ACKNOWLEDGMENT

The author wishes to thank G. Engen, N. Larsen, R. Metzker, and W. Angevine for their assistance in the computer programs, power detectors, hardware construction, and data reduction, respectively.

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Technology Considerations for the Use of Multiple Beam Antenna Systems in Communication Satellites

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***Abstract*—The general usage of multibeam antennas in satellite communication systems is reviewed, and design constraints for a six-beam reconfigurable satellite antenna system are considered. These show that losses in the variable beam-forming network (BFN) limit performance achievable with a conventional common-power-amplifier/receiver system. An alternative design for an active BFN is presented, and relative performance predicted at 4/6, 11/14, and 20/30 GHz.**

I. MULTIBEAM ANTENNA TECHNIQUES

MODERN communication satellites place ever increasing demands on their antenna systems, to accomplish such functions as: 1) improving EIRP over prescribed areas through pattern shaping; 2) allowing frequency reuse by both spatial and polarization diversity; and 3) reducing interference outside desired coverage areas, to meet new WARC requirements on both copolar and cross-polarized energy. Solutions to these problems generally result in larger, more complex antenna structures and systems, which soon become an overriding factor in the design of the entire satellite.

One technique which has evolved to meet these needs is the use of multiple beam antenna (MBA) systems [1]–[5], which are capable of creating multiple simultaneous beams, each of which may be shaped from a number of smaller constituent beams by the principle of superposition. This principle is illustrated in Fig. 1, showing a set of three adjacent constituent beams added together in space to produce a single broader beam with a relatively flat top and steep "skirts". This allows more uniform coverage of the desired area, and more rapid decay of energy outside this area, to reduce interference while also improving efficiency. The antenna designer would prefer to use the narrowest possible constituent beams spaced as closely as possible together; this leads to very large antenna structures and numbers of constituent beams, each of which must be individually formed and fed. A natural limitation occurs in the allowable spacing of feed horns, based on their minimum size; this generally occurs at a spacing of about 0.6 beamwidths. Table I denotes the approximate number of beams which would be required for earth coverage from synchronous altitude (18°) for various

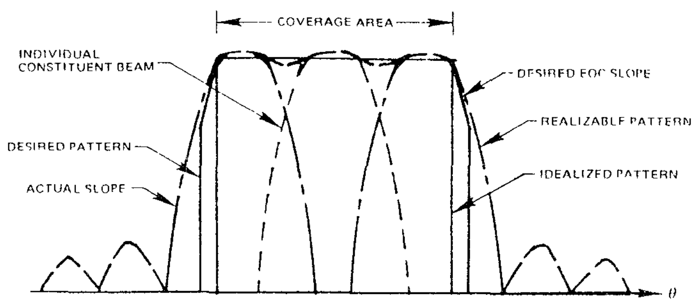

Fig. 1. Superimposed coverage patterns.

Manuscript received April 30, 1979; revised September 15, 1979.

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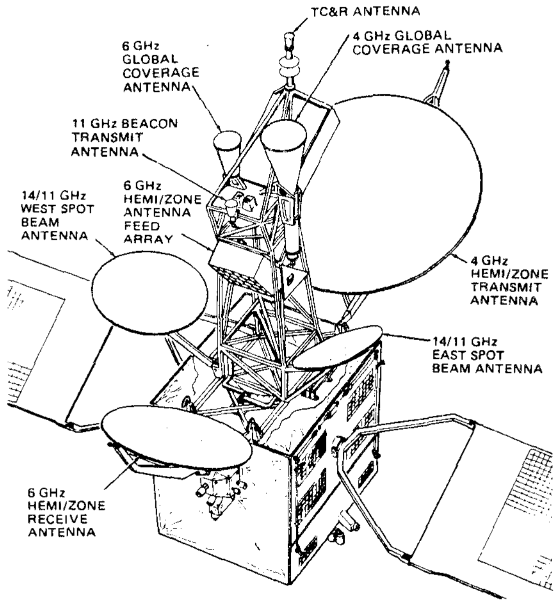

Fig. 2. INTELSAT V antenna configuration.

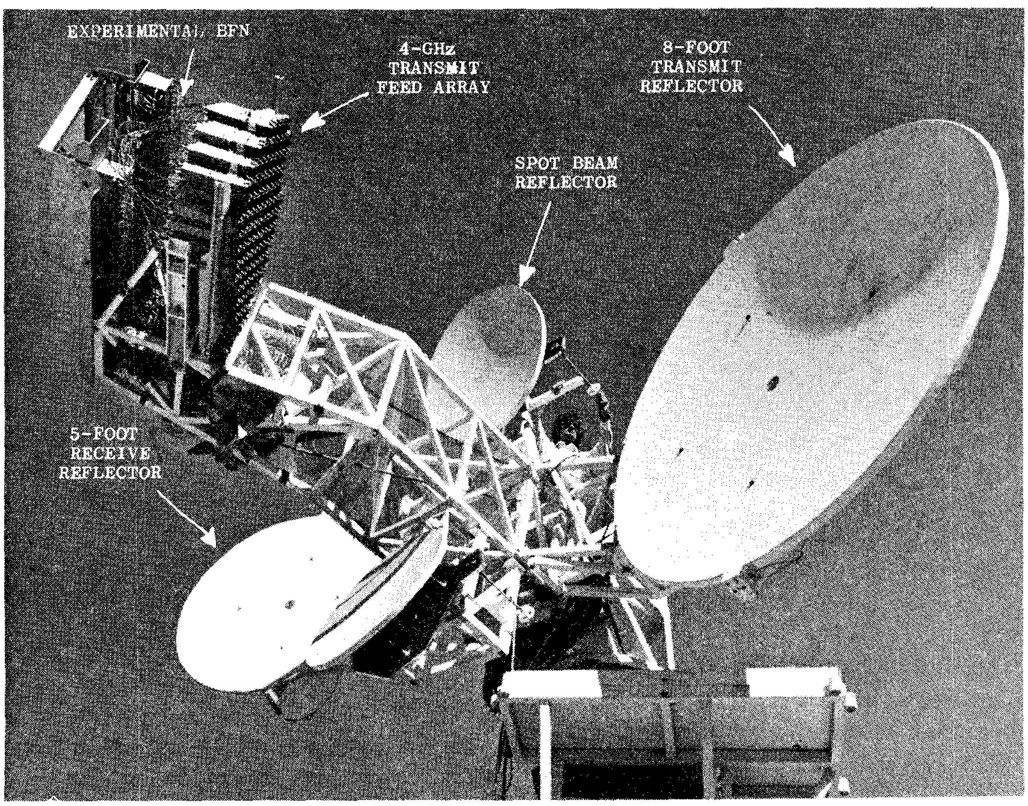

Fig. 3. INTELSAT V communication antennas (engineering model).

TABLE I
MBA 1° BEAMS REQUIRED FOR EARTH COVERAGE

Beam Spacing	0.6	0.8	1.0	1.2
Number of Beams	800	470	300	217
Crossover level, dB	-1.1	-1.9	-3.0	-4.3

beam spacings, assuming a 1° constituent beamwidth (requiring a 17-ft diameter aperture at 4 GHz). The crossover level in each case is also shown; this determines the amount of ripple in the composite pattern between beams. The large numbers of beams result in complex large and heavy beam forming networks (BFN's).

An example of the use of this MBA technique is the INTELSAT V communications antenna [6], [7] which consists of separate offset-fed reflectors for transmit (4 GHz) and receive (6 GHz), as pictured in Figs. 2 and 3. The transmit reflector is 8 ft in diameter, and is fed by an array of 78 contiguous feed horns, each excited with both senses of circular polarization to produce four separate beams, as shown in Fig. 4. Two of these beams cover hemispheric regions of existing ground stations, while the

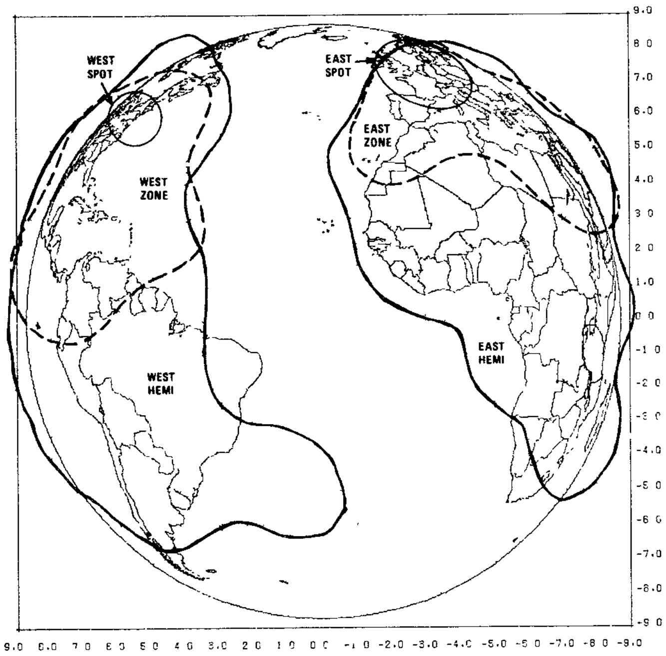

Fig. 4. INTELSAT V Atlantic Ocean coverage.

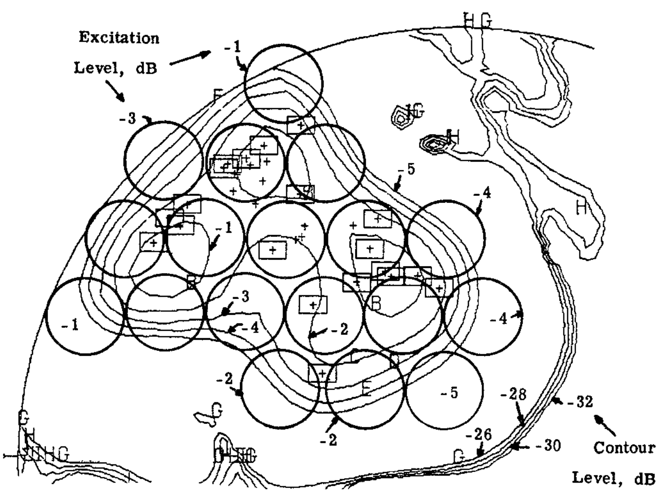

Fig. 5. Calculated INTELSAT V west zone receive beam contours.

other two are cross-polarized zone beams for high-traffic areas. The combination provides four times frequency reuse, with a minimum of 27-dB isolation between beams. In addition, two movable spot beams are included, operating at 11 and 14 GHz.

A calculated contour plot of the west-zone receive beam is shown in Fig. 5, depicting relative locations of the 18 constituent beams used. Each has a beamwidth of about 2°, and all are excited with nearly equal amplitudes, except the edge beams, whose relative amplitudes are shown. Contours up to 30 dB below the beam peak are shown, representing loci where 27-dB isolation from the −3-dB edge-of-coverage contour is provided. This −30-dB contour is thus the nearest edge of another co-polarized beam operable in the same band, and with the desired minimum isolation for frequency reuse. The spacing between edges of such beams is generally at least one full constituent beamwidth, thus placing an upper limit on the number of multiple beams achievable within a given area for a given size antenna.

Excitation of the 78 individual INTELSAT V feed horns with the proper amplitudes and phases is accomplished with an air-suspended stripline BFN shown in Fig. 6. This network consists of a cascade of hybrid-ring power dividers, with interconnecting line lengths adjusted for phase control.

II. Future Projections

Future satellites will undoubtedly require even more complex antennas, including such features as reconfigurability—the ability to adjust beam shapes on command, to meet changing user requirements or to avoid interference. Interest is also growing in the use of higher frequencies to allow more bandwidth—the Japanese have already launched a 20/30 GHz communications satellite[1] with a bandwidth of 2.5 GHz, while INTELSAT V also uses 11/14 GHz for the spot beams shown in Fig. 4.

To explore some of the detailed requirements of future systems, consider a six-beam reconfigurable case. For 1° constituent beams, an antenna system with perhaps 256 beams is usable, by eliminating coverage in unused areas such as near the poles. Reconfigurability could be implemented by a BFN composed of a matrix of cascaded variable power dividers (VPD's). Full flexibility for each of the six beams would require six BFN's with 255 VPD's in each, cascaded in eight levels, plus 256 six-way switches (one at each feed element to select the beam to which it is assigned), plus 256 phasers to control excitation phases, as pictured in Fig. 7. This would entail a total of 1530 VPD's and 1536 switches and phasers; if each weighed only an ounce the total BFN would be over 200 lbs, including interconnections. In addition, its losses would represent a considerable waste of power, as projected in Table II. Naturally, these losses as well as the size and weight of the BFN can be reduced by simplifying the design, at the expense of some system flexibility. However, it appears attractive to look at an alternate form for the BFN—an active BFN, similar in principle to a phased array with separate amplifiers at each antenna element.

III. Design Considerations for an Active MBA

A. *Transmit*

An active MBA is best treated as two separate problems, receive and transmit, since the requirements are much different for the two. For transmit, the higher power levels elicit concern over dc/RF efficiency, intermodulation, AM/PM conversion, filtering, and thermal control. A possible active BFN configuration for transmit is given in Fig. 8.

Design of the feed network will depend on an ultimate compromise between flexibility and complexity; one pos-

[1]The Japanese Communications Satellite for Experimental Purposes (CS) was launched in December 1977. It carries 6 *K*-band (20/30 GHz) and 2 *C*-band (4/6 GHz) transponders, each with 200-MHz bandwidth, and was designed to conduct various experiments in communication systems technology in these bands [8]. Two other Japanese satellites (ETS-II and ECS) also carry *K*-band equipment for various experiments [9], [10].

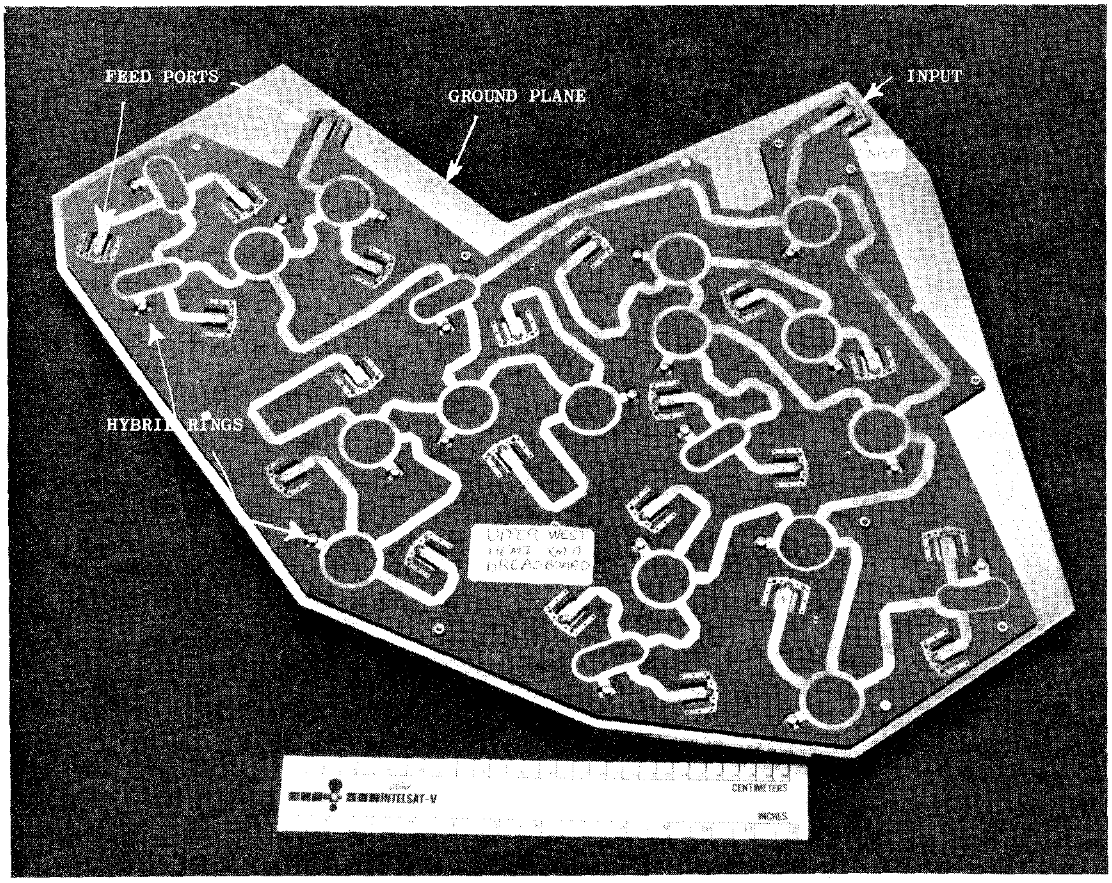

Fig. 6. INTELSAT V west-hemi transmit feed network.

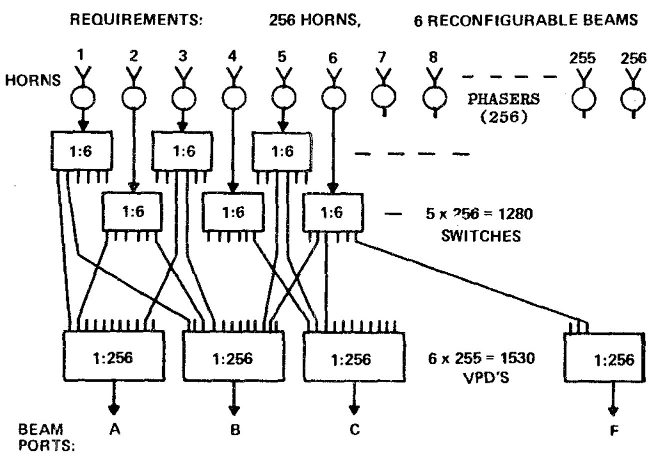

Fig. 7. Completely flexible six-beam BFN.

TABLE II
PROJECTED 256-BEAM BFN LOSSES

Band, GHz	4/6	11/14	20/30
VPD loss (8), dB	1.6	2.4	3.6
Switch losses, dB	0.5	0.8	1.2
Phaser loss, dB	0.4	0.5	0.8
Connection loss, B	0.5	0.8	1.2
Total loss, dB	3.0	4.5	6.8

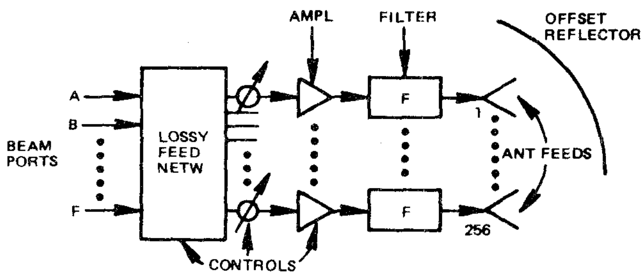

Fig. 8. Active transmit MBA.

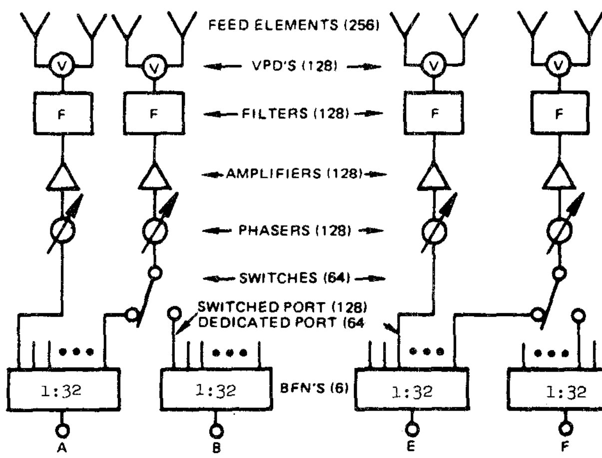

Fig. 9. Active transmit feed configuration.

sible compromise is pictured in Fig. 9. This circuit utilizes a 32:1 VPD network at each beam port, feeding 128 separate power amplifiers, each of whose outputs is shared between two feed elements, as determined by a set of 128 output VPD's. This network requires a total of 314 VPD's, 128 power amplifiers, 128 phasers and 64 switches. This reduced complexity is achieved by dedicating 22 feed elements to each beam, and allowing sets of 44 to be

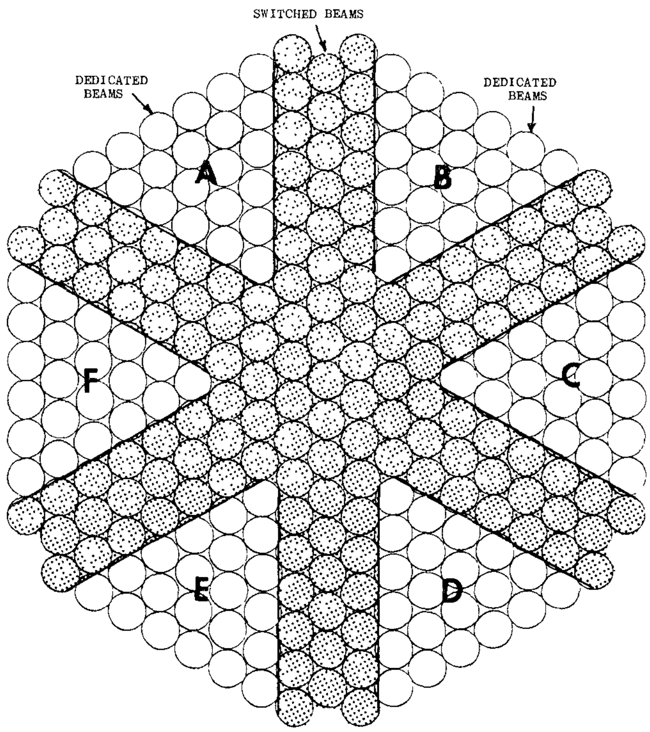

Fig. 10. Possible constituent beam assignments for forming six semiflexible shaped beams.

TABLE III
CHARACTERISTICS OF BFN POWER AMPLIFIERS

Band, GHz	4/6	11/14	20/30
Bandwidth, MHz	500	500*	2500
Type Amplifier	FET	FET	FET**
Output power, watts**	10	2-4	1-2
DC/RF Efficiency (at max. output)	35%	25%	14%

* WARC-79 will probably allow increase to 1 GHz.
** Projected to be feasible by 1982.

shared only by two adjacent beams. This choice allows each beam to be configured anywhere within one-fourth of the total coverage area, with a possible assignment of constituent beams as pictured in Fig. 10. Here the cross-hatched shared beams may be switched to either of the two adjacent shaped beams, *A-F*, while the entire array could be rotated to conform to a desired set of coverage areas.

Descriptions of major components and issues follow.

1) Amplifiers: The individual transmit amplifiers presumably should be solid state because of the large quantities involved and relatively modest power requirements. Projected characteristics for the various bands are listed in Table III, based on anticipated technology for the 1980–1982 period [11], [12]. Because of their superior linearity and efficiency, GaAs power FET's are the preferred transmit devices.

2) Filters: The transmit filters will be required to provide 80 to 100-dB rejection of transmitter noise/intermods over the receive band, with losses as low as possible. Five or six-section designs are indicated, using comb-line or microstrip at *C*-band, but probably requiring waveguide structures at 20 GHz to keep losses in the range of 0.3 to 0.4 dB. Units will have to be flat over the 500 to 2500-MHz passbands, and phase matched so that beam shapes do not vary with frequency.

TABLE IV
CHARACTERISTICS OF BFN PHASERS AND VPD'S

Type		Ferrite	Diode
Switching Speed		1-10 us	1-100 ns
Max. power, watts		10-100	1-10
Average drive power		Latching	100 mw
Phaser loss @	4 GHz	0.4	0.8
	12 GHz	0.6	1.2
	20 GHz	0.75	1.5
VPD loss @	4 GHz	0.25	1.0
	12 GHz	0.4	1.5
	20 GHz	0.5	2.0

3) Phasers and VPD's: These transmit control devices will be 4 to 6-bit digital types, with minimum losses. Depending upon switching speed requirements, they may be either ferrite or diode types, with projected characteristics as listed in Table IV [13]–[15].

4) Performance Factors:

a) Intermodulation: In this application, amplifiers must handle full 500 to 2500-MHz bandwidths, rather than the 40 MHz usually associated with channelized transponders. The potential for cross-talk caused by intermodulation products is great. The degree of the interference problem is highly dependent upon the types of signals in use, and may be addressed as follows:

1) Optimum signal architecture would utilize wide bandwidths with low spectral density so that interference approaches Gaussian noise in appearance.

2) FET power amplifiers are more linear than TWT's and require less back-off to achieve a given linearity. Since the power FET approaches class B operation, the dc consumption drops with reduced signal, giving the FET an additional efficiency advantage over the TWTA.

b) AM/PM conversion: Typically FET power amplifiers exhibit maximum phase variations of 2° to 2.5° per dB approaching saturation, with a total variation of 6° to 10°. Such variations should have a negligible effect on patterns of a MBA system. The effects of AM/PM conversion on signal fidelity are again a function of the type of signals, as discussed above.

c) Stability: Long-term amplitude and phase stability of the power amplifiers is of some concern regarding performance of the active MBA system. Measurements show such long-term variations to be of a gradual nature, easily correctible with the BFN either automatically (such as by temperature sensing) or with an active feedback system.

d) Thermal design: The thermal design of the active MBA system will be one of the key elements determining its success, because of the relatively large heat dissipation by the power amplifiers within a confined space. A 10-W *C*-band unit operating at 35-percent efficiency will have to dissipate 18.6 W, so that the total BFN dissipation would approach a kilowatt if half the 128 amplifiers are

TABLE V
TRANSMIT BEAM CHARACTERISTICS

Band, GHz	4	12	20
Post-amplifier loss, dB	0.6	0.8	1.0
Max. pwr/element, watts	8	3	1.6
Ave. pwr/beam, watts (20 elements)	60	22	10
DC power/beam, watts	300	160	140
EIRP @ beam edge, dbw	52	47	44
Max. EIRP/singlet, dbw	56	52	49
Net DC/RF efficiency	20%	14%	7%
Passive BFN efficiency*	14%	10%	7%
TWT power req'd, watts	130	70	50
Active BFN improvement	6%	4%	0

*Assuming 40% TWT efficiency

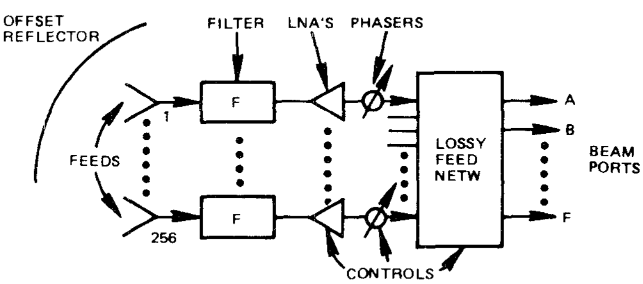

Fig. 11. Active receive MBA.

operating simultaneously. This may call for an active thermal control system using heat pipes.

e) Overall beam characteristics: The overall characteristics of the active MBA system are summarized in Table V for the three bands, assuming that each beam utilizes 20 feed elements, 12 operating at full power and 8 at reduced levels, to produce the total beam powers as listed, including losses following each amplifier. These powers are the maximum available per beam of the given size; higher levels are achievable using additional amplifiers (one at each feed element, rather than one per pair), or lower levels using power amplifiers. Final choice for a satellite design will depend somewhat on available dc power, as implementation of six such beams would require a total of up to 1.8 kW. Effective radiated power levels at the edges of each beam are quite high, since the peak antenna gain is estimated as 37 dB, nearly 20 dB higher than that of an equivalent earth-coverage beam.

A comparison of this active MBA concept with an equivalent system using TWT power amplifiers is in order at this point. The latter entries in Table V show that TWT's with power levels of 50 to 130 W would be required for the same EIRP's, and that the efficiencies of all but the 20 GHz active systems would be higher, by about 1.5 dB. Performance of the 20 GHz active MBA is penalized by low efficiencies of the solid-state amplifiers.

The active MBA exhibits one additional advantage over the TWT version, relative to reliability. If one amplifier fails, only 5 to 10 percent of the beam it serves will be affected. This loss may be alleviated by rearranging power levels to adjacent feeds, or by incorporating some redundancy into the BFN.

TABLE VI
CHARACTERISTICS OF BFN PREAMPLIFIERS

Band, GHz	6	14	30
Type Amplifier	FET	FET	FET/mixer
Noise Figure, dB	3-4	4-6	6-10
DC power, watts	0.1	0.1	0.1-1

B. Receive

The receiving portion of the MBA should preferably be a separate structure to avoid diplexing at each feed element, and to reduce filtering requirements by providing at least 50 dB of spatial isolation. The form of the receive portion of an active MBA is pictured in Fig. 11; it is similar to the transmit, with low-noise preamplifiers in place of power types. Characteristics of available preamplifiers are listed in Table VI for the bands of interest. GaAs FET's are usable in all bands, but the 30-GHz band may use direct mixers with slightly poorer noise, to allow the BFN to be built at *C* or *X* band.

The receive BFN could incorporate 256 preamplifiers, one at each feed element, or powers from pairs could be combined as on transmit (see Fig. 9) to reduce the number of amplifiers to 128. Their power consumption is so low that size and weight considerations would probably prevail, as well as the flexibility of individual element phase control.

Filtering to suppress the transmit signals to an acceptable level should require only 60-dB rejection. Filters of the same type as transmit will be usable, with 3 or 4 sections. Phasers and VPD's will also be similar, with slightly higher losses. The same linearity and stability requirements will apply, especially if any signal cancellation techniques are to be used for interference suppression.

IV. CONCLUSIONS

In summary, an active MBA would exhibit many advantages over a tube type with a lossy BFN, for a system with many constituent beams. Even dc/RF efficiency can be improved with an active MBA. Power supply and thermal design considerations will be the major limitations in satellite design.

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Shallow Bulk Acoustic Wave Progress and Prospects

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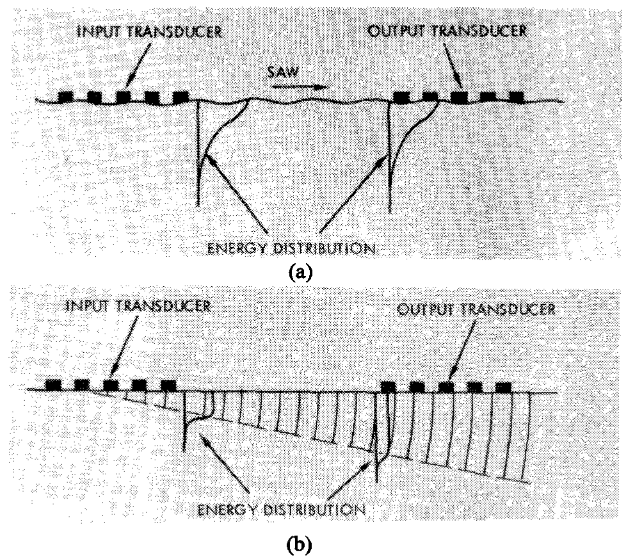
***Abstract*—Shallow bulk acoustic wave propagation in piezoelectric crystals is reviewed from the standpoint of work reported to date. It is compared to bulk and surface acoustic waves as to properties and device potential. Singly and doubly rotated cuts are considered, as are piezoelectric transduction, energy trapping, equivalent networks, as well as areas of future work such as new materials other than quartz, and nonlinear effects.**

I. Introduction

THE PAST 15 years have brought about a revolution in frequency control and acoustic signal-processing capabilities. This has been due in large measure to the development of surface acoustic wave (SAW) devices [1]–[7]. These have supplemented, and in some cases taken over various functions formerly performed by bulk acoustic wave (BAW) devices [8], particularly in the area of filtering. At the same time, SAW technology expanded to create entirely new signal-processing capabilities based on the availability of the wave as a spatially distributed function at the crystal surface. Bulk-wave components, meanwhile, had also found new uses. Foremost among these are new cuts that exhibit compensation of nonlinear elastic effects, leading to resonators that are ultrastable even under severe environmental conditions. Both BAW and SAW devices profit from the favorable electromagnetic/acoustic velocity ratio which assures significant miniaturization and decreased weight with respect to the corresponding electromagnetic devices.

More recently, attention has been given to a new type of acoustic-wave device, utilizing bulk waves that travel nearly parallel to the crystal surface. These are known as shallow bulk acoustic waves (SBAW), or as surface skimming bulk waves (SSBW), and are the topic of this paper. Most of the work reported to date is due to Lewis and his colleagues [9]–[19] and the group under Kagiwada [19]–[29]. Other applicable analyses are due to Mitchell [30], Wagers [31], Jhunjhunwala *et al.* [32], and Lee [33].



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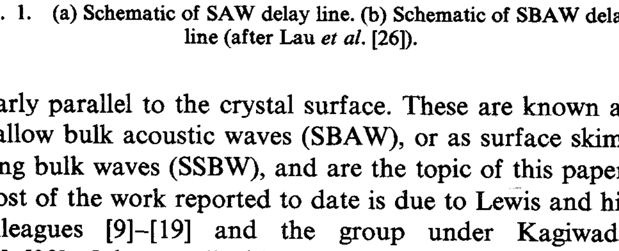

(b)

Fig. 1. (a) Schematic of SAW delay line. (b) Schematic of SBAW delay line (after Lau *et al.* [26]).

Of particular importance to the operation of SBAW components is the interdigital transducer (IDT), consisting of interleaved electrode strips, between which the generating electric field is applied via a signal source, or the received field is detected. The IDT array was first applied to the production of BAW signals [34], [35], then

Manuscript received April 30,1979; revised July 10, 1979.
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