1, S_2, \ldots\ldots S_N$, as shown in Figure 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 [1] many decades ago and used horns, dipoles, open-ended waveguides, etc., for the elements. Since the elements arc large in size at lower microwave frequencies and many elements are needed in order for the reflectarray to be efficient [2], the earlier reflectarray antennas were bulky in size and heavy in weight. Due to the recent advancement of light weight and low-profile printed antennas, such as the microstrip patch, the printed reflectarray becomes physically more realizable and attractive. The reflecting surface can be flat or conformal to its mounting structure and achieves reduced antenna volume and mass. Several different versions of the printed reflectarray have been developed recently. one version, shown in Figure 1, uses identical patches with different-length transmission delay lines attached to compensate for the spatial phase delays [2,3,4,5,6,7]. The second version uses variable-size patches to achieve the required phase delays without any transmission lines attached to the patches [8]. The third version employs variable-size printed dipoles without transmission lines attached [9]. The fourth concept, for circularly polarized reflectarrays, proposes to use identical-size patches with attached identical-length lines to achieve far-field phase coherence by placing the elements at different angular positions[10]. It is expected that the bandwidths of each of the different versions of printed reflectarrays are of the same order of magnitude. Regardless of the configuration, the bandwidth of a printed reflectarrays is limited and is no match for that of a parabolic reflector, which theoretically has an infinite bandwidth. The following section discusses the various factors that limit the bandwidth performance of the microstrip reflectarray.

II. BANDWIDTH STUDY

Bandwidth is often an important quantity for satellite communication, especially with the increasing demand for higher data rates. For example, at Ka-band of 30 GHz, 1 GHz of bandwidth (3 percent) is anticipated to include video signals in the data transmission. In addition, currently for many satellite communication systems, both the downlink and uplink frequencies, separated by 5 to 10 percent bandwidth, are required to be covered by the same antenna. It is the purpose of this section to study and understand the bandwidth characteristics of the microstrip reflectarray and, as a result, optimize the bandwidth performance for a given application.

The bandwidth performance of a microstrip reflectarray is primarily limited by four factors: (1) the narrow bandwidth of 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, an ordinary microstrip patch element can only achieve a bandwidth of approximately 3 percent. To achieve a bandwidth larger than 3 percent, the techniques, such as using a thicker substrate, use of a parasitic radiator, or use of a dual-band stub, can be employed. Ten- to twenty-percent bandwidths for microstrip patch elements have been reported[11]. It is important to keep the element's pattern shape or beamwidth more-or-less the same throughout the bandwidth. This is required because the feed illuminates the entire reflectarray at different incident angles which become larger toward the edge of the reflectarray. If the element pattern becomes narrower as the frequency changes, the edge elements will not receive energy from the feed effectively. The second factor, the array element spacing, limits the reflectarray bandwidth such that, as frequency is decreased, the electrical element spacing becomes small, and excessive mutual coupling effects start to degrade the array performance. On the other hand, as the frequency is increased, the electrical element spacing becomes large, and undesirable grating lobes begin to appear. Fortunately, the basic array theory and many previous calculations have shown that the element spacing effect will not be detrimental until the frequency variation is more than 30 percent (±15 percent around the center frequency). For instance, if the element spacing at center frequency is $0.55\lambda_o$ (λ_o is free space wavelength), a 15 percent reduction in frequency results in an element spacing of $0.47\lambda_o$ and a 15 percent increase in frequency results in a $0.63\lambda_o$ element spacing. It is obvious that these element spacings should not cause significant degradation in array performance. 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 examples. If desired, an Archimedean spiral can be used to achieve more than 100 percent of bandwidth. The fourth limiting factor, called the differential spatial phase delay, has not been well understood and is separately detailed in the following paragraphs.

The differential spatial phase delay can best be explained by referring to Figure 2 where the differential spatial phase delay, AS, is the difference between the reference electrical path S_1 and an arbitrary path S_2. This AS can be many multiples of the wavelength at the center operating frequency, such as $(N+d)\lambda_o$, 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) takes on different values. In order to achieve constant aperture phase for the reradiated waves, the $d\lambda_o$ at each patch location is compensated for either by the appropriate length of the phase delay line attached to the patch or by the differential complex impedance (differential phase) of the different sized elements. However, " as frequency changes, the (N-t d) will change accordingly. Since the compensating phase delay, generated by the phase delay line or the different clement sizes, are more-or-less 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) and cause the reradiated phase front to be incoherent. 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 avoid the use of a reflectarray with a large electrical diameter. With a fixed f/D ratio, the larger the electrical diameter, the larger AS and N will be, which increases frequency excursion error.

The effects of the above mentioned f/D ratio and the diameter on the reflectarray bandwidth performance are calculated using the conventional array theory [2] and are plotted in Figures 3 and 4 where beam directivity versus frequency change is shown. These plots are for the reflectarray elements having identical patches with different-length delay lines attached. The bandwidth effects of the patch element and the feed antenna are not included in these figures; but the effects of element spacing and differential spatial phase delay are included. Figure 3 is plotted for a 32-GHz reflectarray having a diameter of 0.5m, an element spacing of 0.5 λ_o, and a total of 8937 patch elements. Two f/D ratios of 0.5 and 1.0 are plotted in this figure. It is apparent that the f/D ratio of 1.0 gives wider bandwidth performance. Similar curves are plotted in Figure 4 for a 1-m-diameter reflectarray at 32 GHz. The number of patch elements in this case is 35,788. By comparing Figures 3 and 4, one can see that the 1-m reflectarray with the same f/D gives less bandwidth than the 0.5-m one. This is because, with the same f/D ratio, the larger the reflectarray diameter, the larger the AS and N will be and, hence, the smaller the bandwidth. The bandwidth characteristics of Figures 3 and 4 are summarized in Table 1. The radiation pattern of the reflectarray will change as frequency changes. The changes are illustrated in Figures 5 and 6 for two different f/D ratios. The pattern defocusing effect as frequency deviates from the designed center frequency is clearly demonstrated in these figures. The larger the f/D ratio, the smaller the pattern defocusing effect.

Table 1. **Bandwidth performance of the 32-GHz reflectarray**

f/D	O. S-m diameter,	1 O-m diameter,
1 dB drop in gain bandwidth (percent)		
0.5	4.8%	**2.6%**
1.0	8.5%	4.5?40
3 dB drop in gain bandwidth (percent)		
0.5	8.4%	4.3%
1.0	14.0?40	7.5?40

There is one technique that can almost eliminate the effect of differential spatial phase delay. This is the technique of using time delay lines instead of the phase delay lines discussed above. In a time delay line technique, the differential spatial phase delay $(N+d)\lambda_o$ for each element is compensated for by a transmission delay line (connected to the patch) of length equal to $(N+d)\lambda_o$ instead of just $d\lambda_o$. In so doing, as frequency changes the electrical path lengths of S_1 (include the connected time delay line) and S_2 will remain identical to each other and thus eliminate the frequency excursion error. The time delay line method, theoretically, can achieve almost infinite bandwidth, but will suffer from higher insertion loss due to the required longer time delay transmission lines. It will be difficult to find real estate for the physically long delay lines to be etched on the same side of the substrate as the micro strip patches with only 0.5 λ_o element spacing. These long delay lines may be implemented, with increased complexity, on a separate microstrip or stripline layer placed behind the patch element layer.

111. CONCLUS1ON

From the above results and discussion, it can be concluded that, among the four bandwidth limiting factors, the element spacing and the feed antenna factors will not be serious concerns in designing the microstrip reflectarray. It also can be concluded that a 3-dB drop in gain bandwidth of 3 percent will be fairly easy to achieve for a reflectarray having a diameter of 100 wavelengths or less. A 3-dB drop in gain bandwidth of **10** percent is achievable; however, it may require an f/D ratio of 1.0 or larger and a specially designed patch clement.

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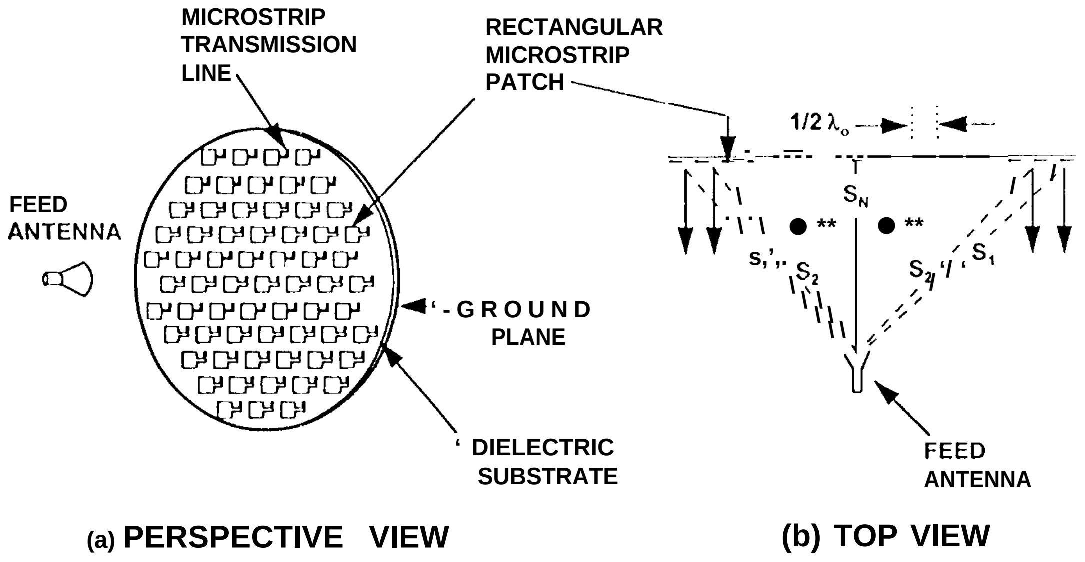

Figure 1. Microstrip reflectarray configuration

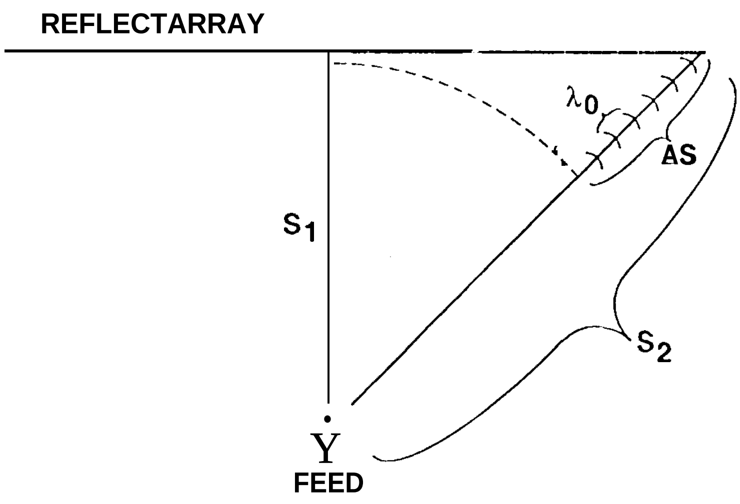

Figure 2. Differential spatial phase delay of reflectarray.

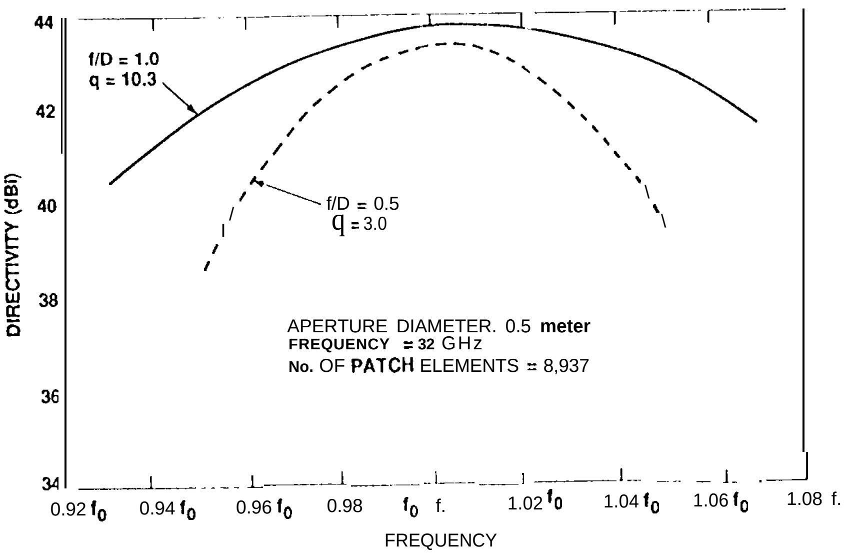

Figure 3. Calculated directivity versus frequency for 0.5m diameter Ka-band reflectarray with $\cos^q(\theta)$ feed factor.

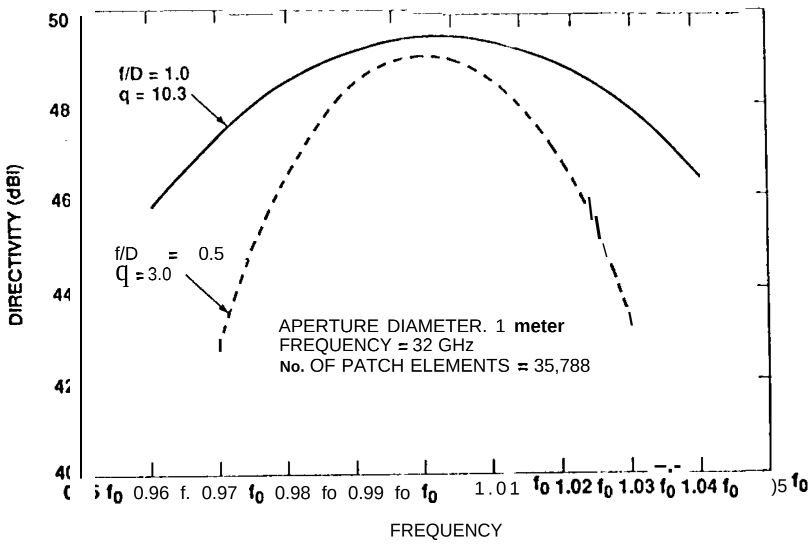

Figure 4. Calculated directivity versus frequency for 1.0m diameter Ka-band reflectarray with $\cos^q(\theta)$ feed factor.

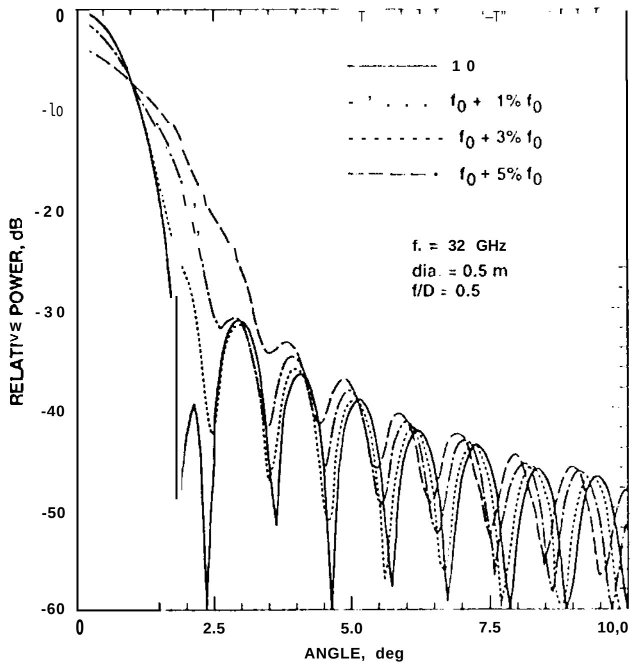

Figure 5. Calculated reflectarray patterns at the design and several off-design frequencies, f/I)=0. 5, number ofelenwnts=8,937.

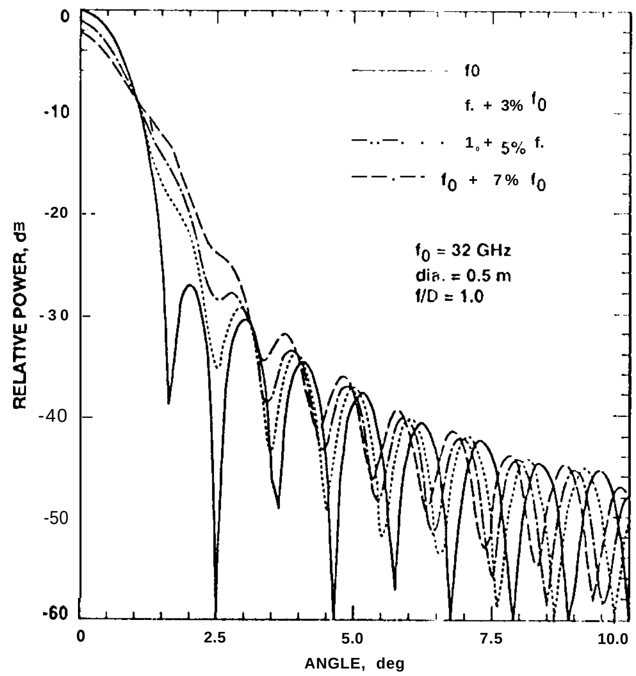

Figure 6. Calculated reflectarray patterns at the design and several off-design frequencies, **f/D=1** .0, number of elements=8,937.