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I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER.(U)

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I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER

Robert R. Moats
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This program is directed toward development of an I/J band, linear format, injected-beam crossed-field amplifier (IBCFA) for electronic warfare. The IBCFA should be capable of power output of 1000W peak, 200W average, between 8.5 and 17 GHz with 20dB gain. A laser-cut shaped-substrate meander line is used.

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20) The performance objectives for E/F band CFAs include 3kW peak pulse power output and 1kW average power output, 20dB gain, 2-4GHz, for electronic warfare; and 2kW peak pulse power output at 10-15% duty, 25dB gain, 3.0 to 3.6 GHz, for phased-array radar.

The first E/F band tube built on this contract showed performance at low duty substantially like the previous CFA built with a laser-cut substrate when tested under electronic warfare conditions, and in addition performed well at 33% duty. For the phased array conditions, gain was too low. A second E/F band tube, built with a longer circuit to increase gain, failed when the substrate cracked and separated from the ground plane.

An I/J band tube was built and tested. The sequence of construction of the circuit with laser cut substrate was revised to reduce breakage, and was demonstrated successfully. However, performance was poor primarily because of excessive RF losses in the circuit. Future efforts will require a review of the factors causing high RF losses.

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SECTION I
INTRODUCTION

The effort in this program was directed toward the development of a high-power broad-band low-cost I/J-band linear format crossed-field amplifier (CFA) for electronic warfare. A laser-cut shaped substrate meander line circuit is used. In addition, E/F-band CFA's of similar construction were built which can be applied either to electronic warfare or phased-array radar.

The laser-cut shaped-substrate meander circuit, a concept originated by ERADCOM personnel, is potentially a major cost saving measure, replacing a set of 80 or more individual insulators with a single part. Furthermore, the individual insulators for I/J-band would be so small as to be impractical.

The objective specifications for the E/F-band operating model for electronic warfare are as follows:

Frequency	2-4 GHz
Peak Power Output	3 kW
Average Power Output	1 kW
Efficiency	35%
Gain	20 dB
Cathode Voltage	7 kV
RF Input Impedance	50 ohms.

The phased array objectives are as follows:

Frequency Range	3.0-3.6 GHz
Peak Power Output	2 kW
Duty	10-15%
Pulse duration capability with grid pulsing	100μsec
Grid cutoff voltage	1 kV max
Efficiency (incl. heater)	30% min
Gain	23 dB min
Line-to-sole voltage	10 kV max
In-band power variation	± 0.5 dB
Input/output connectors	Coaxial
Production cost objective	$1,000 max

The performance objectives for I/J-band are as follows:

Frequency Range	8.5 - 17 GHz
Peak Power Output	1 kW
Average Power Output	200 W
Efficiency	30%
Gain	20 dB
Cathode Voltage	8 kV, max
Input Impedance	50 ohms

In previous programs for ERADCOM, the shaped-substrate concept was demonstrated successfully in E/F-band devices. The first embodiment of this concept incorporated simulated shaped substrates made up of individual ceramic insulators.[1] This work was then followed by the construction of E/F-band IBCFA's incorporating laser-cut ladder-shaped substrates, where the resulting electrical performance was comparable to that observed in IBCFA's of conventional construction.[2] Concurrently, I/J-band cold test models with laser-cut substrates were built and tested. In I/J-band, the most serious problems were the fragility of the substrates and the high RF losses observed, especially after brazing.

The E/F-band tubes for the present program were similar to those built previously.[2] In the first, there were no changes from the previous design, and performance characteristics were similar. In addition, this tube was operated successfully at 33% duty. The second E/F-band tube, with the circuit a little longer to increase gain for the phased-array mode, failed at test because of a substrate bonding problem. This problem, not observed before, is considered correctible.

To overcome the fragility problem of I/J-band substrates, a different sequence of operations was undertaken. The substrate was bonded to the co-expansive ground plane before laser cutting. After some refinement of the laser-cutting procedure, substrates suitable for I/J-band operating tubes were successfully laser-cut. Operating performance was poor because of high circuit losses. The substrate was still very fragile at the corners where RF connections were made to the input and output. At these locations, the substrate is not supported by the ground plane.

The laser-cut shaped-substrate meander circuit has been demonstrated to be viable at least in E/F-band. In I/J-band, the realization of successful meander circuits must still overcome the primary problem of circuit losses which is not yet understood, and also must overcome some problems related to the small size of the structures.

SECTION II
INITIAL STATUS

2.1 Technology

A major part of the effort on the previous contract [2] was the development of the necessary technology for fabricating the laser-cut shaped substrates, and for the assembly of the substrate with the co-expansive ground plane and the meander circuit. The general concept is shown in Figure 1. It was found to be necessary to metallize the blank ceramic coupon before laser-cutting. Since the laser (CO_2) will not cut through copper, the metallized layer was etched in a meander pattern on one side, and laser cutting was performed where the metallizing was etched away. The resulting ladder-shaped substrates are quite fragile. It was possible to cope with E/F-band substrates by handling them with great care, but the breakage rate of I/J-band substrates was extreme. Some preliminary experiments showed that it was possible to laser-cut the I/J band substrate after it was bonded to the co-expansive ground plane. In principle, what happens is that the beam from the CO_2 laser cuts through the BeO ceramic, but is reflected by the copper surface of the ground plane. The reflected energy is scattered to an extent that its intensity is too low to melt any more BeO. Preliminary experiments were performed in which slots were cut in blank pieces of BeO ceramic, 0.006" thick, bonded to a co-expansive ground plane. After some adjustments of

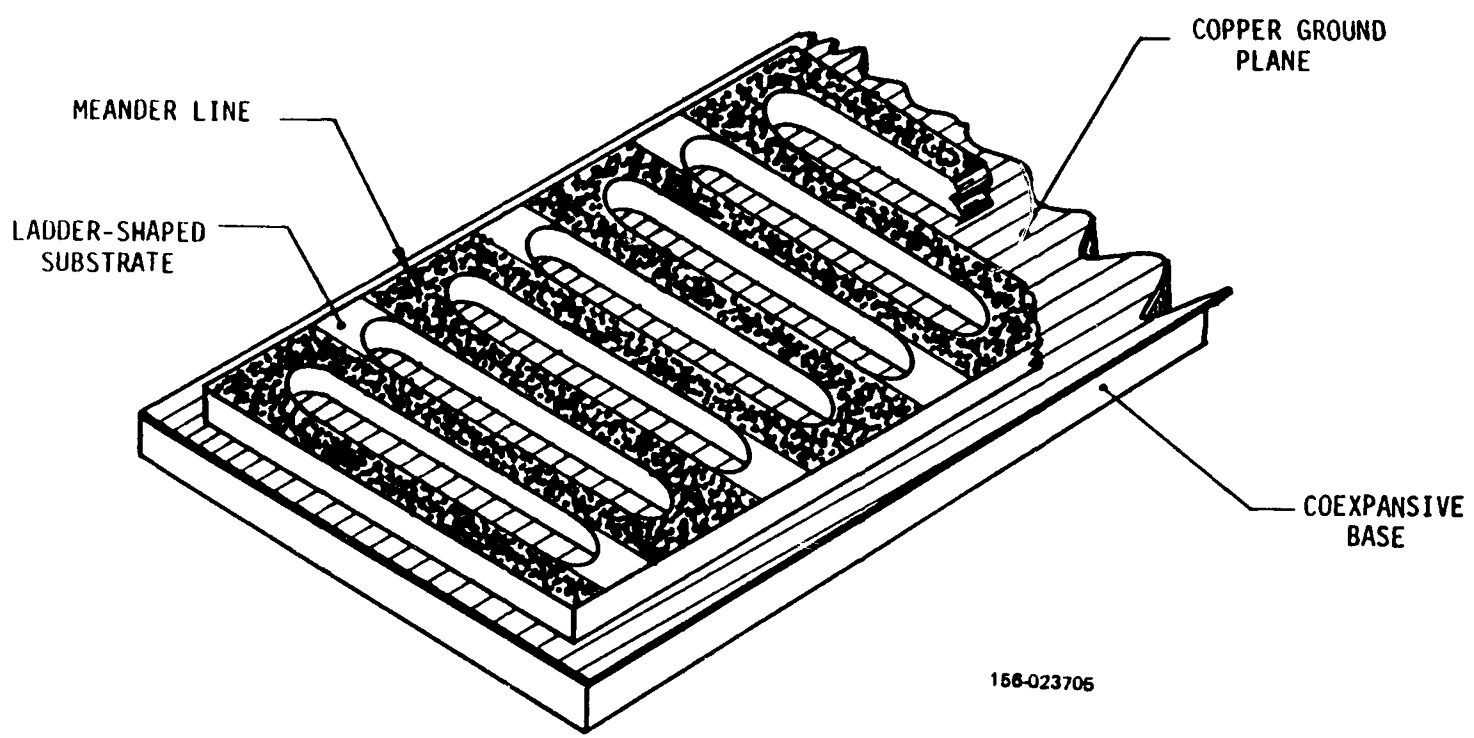

Figure 1. Meander Line on Ladder-Shaped Substrate and Coexpansive Base.

the laser settings, the quality of the slots cut appeared quite satisfactory. This experiment did not take into account the effect of the metallized meander pattern which would be present in an actual substrate for a meander circuit. However, the work pointed the way for further efforts of this kind.

Bonding of the substrate to the co-expansive ground plane was satisfactory provided that the composition of the ground plane material is 68% tungsten, 32% copper by volume.

2.2 E/F-Band CFA's

Two E/F-band CFA's with ladder-shaped substrates have been built and tested. The first showed peak power, efficiency, and bandwidth comparable with a CFA of conventional design, Northrop's RW-619. Results are shown in Figure 2.

The second was apparently limited in peak power output by RF arcing. Such arcing was observed not only when the tube was operating, but also when RF power was fed in from an external source. When this tube was disassembled for inspection, it was found that the ceramic which supports the lead from the input window to the meander circuit had broken loose, evidently from inadequate brazing.

2.3 I/J-Band Cold-Test Models

The two I/J-band cold-test models were scaled from the ERADCOM E/F-band design, using a scale factor of 4/17 with respect to bar width so that the expected frequency corresponding to 90° phase shift per bar was about 14 GHz. The pitch

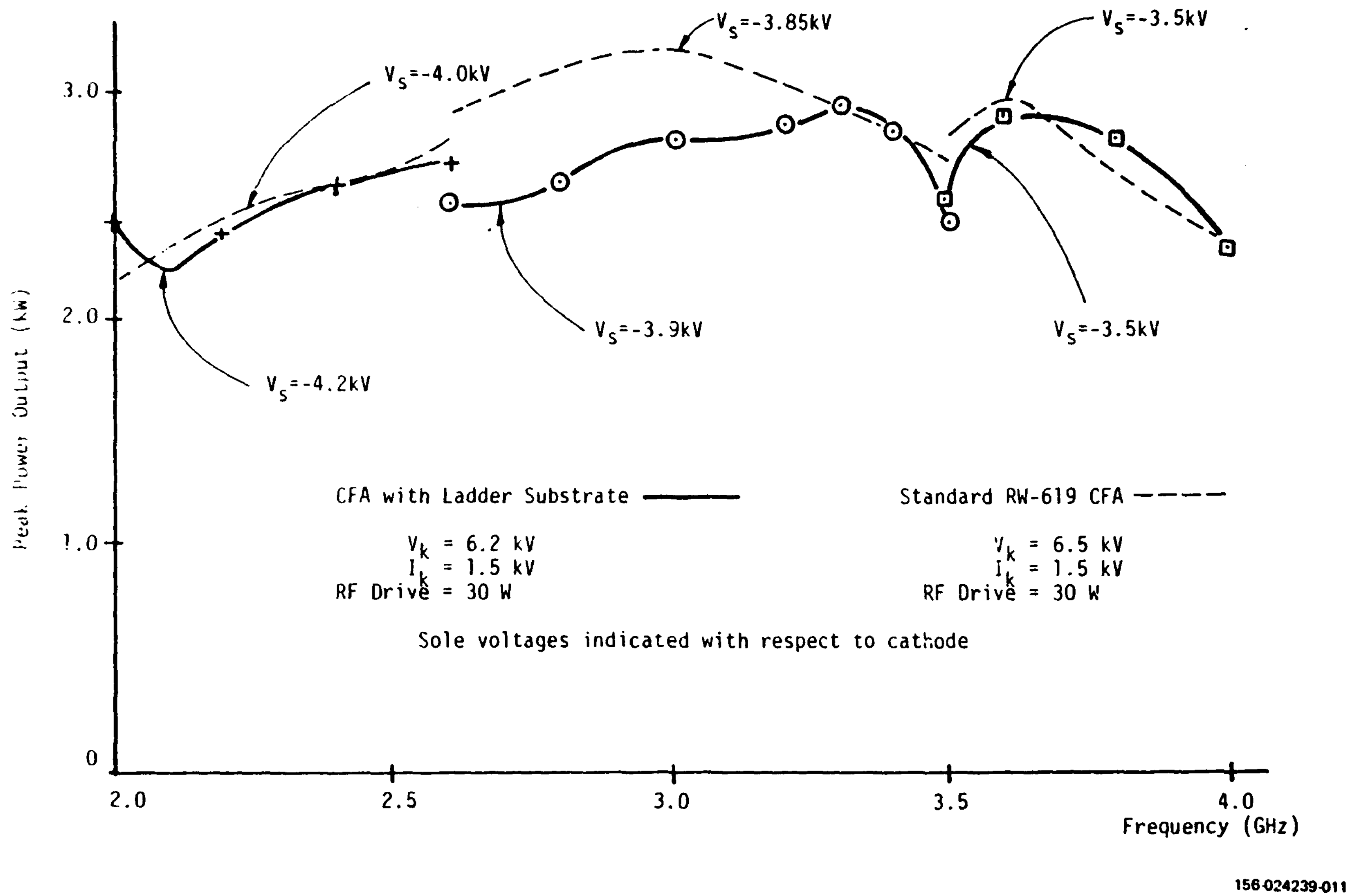

Figure 2. Power Output of CFA No. 1 with Ladder-Shaped Substrate (Previously Built Model).

was further modified so that the delay ratio would be about 12 at this frequency, a value considered appropriate for operation at a cathode voltage of 8 kV. Using these scale factors, pitch was 0.018", and to maintain the same pitch-to-thickness ratio the thickness should be about 0.006".

The first cold test model was made with an unmetallized substrate 0.010" thick. The substrate was cemented to a ground plane and a photo-etched meander circuit was cemented to the top. Greater dispersion than desired was observed, as expected from the greater substrate thickness. Losses, on the basis of dB per delayed wavelength, were approximately as expected on the basis of surface resistivity increasing as the square root of frequency.

The second cold-test model was made with a metallized substrate 0.006" thick, which was bonded to a co-expansive ground plane, and a photo-etched meander was then bonded to the substrate. Losses were much greater, and the delay ratio was much greater. The reasons for these differences from the first I/J-band cold-test model and from the E/F-band circuits were not clear at the time. The difference in delay ratio was subsequently accounted for by a new method of computer analysis developed under Air Force support[3] and summarized in the Second Interim Technical Report of this contract (Report DELET-TR-78-2981-2). The increase in losses was only in part accounted for by this computer analysis. It now seemed possible that the brazing process somehow adds to the losses.

SECTION III

E/F-BAND TUBES

The first E/F-Band CFA in this program was built using the same length circuit as those previously built. Test results for the electronic warfare mode (1.5A peak beam current) are shown in Figure 3 for both 10% duty and 33% duty. Operation at 33% duty was quite uneventful. At 33% duty, mid-band power was slightly less than at 10%, perhaps because the sole voltage setting favored the lower end of the mid-band segment (2.6 - 2.8 GHz). From 2 to 2.6 GHz, power output was strongly dependent on RF drive power. Power output as a function of RF drive in this frequency range is shown in Figure 4. For the electronic warfare mode, the results show substantially the same power output and efficiency at mid-band as the previously built CFA of this design, the first ever with a laser-cut substrate, for which results were shown in Figure 2. At the high frequency end of the band power output and efficiency in the present CFA are better, and they are not as good at the low-frequency end of the band. Because of defects in brazing, the previously built E/F-band CFA was not tested at full duty of 33%.

Results for the phased-array mode are shown in Figure 5. Magnetic field and applied voltages have been reduced to optimize performance at the lower power level. Even so, gain is too low as indicated by the curves in the figure for different RF drive levels.

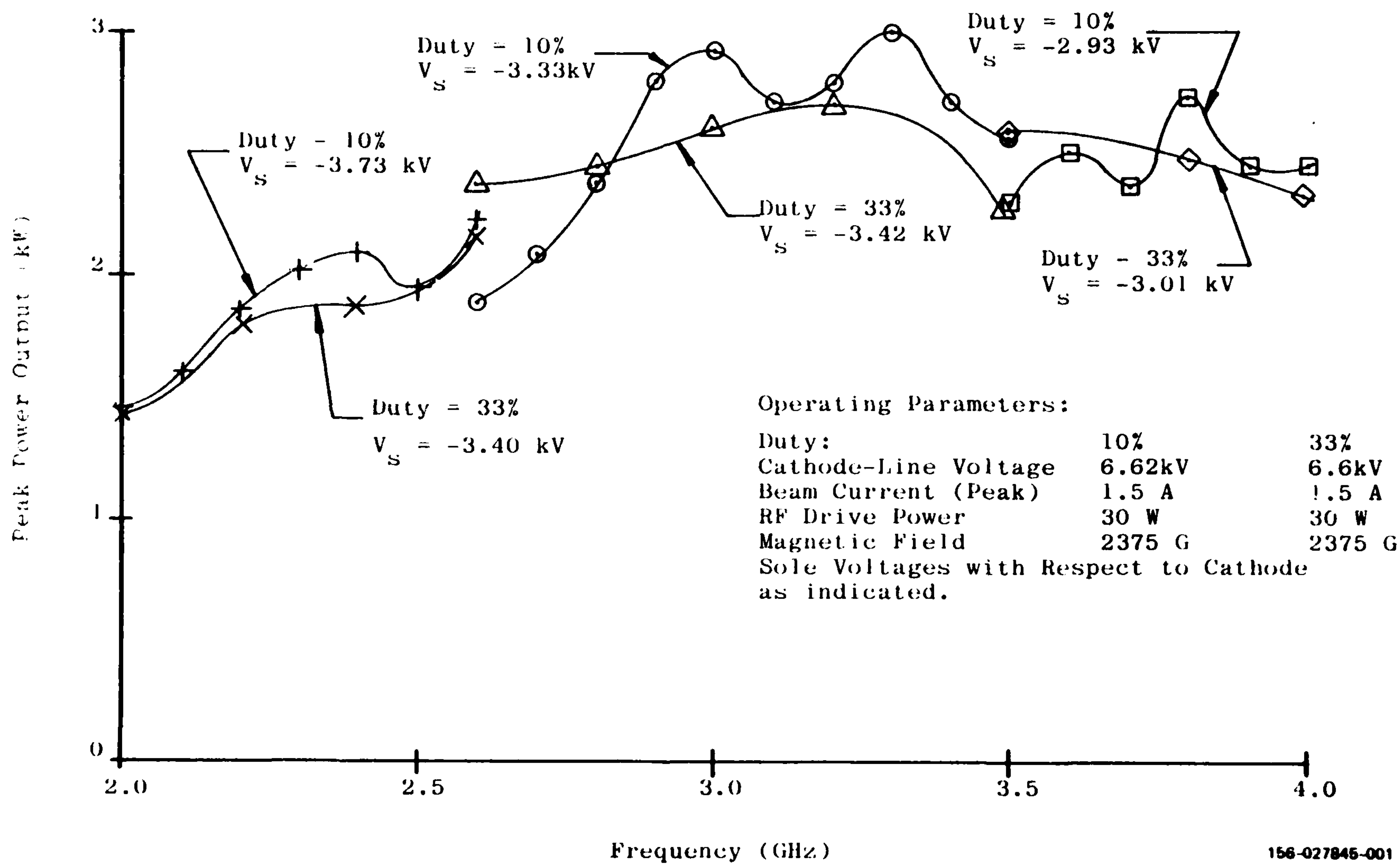

Figure 3. Power Output vs. Frequency, E/F-Band CFA

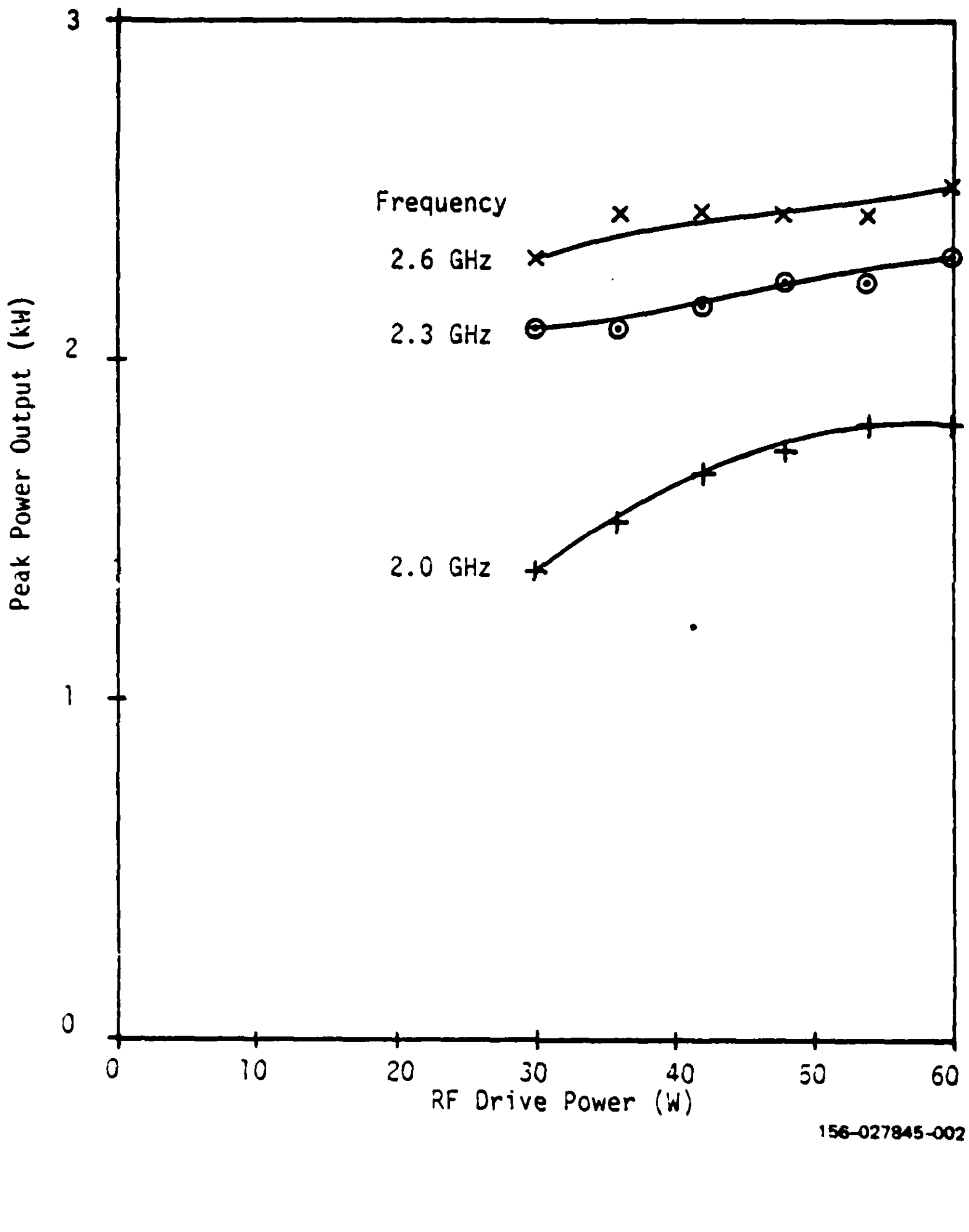

Figure 4. Power Output vs. RF Drive, E/F Band CFA.

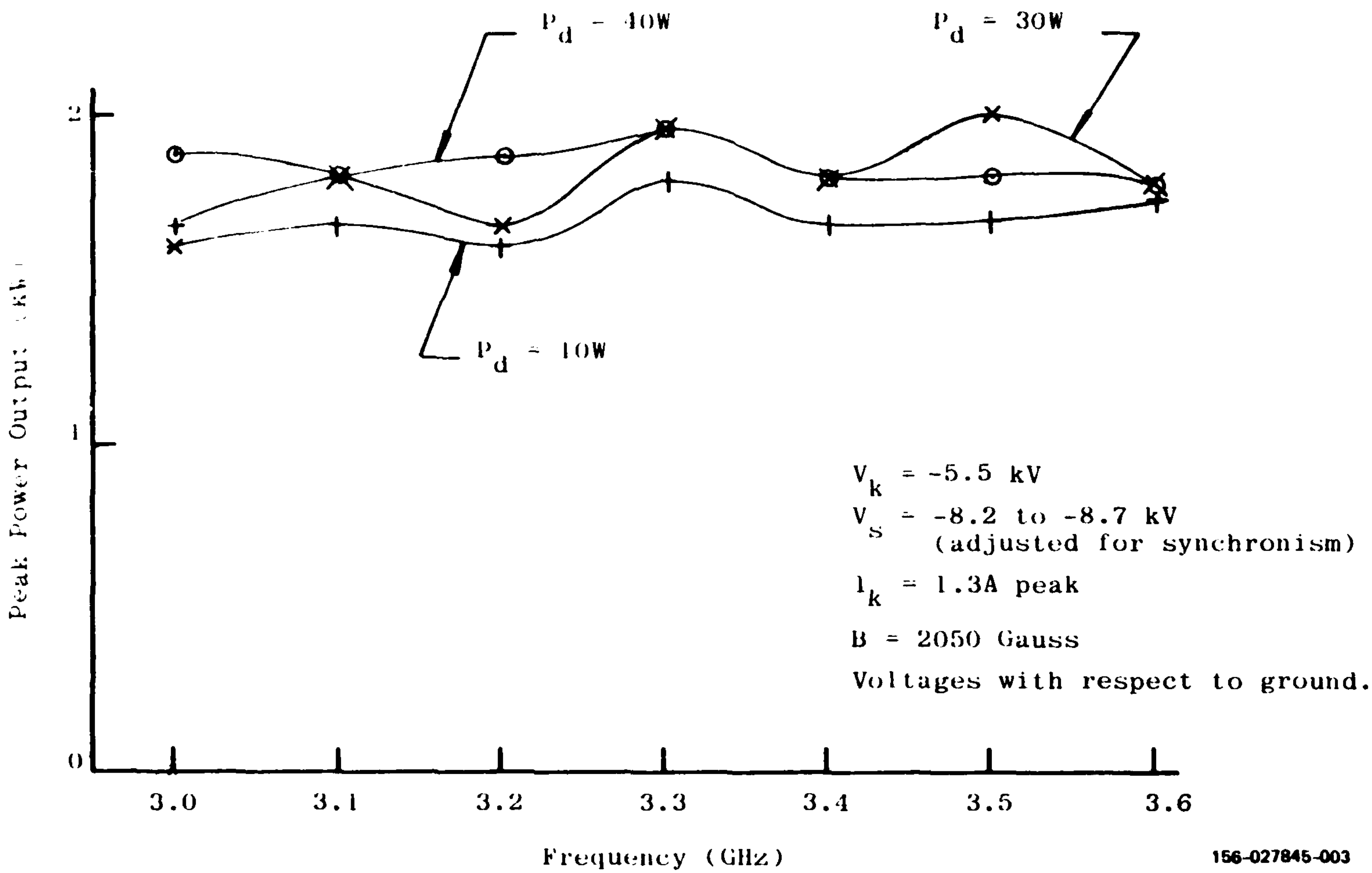

Figure 5. Performance in Phased-Array Mode

Data from the previously built E/F-band CFA also showed the need for increased gain[2]. It was therefore concluded that the circuit length should be increased, for performance both in the 2-2.6 GHz range in the electronic warfare mode and also in the phased-array-mode.

The second E/F-band CFA in this program incorporated a circuit six bars longer than before. Thermal tests of the circuit were the best yet measured. (Thermal tests are made by passing 30 to 40A through the meander circuit, 60Hz, with the base block cooled, and measuring the temperature difference between the meander and the ground plane by thermocouple.) After exhaust, this tube was not operable at all because of severe arcing. When this tube was opened for examination, it was found that the last cross bar of the ladder-shaped substrate, at the output end, had broken off and separated from the ground plane, causing a break in the meander as well. In addition, there was a line of cracks, which were not disabling to the functioning of the meander circuit, in the cross bars over the half of the substrate toward the output and about 1/8" from the edge. The last bar of the substrate evidently broke off during the exhaust and bake-out cycle where it was subjected to a maximum temperature of 500°C. During the bonding cycle, the same assembly had been subjected to temperatures up to 1050°C while constrained by the fixture. This kind of problem has not been encountered before. Possible corrective measures include extending the ground plane slightly farther lengthwise beyond the ends of the substrate, and also further investigation of the ground plane material. Appropriate experiments on mock-ups of these assemblies are needed.

SECTION IV

I/J-BAND TUBES

4.1 Technology

The most crucial aspect of the I/J-band tube development is the technology of fabricating the meander circuits. During the course of the present contract, a revision in the sequence of operations for construction of the meander assembly was implemented. It had been found almost impossible to handle the laser-cut ceramic substrates of I/J-band dimensions through the various operations necessary to construct the meander assembly without breakage at one step or another. There was difficulty with the E/F circuits because of fragility, but this was of manageable proportions.

In the revised sequence, the ceramic substrate is bonded to the ground plane before laser cutting but with the meander pattern already formed by photo-etching on the side opposite that to which the ground plane is attached. Laser cutting in this sequence is possible because the beam generated by the CO_2 laser cuts the BeO ceramic effectively, but is almost totally reflected by the copper surface of the ground plane and stops cutting when it reaches the ground plane. For this procedure to work properly, it is necessary that when the laser beam hits bottom [illegible] all the way through the

BeO), no copper is moved. Such a requirement depends upon the laser light which strikes the copper being reflected in a diffuse manner such that it does not cut any more BeO. Further, it is necessary that when cutting the BeO close to the copper that whatever copper is evaporated by conduction from the hot BeO recondenses on the BeO to such a small extent that it does not adversely affect the insulation qualities of the freshly cut BeO surface.

Establishing an adequate vendor to perform the laser cutting presented some unexpected problems. The requirements included (1) equipment, (2) experience, and (3) flexibility. Critical items with respect to equipment included not only an adequate CO_2 laser, but also an x-y table of sufficient accuracy, viewing optics for location, and proper focusing of the laser beam. A lens of 1.5" focal length on a Coherent CO_2 laser produces a spot size of 0.002" to 0.003" diameter while a lens of 2.5" focal length produces a spot size of 0.004" to 0.005" diameter. The smaller diameter is quite advantageous for I/J-band structures, where the groove width may be as small as 0.007". Two vendors, Lasermation, Inc., of Philadelphia, and Laser Services, Inc. of North Billerica, MA, were used previously. Lasermation lacked flexibility because of their substantial production volume. Laser Services did not have an x-y table of sufficient accuracy. Only Laser Services used the 1.5" focal length lens. A number of other possible vendors were contacted, and found to be deficient in experience and/or equipment. Eventually Laser Services acquired a very accurate x-y table, making it possible for them to perform the work necessary for I/J-band.

The sequence of steps finally adopted for making the I/J-band meander circuit is the following:

(1) Metallization of blank ceramic coupon (both sides). Coupon may be large enough to make several meanders.

(2) Photo-etch meander pattern(s) on one side.

(3) Cut coupon to final size of individual substrate(s).

(4) Bond to co-expansive ground plane.

(5) Laser cut.

(6) Add copper meander circuit.

In the course of performing the laser cutting, the distribution of beam intensity over the cross section of the spot was found to be a factor. The top portion of Figure 6 illustrates the distribution of light intensity as a function of position. The result was that the edges of the cut were ragged, and it is necessary that they be sharp at the edge of the metallization. To make the beam sharper, an iris was made and inserted into the optics to sharpen the edges of the beam. With the improved beam sharpness, three meander circuits were laser cut successfully after the substrates were

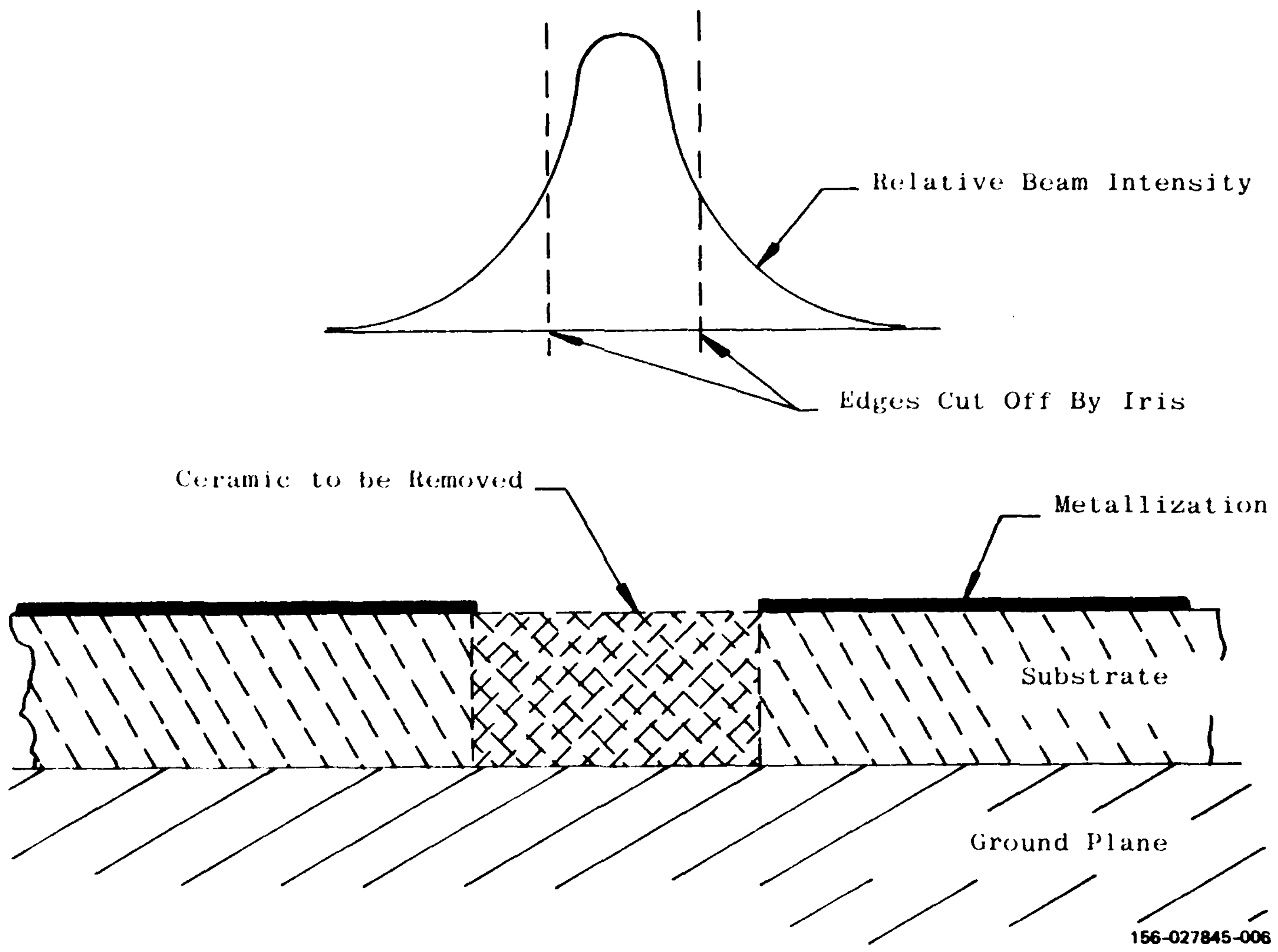

Figure 6. Laser Spot Size Control

bonded to the ground plane. Two were usable in operating tubes, and one was not because a corner of the ceramic broke off where it was unsupported by the ground plane in the area provided for input or output connection. The iris did not improve the laser cutting when tried with substrates not bonded to a ground plane.

An effort was made to simplify further the construction procedure. A sheet of copper is bonded to one side of the substrate after metallizing, and then the etching process removes both copper and metallization to form the meander. It was expected that such a procedure would eliminate the need for the add-on meander. Results were disappointing. After laser cutting, the edges of the copper meander (0.001" thick) were not well defined, and it was considered necessary to add on a photo-etched meander in the same manner as without the added sheet of copper. One of the two good laser-cut meander circuits was made this way.

The ceramic-to-metal bonding in all of these cases depends on sputter metallization, which consists of a layer of titanium about 250 Angstroms thick, a layer of molybdenum, and a relatively thick layer of copper.[4,5] The molybdenum serves as a barrier layer to keep the copper from getting into the grain boundaries of the BeO ceramic, which has been observed to occur at temperatures in the vicinity of 1000°C. The bonding of the metallized ceramic to the copper is accomplished by copper-to-copper diffusion at high temperature and under pressure. The result is an interface which adds very little to the RF losses. For I/J-band, the molybdenum layer is kept to a thickness of 3000 Angstroms or less to avoid excessive contribution to the losses [6]. The copper layer is typically 10,000 Angstroms or more.

4.2 Cold-test Results

In this section we are summarizing the cold-test measurements made on the present contract and also on the previous contract to provide as complete an over-all picture as possible. Results are included for three different models made specifically for cold tests, and for the operating I/J-band CFA as well.

The first I/J-band cold test model to be built had an unmetallized BeO substrate 0.010" thick which had a pitch of 0.018". The substrate was cemented to a base, and a photo-etched meander was cemented on top. In this model, as in all of the others made for cold test only, input or output matching was rather simple-minded, consisting only of a wire between the meander and an OSSM connector. There was at each end of the circuit a copper block with an edge parallel to the first (last) meander bar which could be adjusted in position to improve the match. In this model, the matching was at best only fair. It was however possible to make a direct measurement of attenuation.*

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* Report No. DELET-TR-77-2642-2 Second Interim Report on Contract DAAOB-77-C-2642, December 1978, p 16.

Even without good matching, phase velocity is easily measured by the length of standing waves.

Cold-test models No. 2 and No. 3 were constructed with substrates of the same dimensions as the first except that the thickness was reduced to 0.006" to reduce dispersion. These assemblies of ground plane, substrate, and meander line were bonded together by copper-to-copper diffusion after Ti-Mo-Cu metallization. Model No. 2 was inadvertently bonded together with the side of the substrate which was metallized all over facing the meander. The meander was brazed on, and the excess metallizing then removed by etching. The etching process did not greatly affect the dimensions or the appearance of the meander, but the results, notably the high attenuation observed, were a little suspect. Model No. 3, with the same dimensions as No. 2, was therefore built and tested. An initial set of tests was performed without the meander added, the circuit consisting of only the meander pattern etched in the metallized surface, where attenuation was very high. Tests were repeated after adding a photo-etched copper meander 0.003" thick. There was a crack in the substrate about the middle of the circuit, but it was possible to take this discontinuity fully into account in making the measurements. Matching of both of these models was poor, and attenuation measurements depended on the Q of resonances which were intentionally introduced by loose external coupling at one end and no coupling at the other.

The fourth set of measurements presented here consists of the cold-test data on the operating CFA, where the pitch was reduced to 0.014" with a substrate 0.006" thick. This circuit had been made by laser cutting after bonding to the ground plane.

Table I summarizes the test results for phase velocities and attenuation. Attenuation is expressed in dB per slow wavelength as a standard of comparison. Experience has shown that efficient IBCFA's normally exhibit 0.25 dB per slow wavelength or less, and that values of more than 0.5 dB per slow wavelength lead to very poor results. In addition to measured values, calculated values based on Reference 3 are included.

In all cases, the phase velocities agreed quite well with the calculated values. When cold-test model No. 2 was first tested, the difference between the phase velocity of this circuit and that of model No. 1 was much greater than expected. However, after the computer program was developed [3], the difference was understandable, as shown by the calculated values in the table. The relative phase velocity for the operating CFA, not previously reported, is shown in Figure 7. Coupling impedance is shown in Figure 8.

Measured attenuation exceeds calculated attenuation by a considerable amount in all cases except No. 3, where measurements could be made only below 12 GHz. The difference is much more than observed in E/F band. The most severely excessive attenuation was observed in the circuit for the operating CFA, and the attenuation became especially severe

TABLE I

SUMMARY OF COLD TEST DATA

Circuit Dimensions (mils)				v_{ph}/c				Attenuation (dB per wavelength)			Remarks
Pitch	Substrate Thickness	Width	Meander Thickness	f (GHz)	Meas.	Calculated (W)	Calculated (S)	f (GHz)	Meas.	Calculated	
10	18	124	3	8.5	0.112	0.121	0.111	9	0.40	0.23	Cemented Together
				12	0.106	0.109	0.103	12	0.32	0.23	
				17	0.093	0.089	0.092	17	0.42	0.21	
6	18	124	3	8	0.094	0.097	0.091	10.7	0.88	0.31	Note 1.
				12	0.088	0.091	0.086	12.5	0.54	0.30	
				17	0.078	0.079	0.082	13.6	0.88	0.29	
6	18	124	3	8	0.095	0.097	0.091	8.35	0.34	0.33	Note 1.
				12	0.088	0.091	0.086	8.86	0.40	0.33	
				17	0.079	0.079	0.082	9.4	0.36	0.32	
								10.4	0.34	0.31	
								11.4	0.34	0.31	
6	14	122	3	8	0.085	0.091	0.083		0.59	0.36	Operating CFA.
				12	0.077	0.085	0.078		0.63	0.35	
				14	0.073	0.076	0.075		1.2	0.35	

Calculations by (W) - Weiss equations; (S) - Sobotka equations.

Note 1: Attenuation by Q of resonances.

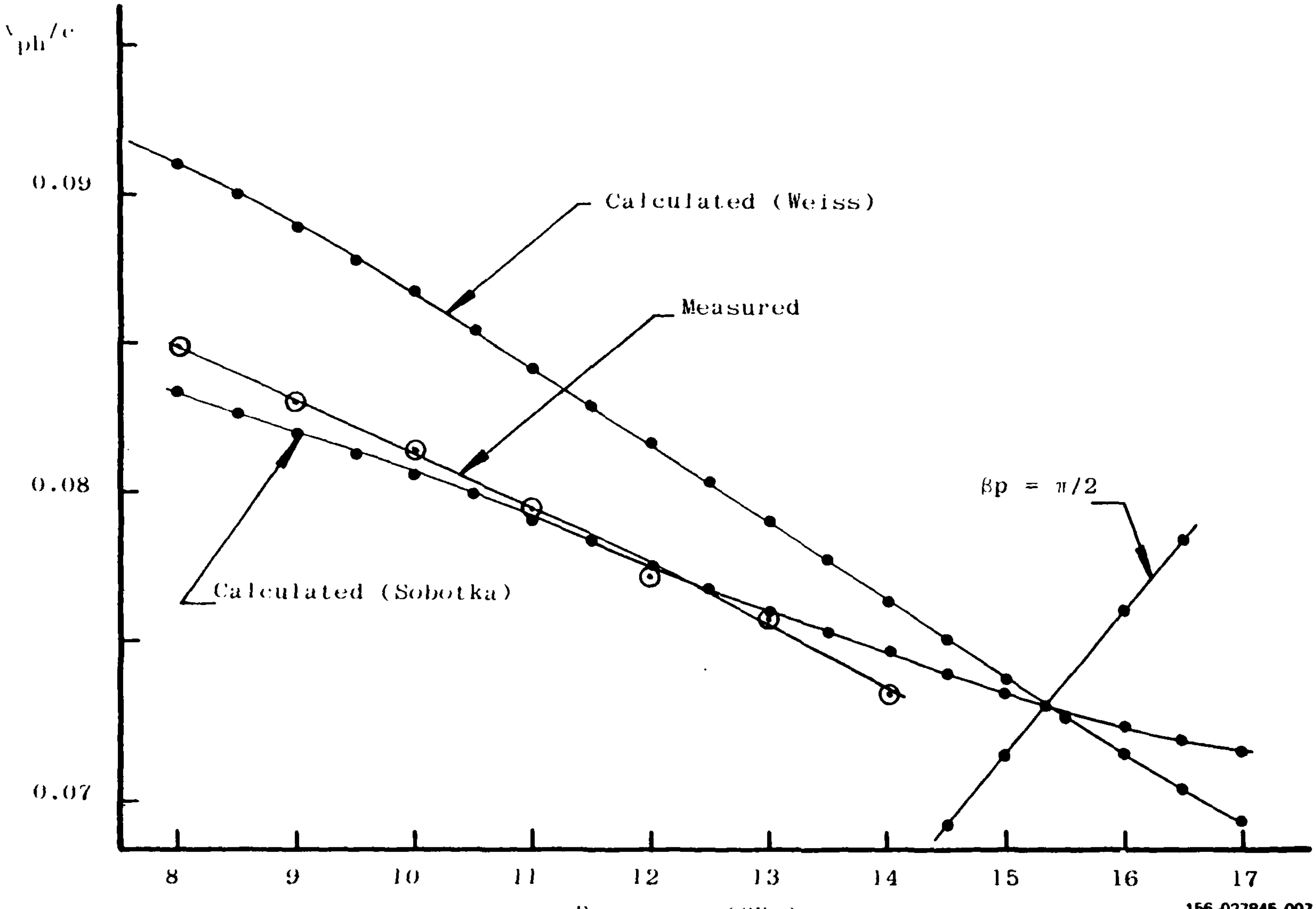

Figure 7. Phase Velocity of I/J-Band Circuit

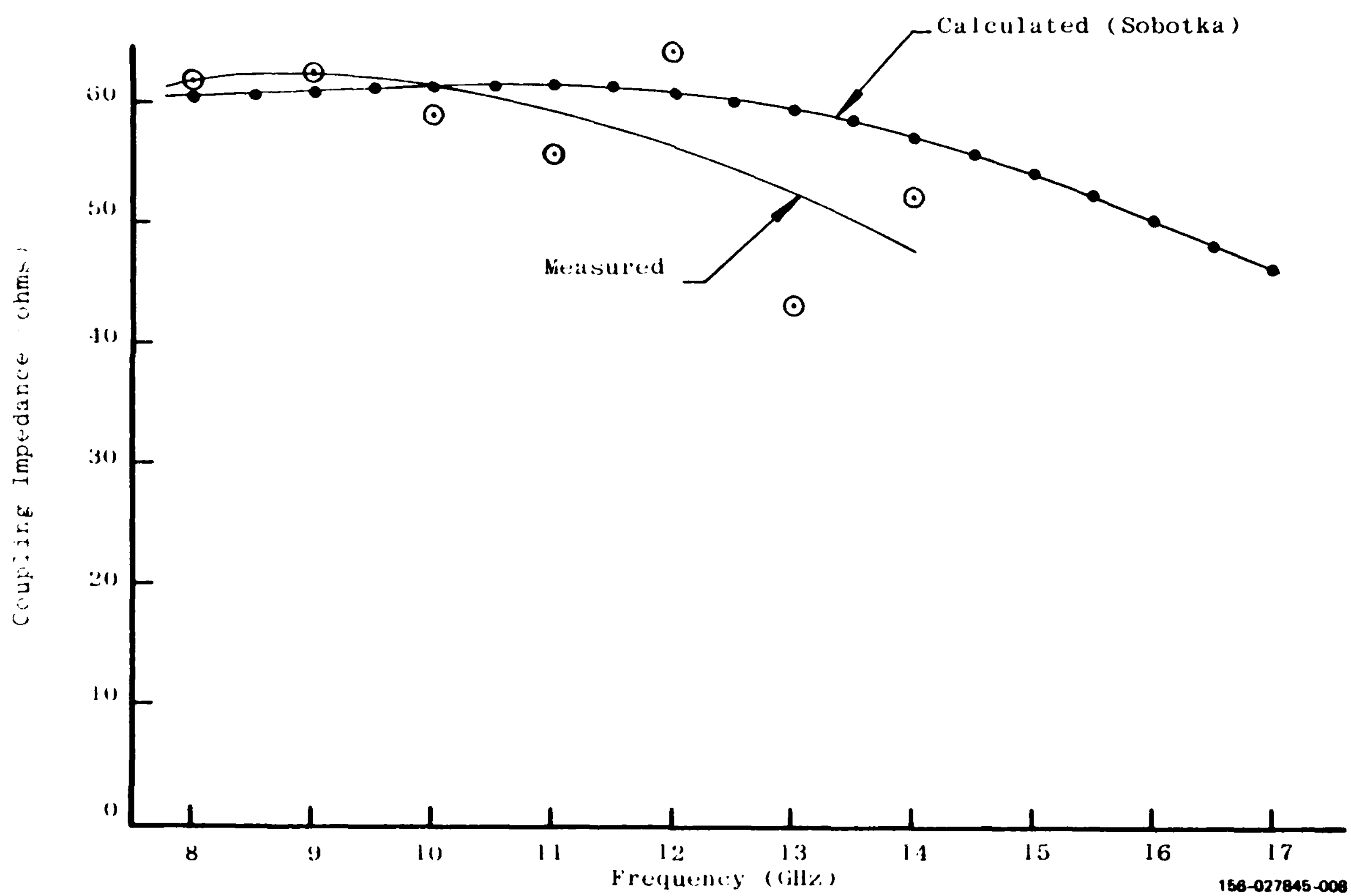

Figure 8. Coupling Impedance of I/J-Band Circuit

as phase shift per bar approached 90°. Measured attenuation of the circuit as first assembled is shown in Figure 9. The very high readings for insertion loss are worsened by very poor matching above 12 GHz. Input and output VSWR measurements are shown in Figure 10.

Some possible causes of excessive attenuation and suggested remedies are given below:

1) The laser cut edges of the substrate are slightly uneven where they meet the meander line, and alignment of the meander line with respect to these edges may be such that there is exposed metallizing, i.e., not covered by the line. A corrective measure is to let the meander line overhang the supporting ceramic on both sides.

2) There may be some residual molybdenum on the exposed faces of the substrate at its edges. The copper etchant does not remove molybdenum. The corrective action is more diligence in molybdenum removal. Also, consider whether the extremely thin titanium layer (only a few hundred Angstroms thick) causes a problem.

3) Determine whether a trace of copper penetrates the molybdenum barrier layer during bonding, thus increasing dielectric losses. Is the sputtered molybdenum layer truly continuous?

4) The insulating properties of the cut edge of the substrate may be degraded by laser cutting after bonding to the ground plane. Corrective action

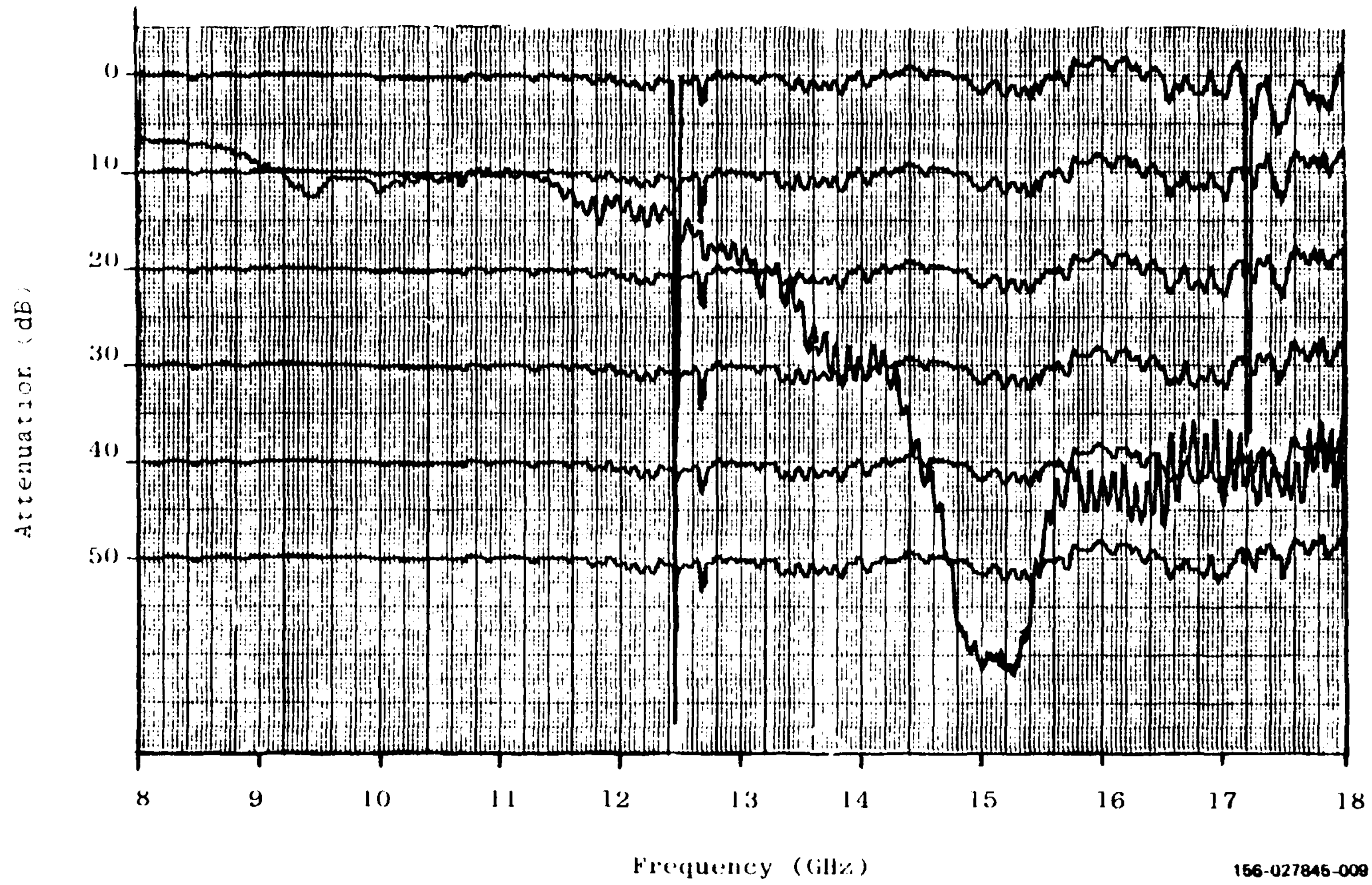

Figure 9. Attenuation of I/J-Band CFA (First Assembly)

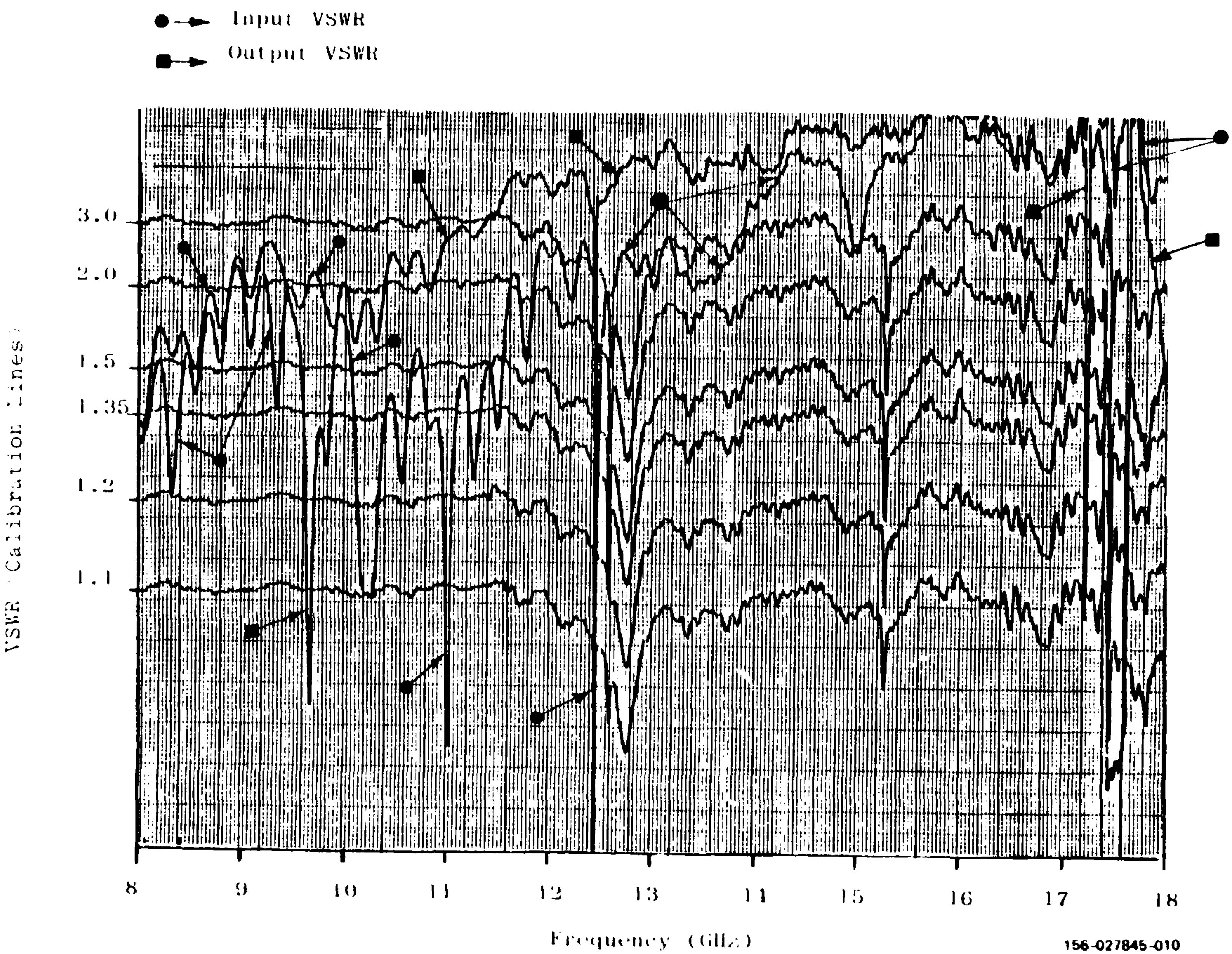

Figure 10. Input and Output Match of I/J-Band CFA

is to laser cut before bonding, at the same time looking to new methods of handling the laser-cut substrates to prevent breakage.

4.3 Input/Output Windows

A coaxial window design suitable for the required output power level frequencies up to 18 GHz was designed. The frequency limitation depends primarily on the TM_{01} mode, which is excited by the step on the center conductor necessary for impedance matching. If this mode is cut off, the effect of the TM_{01} mode is a localized capacitance which may be easily compensated for. If this mode can propagate, a serious mismatch occurs. For the previously tested window designed for an X-band radar CFA the calculated TM_{01} cut-off occurs at about 14.5 GHz, which is close to its measured upper limit for good matching. In the new design, the calculated TM_{01} cut-off occurs at 18.2 GHz. Cold-test measurements showed values of VSWR no greater than 1.2 between 2 and 18 GHz. The only remaining problem is low yield due to leaks at the center pin seal. A possible corrective measure is to replace the solid center pin molybdenum with tubing.

The dimensions of this window were scaled by a factor of about 0.8 from the coaxial input output which was designed for an X-band CFA to operate at 20KW peak, and with which peak power outputs up to 14KW were observed with no indication of output window arcs. Equivalent voltage gradients would occur at [illegible]kW peak power in the scaled window. Therefor[illegible] [illegible] for the 1kW peak required here.

4.4 Design of Interaction Space

A number of large-signal calculations were performed using the computer model of Cooke, Dohler and Shaw[7]. A set of computations was performed based on preliminary estimates of circuit properties based on cold-test data from models No. 1 and No. 2, and some rough assumptions were made as to the effect of changes of pitch and of substrate thickness. A subsequent set of large signal calculations was made which incorporated the results of computer calculations of the circuit design. For each set of design parameters, sole voltage was set at synchronism, while the magnetic field, cathode-to-line voltage, and beam current were fixed. The general conclusions were:

1. Best performance when circuit attenuation is relatively high occurs when magnetic field is lowest, with critical magnetic field based on DC cutoff assumed to be the minimum allowable.
2. There is little merit in increasing the magnetic field and decreasing the line-sole spacing, d, accordingly. The maximum values of [illegible] where [illegible] is the propagation constant of the slow wave used in the calculations was about [illegible] at the high end of the band.

with the sole tuning, and in spite of the higher interaction impedance and lower circuit losses of the circuit with the thicker substrate.

(4) Pitch of 0.014" was preferable to larger values of pitch, in spite of higher circuit losses. This is the case because the lower beam velocity allows lower applied voltages and higher beam current.

The final design arrived at put the applied cathode-to line voltage at 6700 V, magnetic field at 4800 G, line-sole spacing at 0.040", with a pitch of 0.014" and substrate thickness of 0.006". Beam width in all cases was assumed to be 0.120". The optimum calculated length for the circuit was 1.8", but a value of 1.5" was chosen based on considerable previous experience which shows that the actual small-signal gain is greater than the calculated small-signal gain.

4.3 Operating Tube

The physical structure of the operating tube was based as far as possible on production tubes so as to use common parts and well understood technology. Only the circuit represented really new technology. An [illegible] gun was used with electrodes shaped for optimum beam laminarity. For more detail see the First Interim Report [illegible], Report No. [illegible]-TR-7[illegible].

corner of the laser-cut substrate cracked at the location where the output lead is connected, and where it can not be supported by the ground plane. Great difficulty was encountered on input and output match, as was shown in Figure 9. The poor match is attributed to difficulty in holding the extremely tight tolerances necessary.

With the first assembly of the operating tube, no test data could be taken because of poor cathode emission. The tube was opened and the gun assembly was replaced using a cathode supplied by a different manufacturer. There was some further degradation of the attenuation (by about 5dB across the band), attributed at least in part to the fact that the circuit was exposed to material evaporated by the first cathode when it was intentionally overheated in an effort to get it to emit.

As would be expected from a CFA with very high circuit attenuation, gain and efficiency were disappointing, and there was little if anything by way of performance above 9.5 GHz. Some results are shown in Figures 11, 12, and 13.

Because of the very high circuit losses, representative results to show what performance is possible in I-J-band CFA were not achieved. It is necessary to reduce the RF losses to a level which is consistent with calculated values, as is presently the case in the E-F-band CFA's with laser-cut substrates and also in Northrop production CFA's, [illegible].

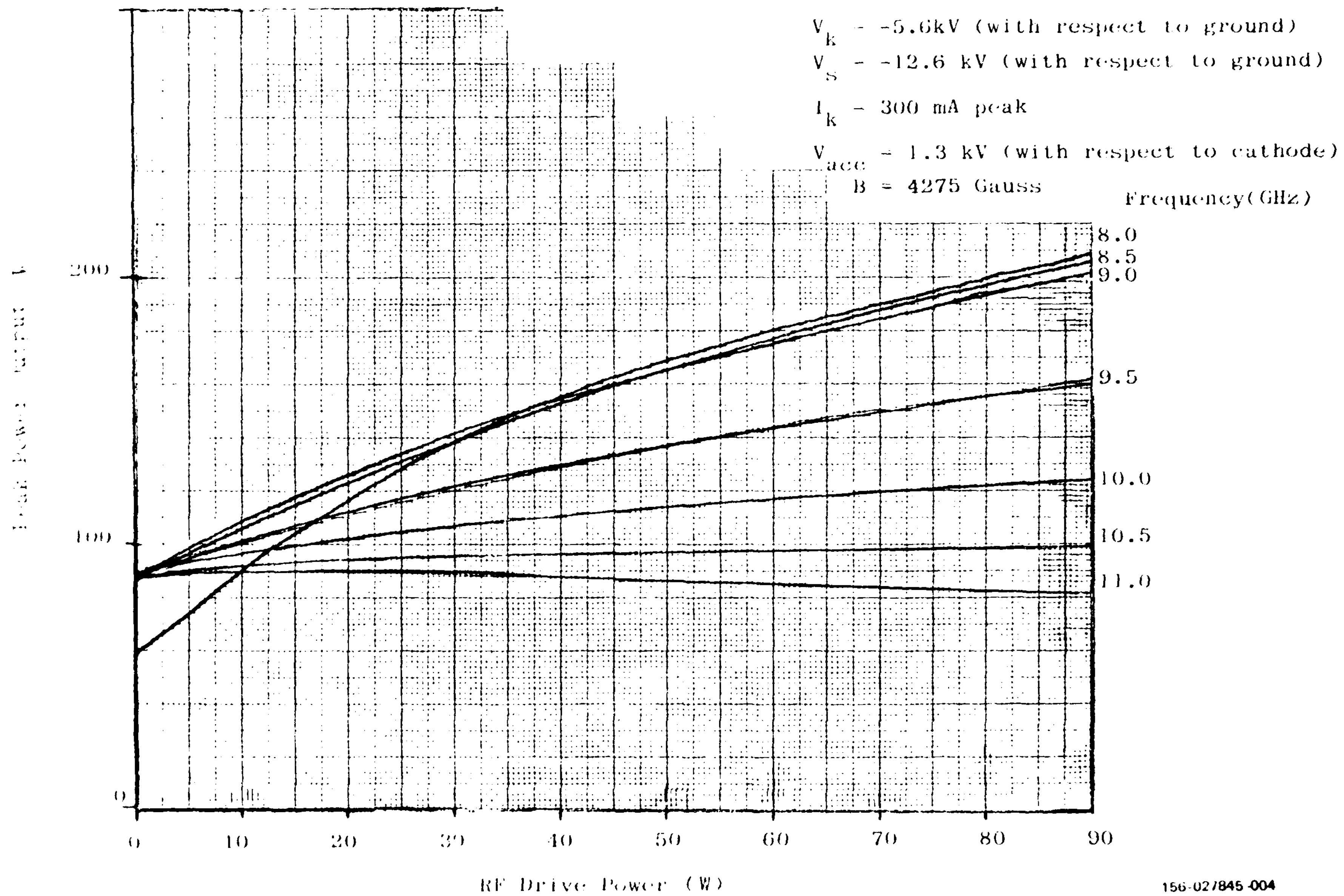

Figure 11. I/J Band Power Transfer Characteristic (300 mA)

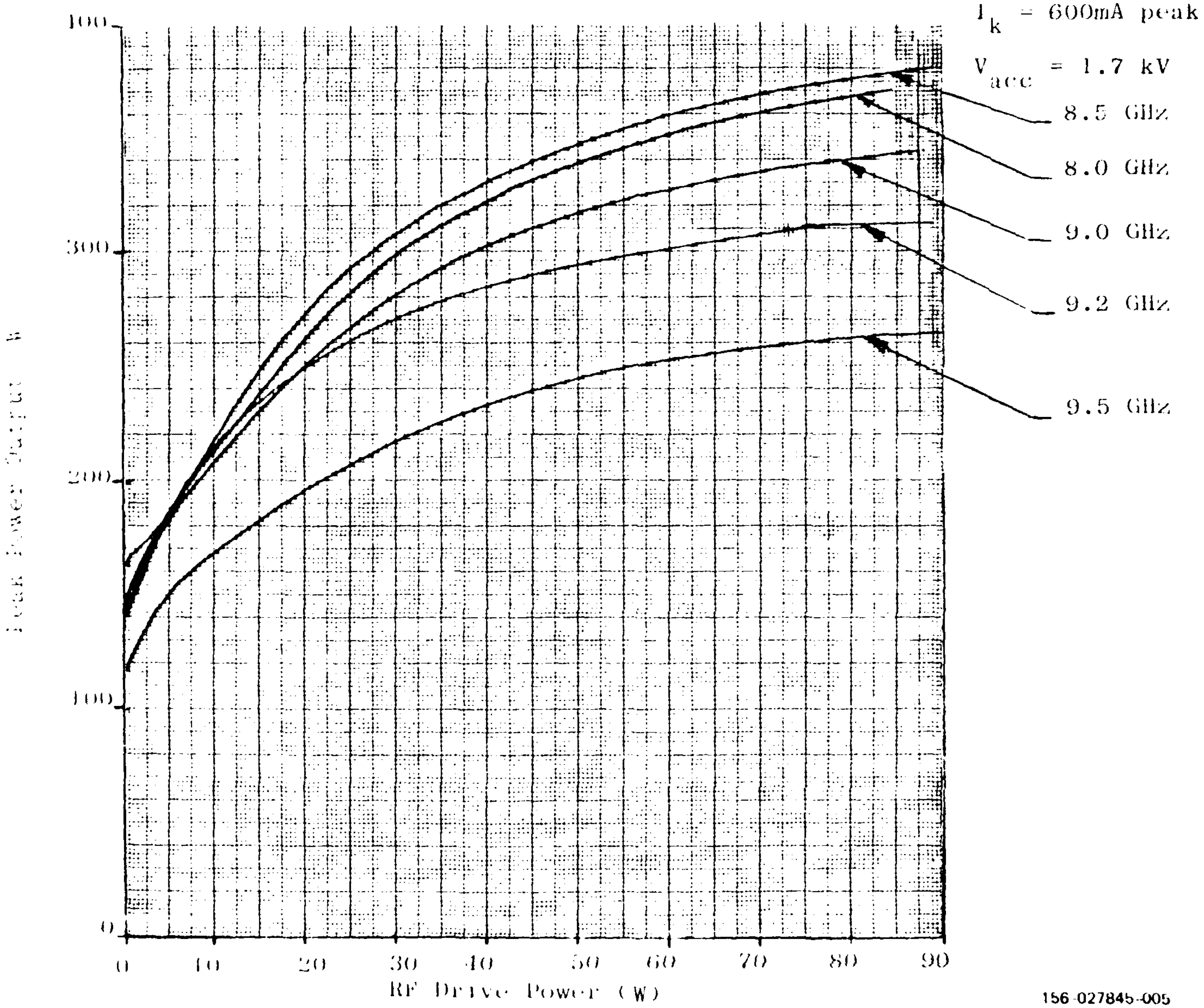

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Figure 12. I/J Band Power Transfer Characteristic (600 mA)

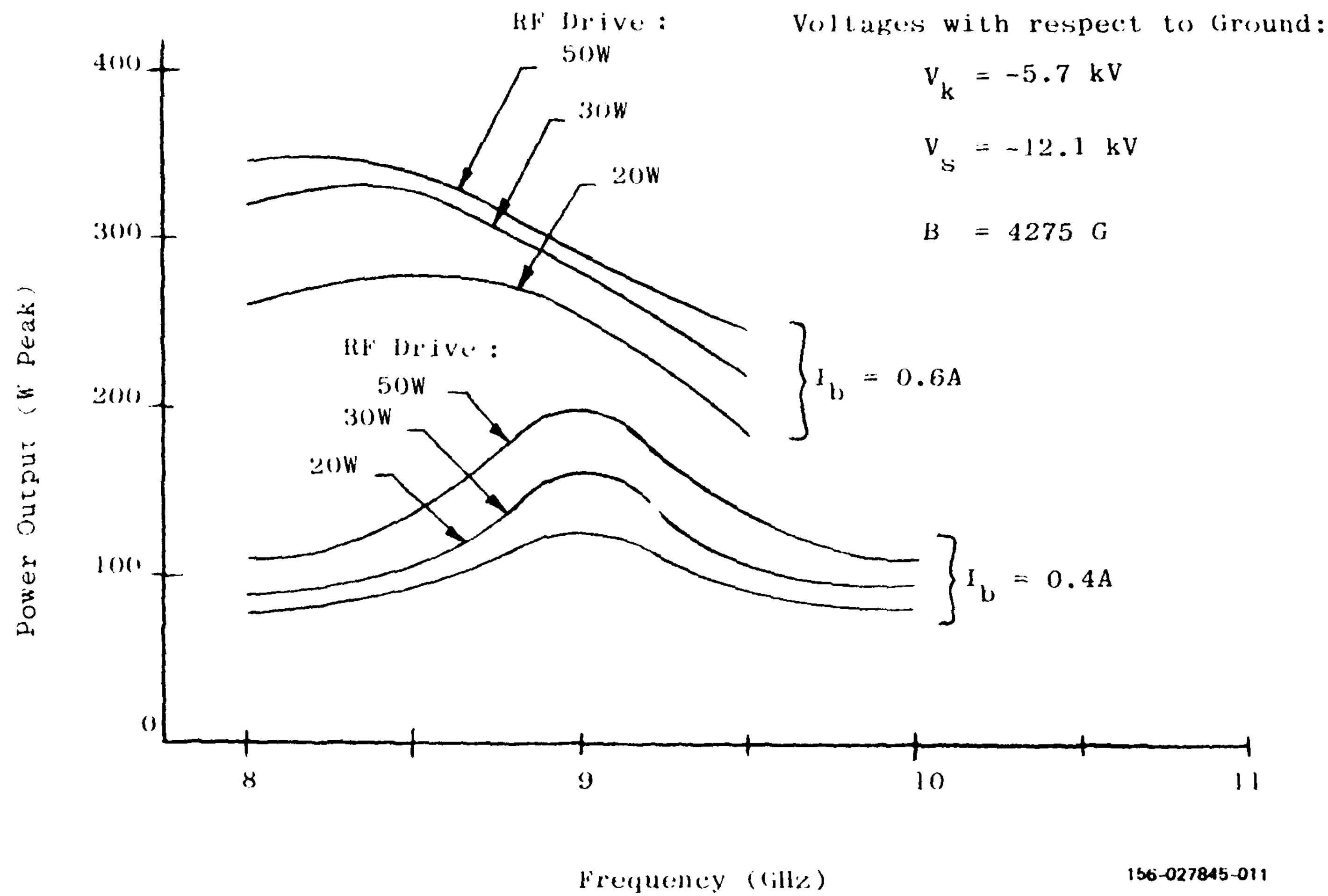

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Figure 13. Bandwidth Curves I/J-Band CFA

SECTION V

SUMMARY AND CONCLUSIONS

5.1 E/F-Band CFA's

The electrical design for the E/F-band CFA with laser-cut shaped substrate is considered sound and performance is sustantially repeatable. The expected saving in assembly time for the circuit was realized, and parts are a little simpler to make as compared with the conventional design using individual insulator bars. Operation at 33% duty factor and approximately 1kW average power output has been demonstrated. Gain is adequate for the electronic warfare mode. A little greater gain is desirable for the phased array mode, which can be accomplished by lengthening the circuit a little. One tube which was assembled with a longer circuit failed when the substrate cracked and separated from the ground plane. This was the first time for this kind of failure mode. A review of the mechanical design for a little more margin of safety seems in order.

5.2 I J Band CFA

Laser cutting of substrates of dimensions suitable for I J band, and after bonding to the ground plane, has been demonstrated successfully, and better laser spot size control contributed to better tolerances than before, and was essential for laser-cutting after the substrate was bonded to the ground plane. The substrate-ground plane assembly is very strong, and is fragile only at the corners where the input or output circuit attachment is made. At these locations, the substrate is not supported by the ground plane. The obstacle of good performance of this kind of circuit in an operating CFA was high RF losses. Attentuation was especially high above 10 GHz, and meaningful performance results were observed only below 10 GHz. The substrate cracked at the corners where input/output attachments were made, causing high VSWR.

The small size of RF circuit parts is still a problem, and usual techniques of input/output matching could not be applied. A major problem over-all seems to be the size and clumsiness of human fingers, even when tweezers or other small tools are used as extension of those fingers.

SECTION VI

RECOMMENDATIONS

6.1 E/F-Band

A longer circuit than originally used in E/F band tubes is necessary for the phased-array mode, and is desirable for the electronic warfare mode. More stability in the presence of higher gain will be achieved by adding a little attenuation near the input.

The mechanical structure of the E/F-band tube is fundamentally sound, but some improvements are desirable. First,the mechanical relationship between the ground plane and the substrate at each end of the circuit can be made a little more robust if the ground plane extends slightly beyond the substrate. Second, further optimization of the composition of the ground plane material to match the expansion of the substrate is desirable. Third, the method of attaching input/output connectors to the circuit should be reviewed to make it more sturdy and more reproducible. Finally, the design of other parts of the tube can benefit by a design review to match the cost reduction achieved in the circuit.

6.2 I/J-Band

The chief obstacle to success in I/J-band is circuit losses. To alleviate this problem, it is necessary to determine the reason that the attenuation realized exceeds the calculated value by so great a margin, a condition not found in lower frequency CFA circuits. Some possible causes and corrective measures were discussed in Section IV. They included:

(1) Overhang of the meander beyond the supporting shaped substrate.

(2) More careful etching of the meander pattern on the substrate to assure removal of molybdenum and titanium.

(3) Assurance of integrity and effectiveness of the very thin molybdenum barrier layer.

(4) Laser cutting before bonding to the ground plane, along with improved methods of substrate handling.

A further consideration is the dielectric losses in the substrate. The loss tangent of BeO ceramics is reported in the literature at 10GHz (where it is low) and 25GHz (where one source indicates that it is high), and not any intermediate frequency. The loss tangent of BeO ceramic material should be measured at least at 15GHz.

It is also necessary to establish greater mechanical integrity of the input/output connections to the circuit. At the same time, it is probably desirable to modify the substrate design for a little greater pitch and thickness, even though calculated performance would not be as good.

An eventual objective is a gridded gun. Dimensions need to be too small for conventional grid designs. Recent work at

Northrop* has been encouraging with respect to the practicability of a grid supported from the cathode with dielectric posts. Another eventual objective is to reduce the over-all dimensions of the tube so that they are consistent with the small size of the circuit.

Finally, to build devices of such small size successfully, it is not sufficient merely to put down on paper parts dimensions of very small size as scaled more or less directly from lower frequency bands. It is necessary to take into account the very small sizes of parts and practical methods of dealing with such parts and assemblies.

* Air Force Contract No. F33615-78-C-1492, "Integrated Gun Design."

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[1] Technical Report No. ECOM-75-1343-1, "Low Cost Crossed-Field Amplifier", Final Technical Report, prepared by Northrop for U. S. Army Electronics Command, June, 1977.

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[4] M. L. Cooke, R. R. Moats, "Influence of Metal-Ceramic Bonding Processes in Crossed-Field Amplifier Performance", Conference Record of 1973 Conference on Electron Device Techniques, pp. 76-83, IEEE, New York.

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