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I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER

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Robert R. Moats
NORTHROP DEFENSE SYSTEMS DIVISION
Electron Tube Section
Des Plaines, IL 60018

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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 1000 W peak, 200 W average, between 8.5 and 17 GHz with 20 dB gain. A laser-cut shaped-substrate meander line is used. Performance in an E/F band IBCFA is evaluated, for which the objective performance in the 2-4 GHz band is 3.0 kW

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peak power output, 1.0 kW average power output, also with 20 dB gain. In addition, a gun for I/J band is to be designed and evaluated.

For E/F band, a cold-test model was built using the same technology as contemplated for operating tubes. Values of delay ratio, coupling impedance, and attenuation were substantially as expected.

An E/F-band operating CFA using the shaped-substrate meander line, and other parts common with a standard E/F-band CFA design, was built and tested. Performance was comparable with a typical CFA of standard design, slightly lower in efficiency at mid band and approximately the same over the remaining part of the 2-4 GHz band.

An I/J-band cold-test model was built, and measurements of delay ratio, coupling impedance, and attenuation were made. Results showed that a reduction of pitch and a thinner substrate are necessary for an efficient I/J band tube.

The primary problems remaining are related to the technology of the laser-cut substrate. Improvements in laser cutting and in dealing with the fragility of the resulting pieces are necessary. One alternative to be considered is to perform the laser cutting after the metallized ceramic is bonded to the co-expansive ground plane. This approach is to be investigated in parallel with improving previously used approaches to constructing CFA's with one-piece shaped substrates.

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SECTION I

INTRODUCTION

The effort in this program is directed toward the development of a high-power broad-band low-cost linear format injected-beam crossed field amplifier (IBCFA) in I/J-band for electronic warfare. The work to date has included the construction and testing of an E/F-band cold-test device, an operating E/F-band tube, and an I/J-band cold-test device.

A major cost factor in present IBCFAs is the meander slow-wave structure, which incorporates a meander strip of copper and a separate ceramic insulator supporting each segment of the meander. By replacing the set of insulators with a single shaped substrate which can be manufactured at moderate cost, very substantial cost savings in both time and labor can be achieved. The laser cut, shaped-substrate concept was originated by U.S. Army ERADCOM personnel, and has been the subject of study by C. Bates and J. Hartley of ERADCOM.

The objective specifications for the E/F-band operating model 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 (max)
RF Input Impedance	50 ohms

The cold-test circuit to be built for I/J-band is directed toward the achievement of the following objective specifications:

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
RF Input Impedance	50 ohms

For realization of an E/F-band model, it has been necessary to develop suitable technology with respect to cutting the shaped substrate from beryllia ceramic, metallizing it, and bonding it to the coexpansive ground plane and to the meander line. Serious problems with the fragility of such substrates remain with respect to both manufacture and assembly. Nevertheless, substantial progress has been made as evidenced by the devices built and tested.

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SECTION II

TECHNOLOGY

In the previous report on this program[1], there was described a problem of flatness of the co-expansive copper-tungsten composite material (ground plane) when it was brazed to the yieldable support posts. A test with this plate thickened for added stiffness indicated no improvement. However, when the support posts were made thinner over one-quarter of the length of the assembly at each end, flatness was within 0.001" over the total length. The assembly with thinner posts is shown in Figure 1, and may be compared with Figures 2b and 4 of the previous report.

In the previous report, several possible sequences of operations for making the assembly of meander line on the laser-cut substrate and co-expansive plate were described. The sequence which was adopted was:

(1) Metallize the ceramic blank on both sides.
(2) Photo-etch the meander pattern on one side.
(3) Laser-cut the slots.
(4) Bond the assembly of photo-etched meander, laser-cut ceramic, and co-expansive plate.

With this sequence, the laser cuts from the photo-etched side of the ceramic blank into bare ceramic. At the boundary between metallizing and ceramic, tiny globules, or burrs, of ceramic appeared, which were large enough to prevent the photo-etched meander from lying flat on the substrate. The globules were removed by hand for the first test. An objective for the future must be to prevent the formation of these globules, or to find means of eliminating their adverse affect.

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[1] Interim Technical Report, I/J Band Low-Cost Crossed-Field Amplifier, Report No. ECOM-77-2642-1, By Northrop Defense Systems Division for U.S. Army Electronics Command, Feb. 1978.

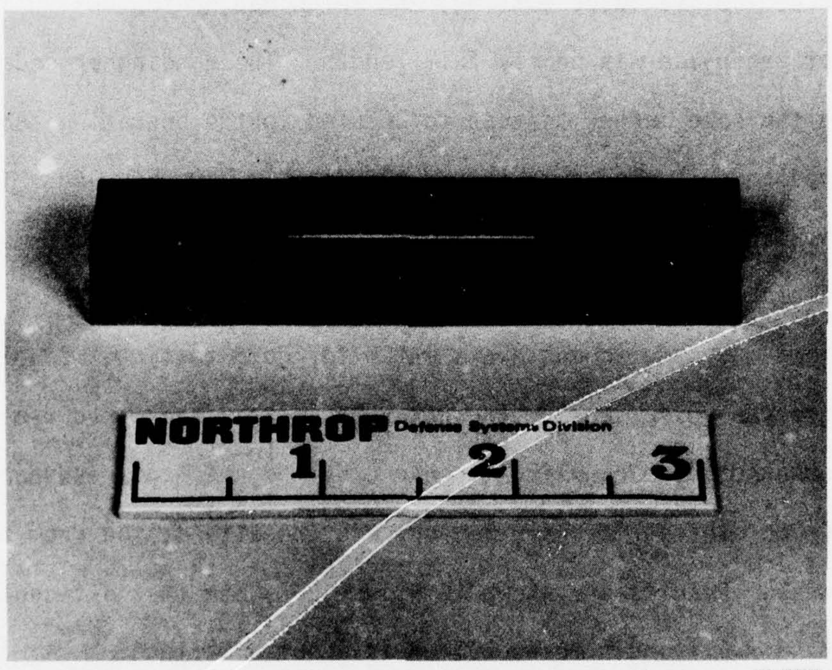

Figure 1. E/F-Band Cold Test Model with Added Slotting of Support Posts.

SECTION III

E/F BAND CFA

3.1 Cold Test Model

A cold-test model for the E/F-band design was constructed, using as a starting point the mock-up of the co-expansive ground plane and yieldable posts, where the ground plane was flat within 0.001" as described in the previous section. The shaped substrate was one on which a meander pattern had been etched before laser cutting, and which had broken during laser cutting so that one piece was nearly full length. The bonding procedure was carried out in the same manner as that to be used in the operating tube. The bond appeared good, and no cracking of the ceramic was observed. This assembly was shown in Figure 1. The assembly included a photo-etched meander strip 0.005" thick on top of the substrate.

No effort was made to achieve a match for cold testing. Coupling to the signal source was quite loose. The delay ratio was determined from the successive resonances, the coupling impedance by the shift of resonance frequencies due to dielectric perturbation, and the attenuation from the Q's of the resonances. Results are shown in Figure 2. Note that attenuation is in dB per inch; a full-length meander line is about 3.5" long.

3.2 Operating Model

An operating IBCFA was constructed using the design described in Reference 1. When the ladder-shaped substrate was bonded to the ground plane, the bars on each end fractured. The broken bars were filed off, and pieces of broken substrates of the same design were patched in. It is expected that modification of the fixture will prevent this problem in the future. In the design which was used, a stainless steel piece was used to apply pressure to

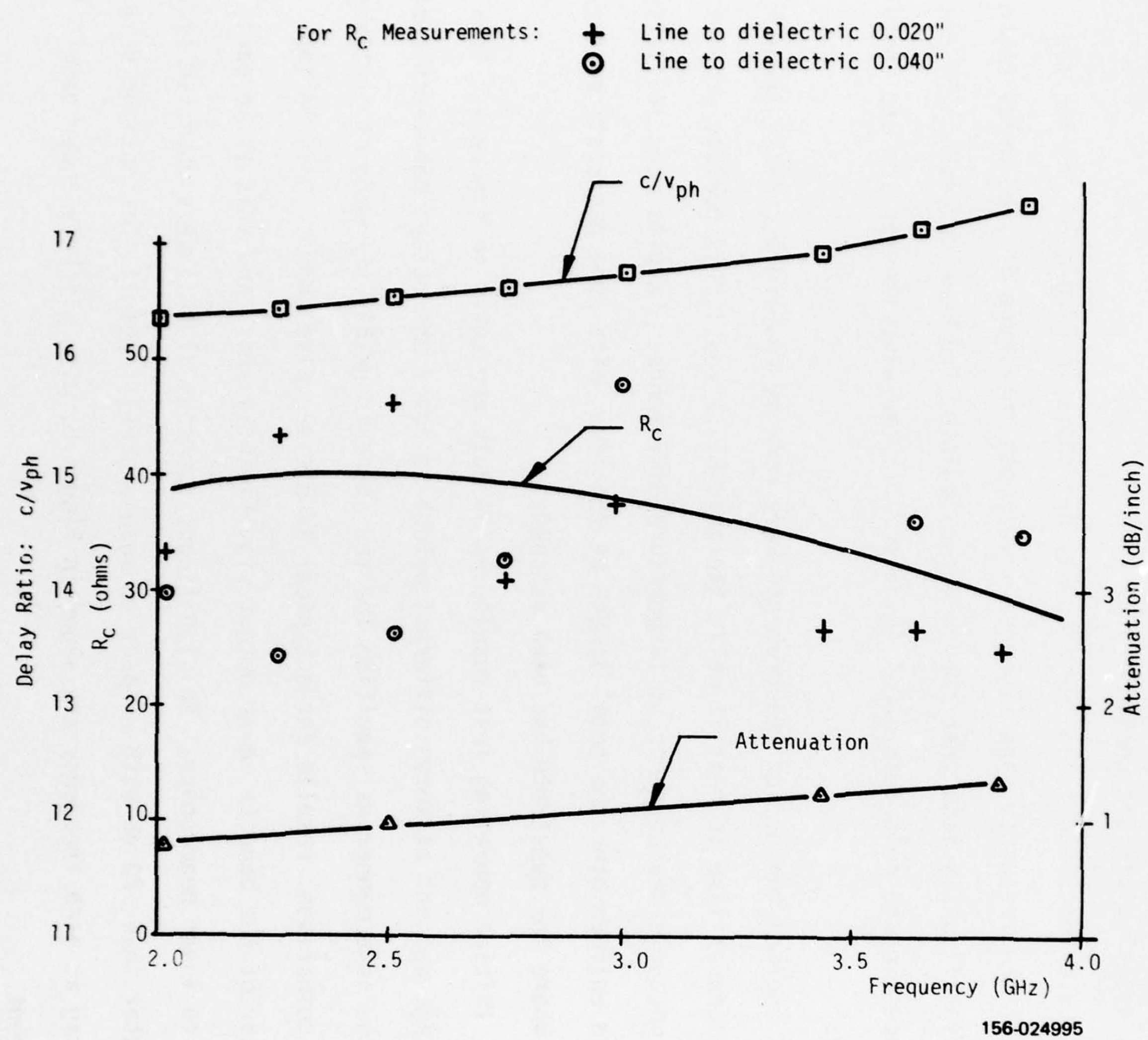

Figure 2. Delay Ratio (C/V_{ph}), Coupling Resistance (R_c) and Attenuation of E/F Band Line On Laser Cut Substrate.

the substrate as part of the bonding process. In repairing the assembly, and in future assemblies, a ceramic piece will be used to apply the necessary pressure, thus assuring uniform thermal expansion during the bonding cycle. A photo-etched meander line was brazed to the top of the repaired substrate, thus assuring circuit continuity.

Cold test results on the assembly are shown in Figure 3. At the low end of the frequency band (longest wavelength in Figure 3), the delay ratio is significantly less than the values calculated from the succession of resonances in the cold-test model (Figure 2). Otherwise the results are comparable.

Thermal conduction measurements were made by passing a current through the meander line to heat it while the base block was liquid cooled, and making thermocouple measurements of temperature difference. Results were initially quite uniform over the total length of the line, with some degradation at each end where the substrate had been patched.

Initial operating test results at 5% duty are shown in Figure 4. Sole voltage was set at three different values to cover the octave bandwidth range in the same manner as specified for the standard RW-619 CFA made at Northrop. For comparison, results for a typical RW-619 are also shown. Only in the center of the band is power output significantly less, and this is in part due to lower beam power. No significant spurious signals were observed (i.e., greater than -20 dB with respect to main signal). Results for optimum sole tuning at each frequency are shown in Figure 5, with slightly lower beam current.

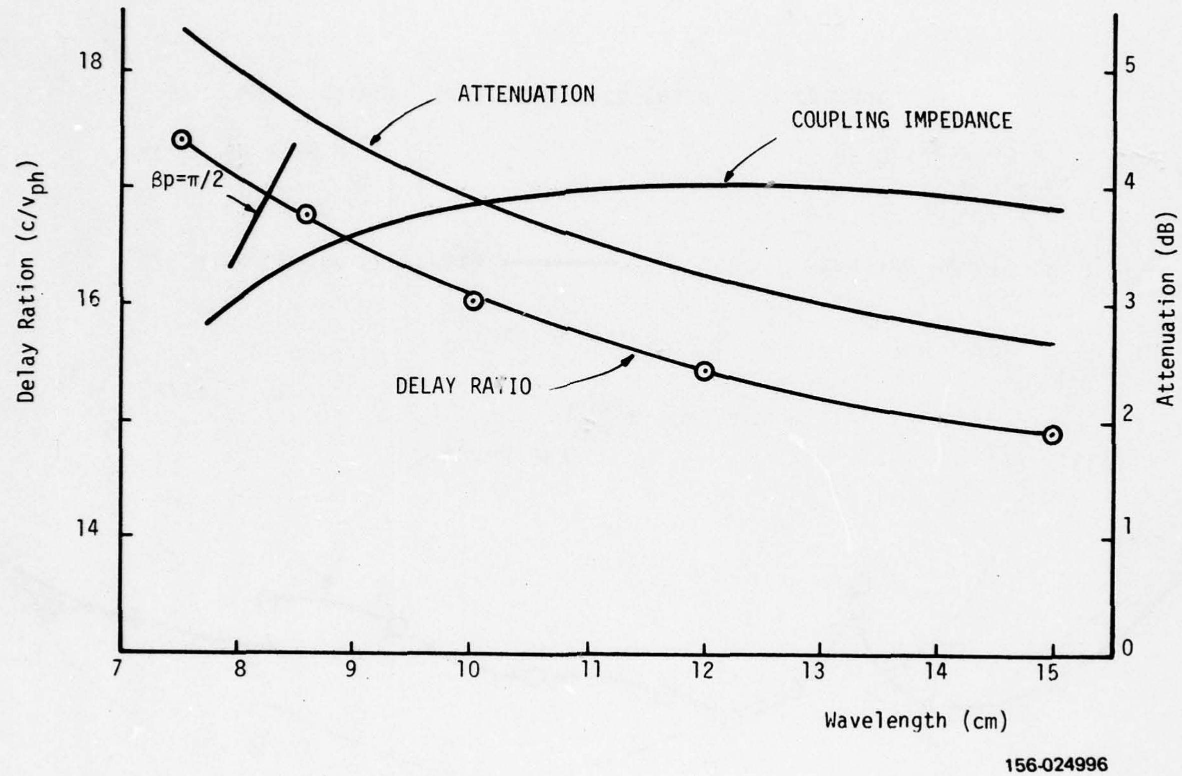

Figure 3. Cold Test Data for Operating CFA.

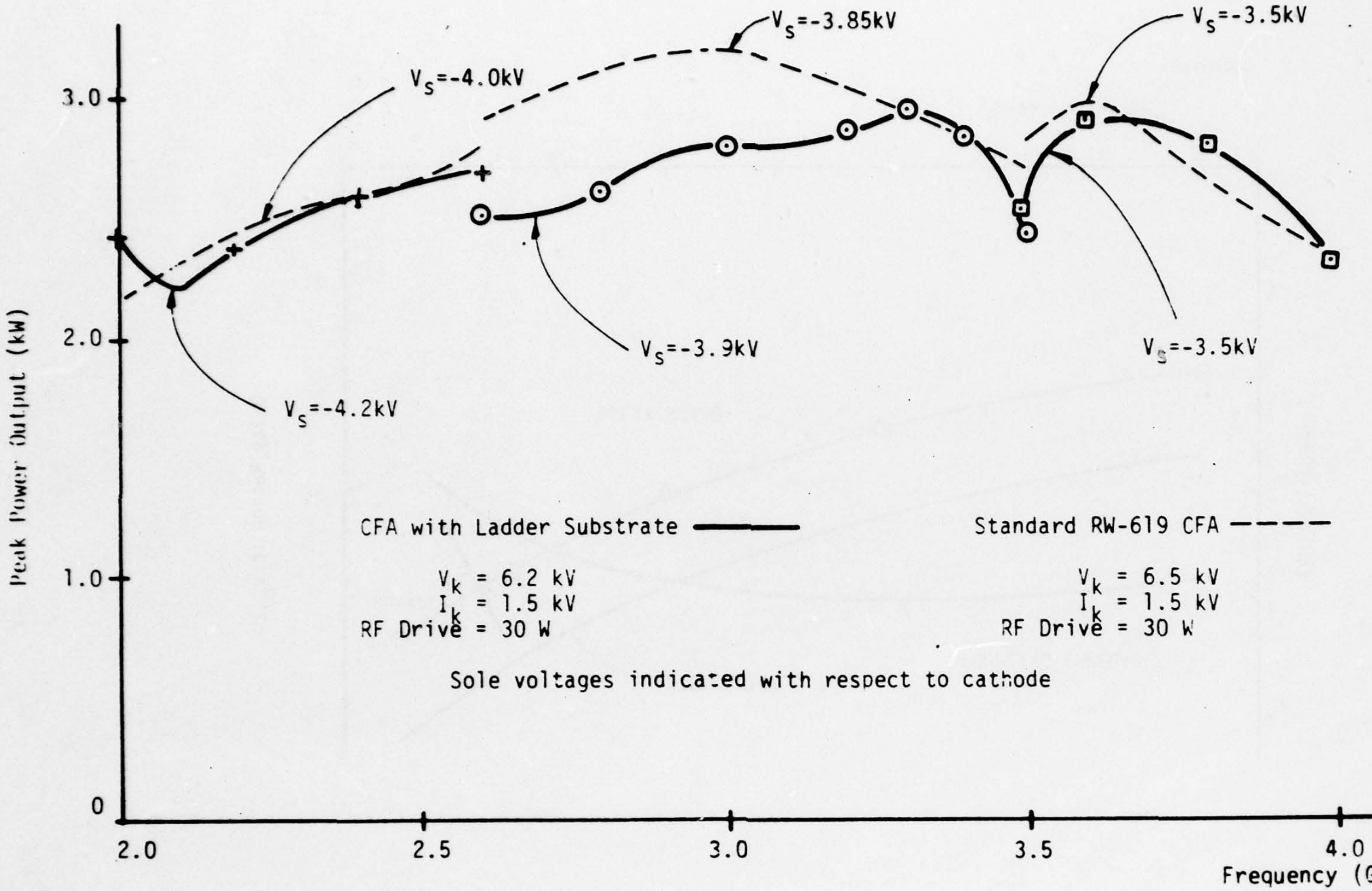

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Figure 4. Power Output of CFA with Ladder-Shaped Substrate Typical Standard CFA for Comparison.

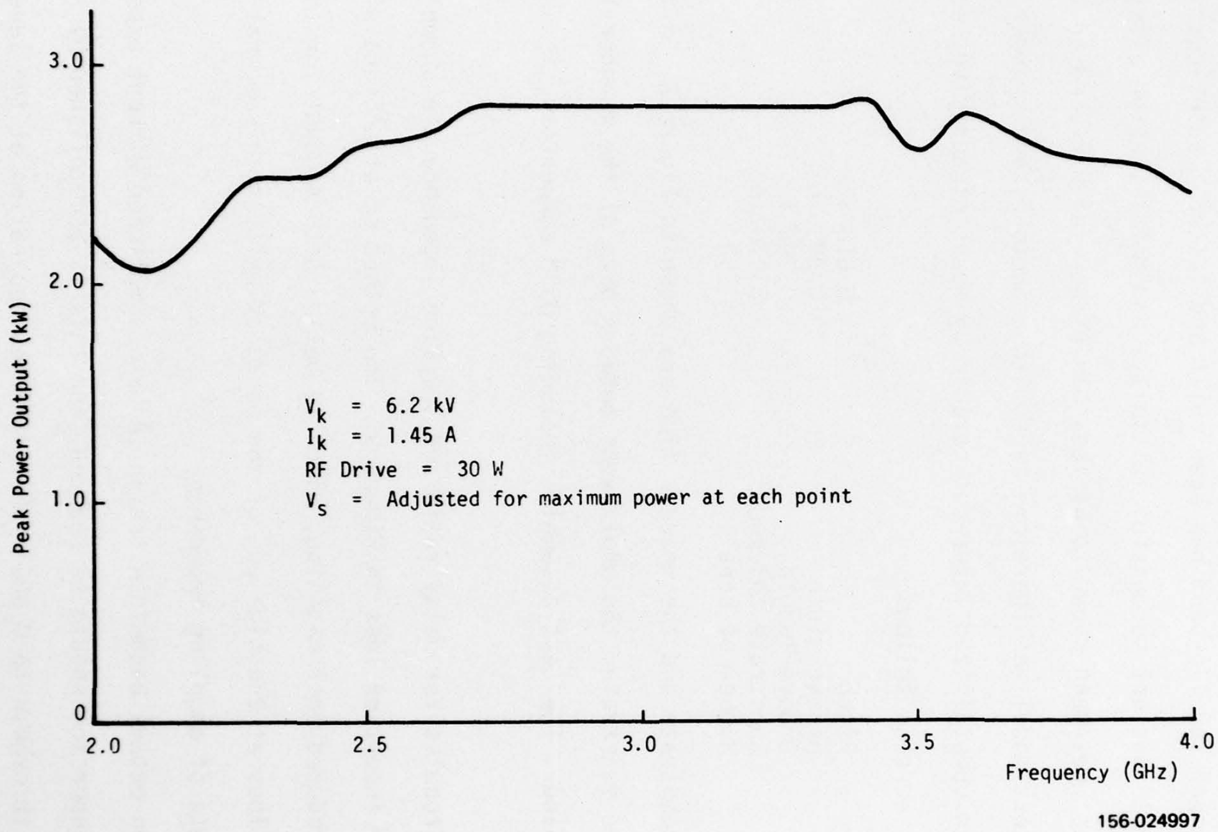

Figure 5. Power Output of E/F Band CFA, Sole Optimized.

SECTION IV

I/J BAND

A cold test model delay line on a laser-cut ceramic substrate with dimensions designed for I/J-band has been built and tested. Laser cutting of metallized parts was not successful initially, and metallization after laser cutting has not yet been shown to be feasible either for E/F-band or I/J-band. The cold test model was therefore made with a photo-etched meander line attached to an unmetallized laser-cut ceramic by means of adhesive cement. The dimensions were as follows:

Pitch	0.018 in.
Groove width	0.008 in.
Groove length	0.106 in.
Substrate thickness	0.010 in.
Number of bars	50

The substrate and the meander line are shown in Figure 6. After attachment to the substrate, the small webs between bars of the meander line are removed by hand. The test assembly, including OSSM connectors, is shown in Figure 7.

Test results for delay ratio and coupling impedance are shown in Figure 8, and for insertion loss in Figure 9. The method of attachment of the connectors produced poor matching, which is believed to account for the excessive insertion loss at the high end of the band, as well as to somewhat erratic measurements of coupling impedance.

For an octave bandwidth design to be accomplished without excessive sole tuning, dispersion should be reduced, and this is accomplished by reducing the substrate thickness to 0.006". For efficient operation at the level of 1 kW peak power output, the delay ratio is too low, and a smaller value of pitch is required to take into account a satisfactory value of beam impedance. For good efficiency, a pitch of 0.014" is considered more desirable, and is not

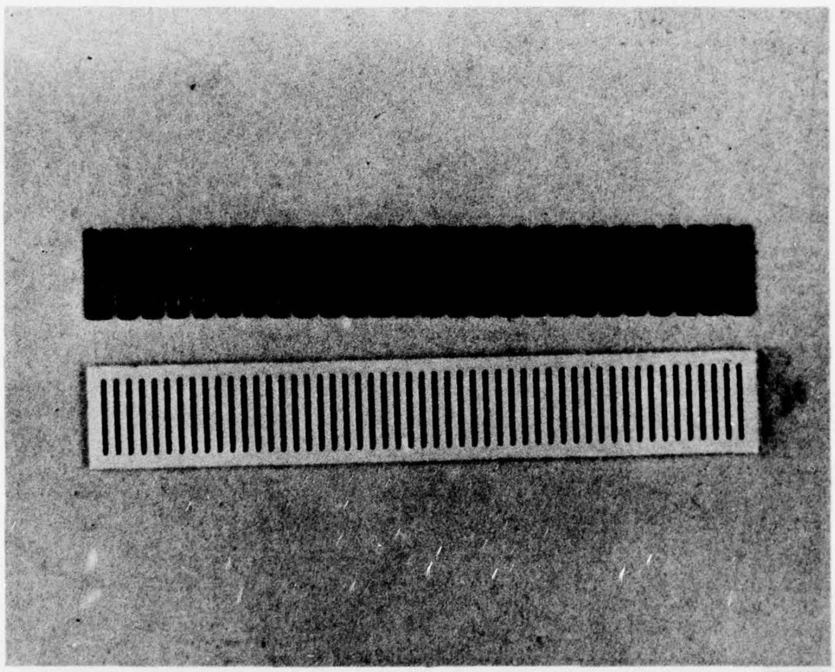

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Figure 6. Substrate and Meander Line for I/J-Band Cold Test Model.

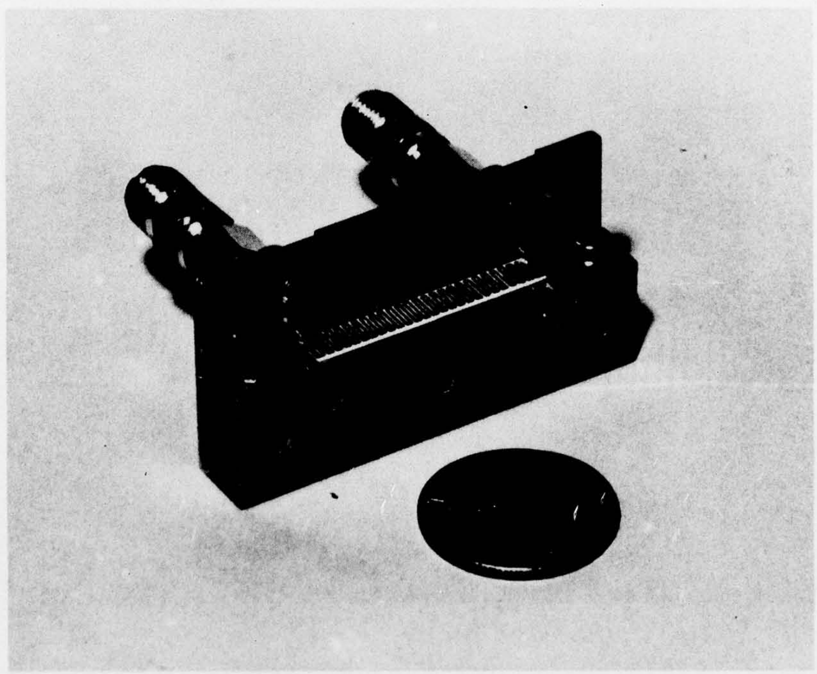

Figure 7. I/J Band Cold-Test Model.

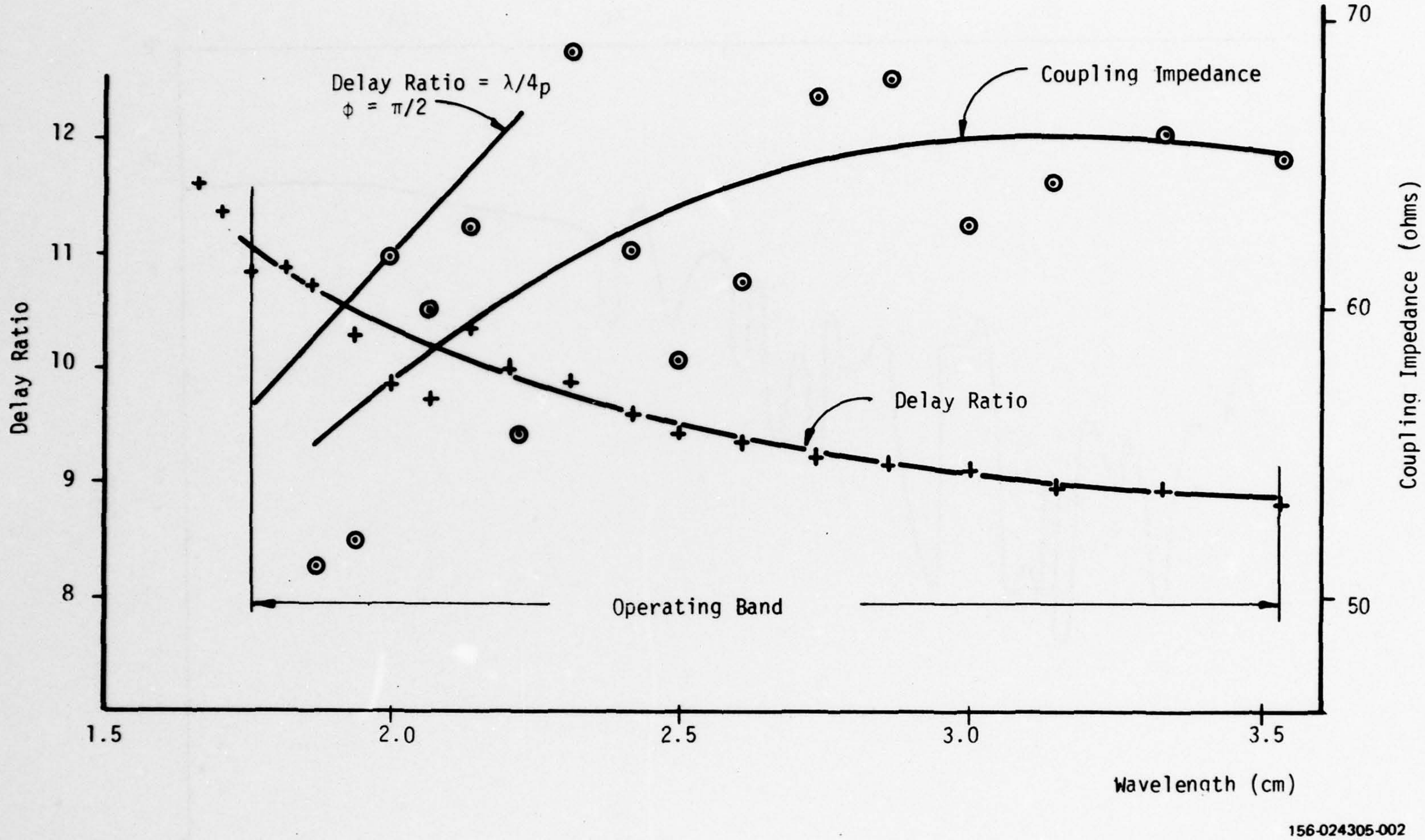

Figure 8. Delay Ratio and Coupling Impedance I/J Band Meander Line On Ladder Substrate.

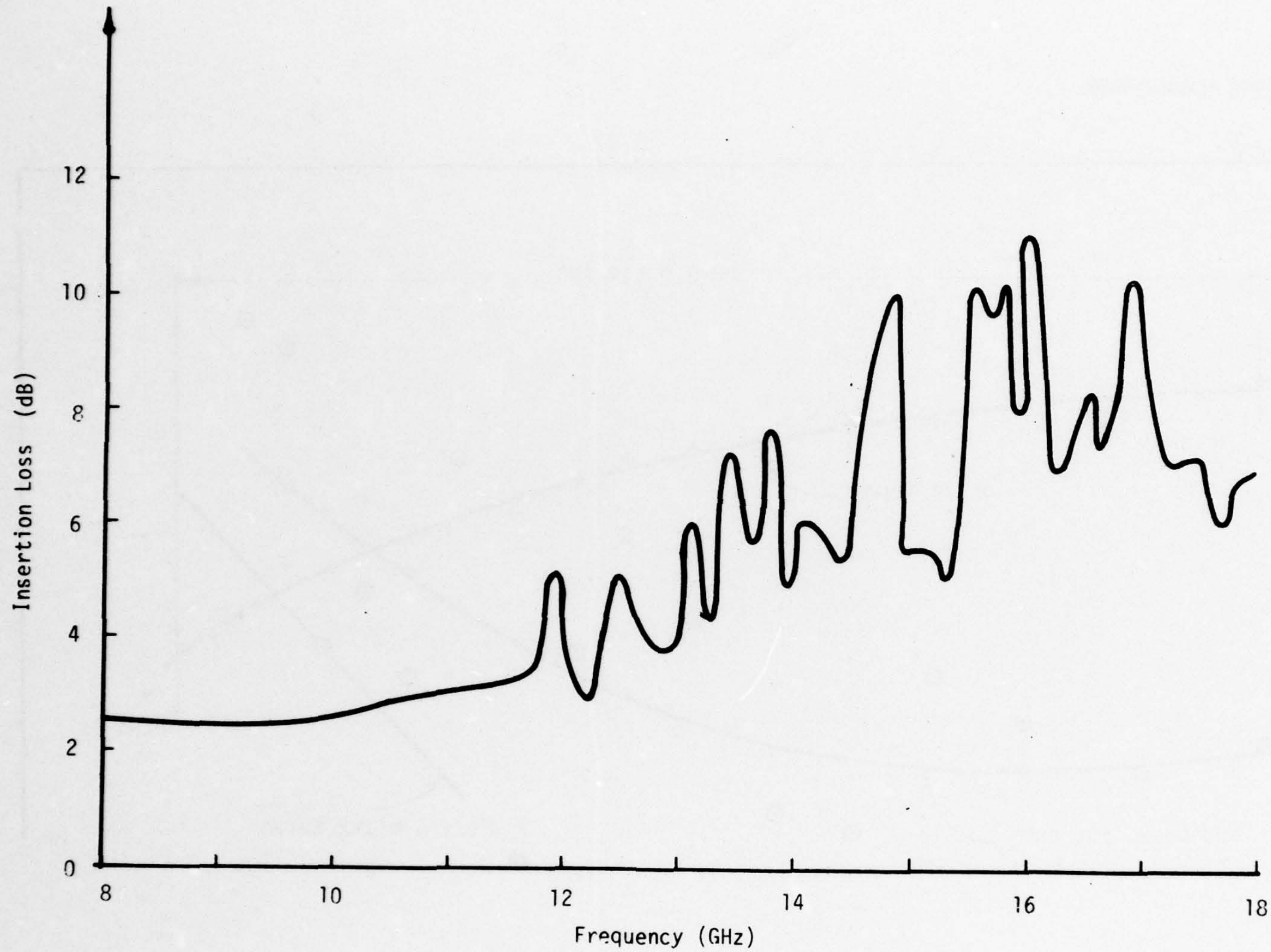

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Figure 9. Insertion Loss of I/J-Band Cold Test Model.

expected to increase the difficulty of substrate manufacture very greatly as compared with 0.018" pitch.

SECTION V

FURTHER WORK TO BE PERFORMED

5.1 Technology

The key problem remains the laser cutting and fragility. The fragility problem appears as breakage during laser cutting and breakage during tube construction.

A modification to the laser cutting sequence is to be investigated. In the proposed new sequence, the substrate is bonded to the co-expansive ground plane before laser cutting. Preliminary experimental effort is necessary to determine whether this approach is feasible in principle. The laser is expected to cut through the ceramic in normal fashion, but when the ground plane is exposed, the copper will reflect substantially all of the laser beam that strikes it. If a clean cut of the ceramic takes place, along with no more than minor erosion of the ground plane, this sequence should be successful.

As a parallel effort, refinement of the presently used process is required. The apparent problem of beryllia "burrs", which appear during laser cutting after metallizing and etching, must be resolved if the laser-cut substrate is to be effective with respect to cost. Hand deburring of the substrates would be costly because of time and because of probable breakage of some of them. Dimensional changes at the edge of the ceramics to provide greater strength may be considered.

Another subject to be considered is the formulation of the co-expansive material for the ground plane. Commercially available Elkonite* has a

*Trade Mark, P.R. Mallory & Co., Inc.

composition of 43% Copper, 57% tungsten by volume. This composition corresponds to a coefficient of linear thermal expansion of about 10 x 10^{-6}/°C according to Mallory data, as compared with about 8 x 10^{-6}/°C for beryllia ceramic material. A composition of 32% copper, 68% tungsten by volume is considered desirable. Special billets of copper-tungsten composite are to be formulated, with the additional feature of OFHC instead of electrolytic copper.

5.2 E/F-Band

Additional E/F-band effort is to be directed toward improved line-substrate-ground plane assemblies. Particular emphasis is to be placed on thermal conduction and freedom from fracture, with the objective of maximizing average power capability.

The operating CFA previously built will be tested further. Testing above and below the specified frequencies and tests with lower and higher RF drive power will be conducted. In addition, optimum operating parameters for lower and higher values of peak beam power will be sought.

5.3 I/J-Band

Based on data already obtained, the design of the I/J-band meander line needs to be modified to incorporate a thinner substrate and reduced pitch. Appropriate cold-test models are to be made with metallized ceramics. The design assumptions are to be supported with large signal calculations.

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