X-Band Resonant Ring Operation at 450 kW

D. Hoppe and R. Perez
Radio Frequency and Microwave Subsystems Section

This article documents the operation of the X-band (7.2-GHz) ring resonator at a power level of 450 kW, which represents the highest power level achieved in the resonator to date. The ring resonator and the overall experimental setup are summarized. The motivation for the present ring resonator experiment is described, and specific results are presented. More general observations made while operating the ring at these power levels are described, and conclusions are drawn.

I. Introduction

Resonant ring tests have been successfully conducted by the DSN at 7.2 GHz and 450 kW. The component under test is a reduced-size square waveguide that is intended to simulate a critical area of a proposed 1-MW feedhorn. In addition to these results, general observations made when operating the ring resonator at these power levels are summarized. The experimental setup, including computer control for real-time frequency correction, is described in the following section.

II. Description

The 7.2-GHz resonant ring (Fig. 1) consists of an electrically continuous loop of copper waveguide (WR 125), 2.64 meters in mean circumference. Two coupler sections are included in the loop: a 13-dB (nominal) coupler for signal injection and a dual 58-dB (nominal) coupler used to sample the forward and reverse components of the traveling wave in the ring. Two dual tuners form part of the feed path and allow optimization of the resonant ring operation for different parameters.

As described in [1] and in JPL Publication TR-1526,[1] the signal source used to drive the resonant ring is a 7.19-GHz klystron transmitter with an output power range of 0.5 to 23 kW. During steady-state operation of the resonant ring, essentially all of the input power from the transmitter source is dissipated due to resistive losses in the waveguide walls. This dictates water cooling of the waveguide, achieved by soldered copper water jackets on each of the broad waveguide walls. Separate cooling circuits are provided for the input waveguide and tuner assembly, as well as for the test piece section of the resonant ring.

The resonant ring acts as a high-Q resonator ($Q \approx 5600$), with its resonant frequency determined by the electrical length of the waveguide loop. Under steady-state conditions, a traveling wave is sustained in the ring of a magnitude a times the input power. This factor a is the gain of the resonant ring and

---

[1] R. B. Kolbly, *X-Band Traveling Wave Resonator (TWR)*, JPL Publication TR-1526 (internal report), Jet Propulsion Laboratory, Pasadena, California, October 1973.

is dependent upon the insertion loss of the waveguide loop that forms the ring. That is, during optimum operation of the resonator, the input power is dissipated entirely in the resistive loss of the resonator.

Figure 2 shows the experimental configuration used for the resonant ring testing. The dual 58-dB power sampling couplers were calibrated using an HP 8510A network analyzer. A previous publication on the resonant ring[1] describes the dual-power sampling coupler as having -60 dB coupling. While this is valid for a measurement frequency of 8.5 GHz, it is erroneous to assume this value at 7.19 GHz. This is of importance, because the ring is capable of resonance at many frequencies, including 8.5 GHz and 7.19 GHz. The new calibration indicates a 2-dB or 58 percent error in any power levels computed using -60 dB of coupling at 7.19 GHz.

The use of the dual power meter also enabled a direct display of the ratio between the forward and reverse power levels in the ring. Because of thermal expansion due to the power dissipated in the waveguide walls, the physical length of the ring increased with increasing power levels, thus lowering the frequency (see Fig. 3 [a] and [d]). This created a need for an automated frequency correction system in order to keep the system at the optimum resonant frequency for each power level. A program was written to vary the source frequency in 25-kHz steps until the point of maximum resonant power was found. As shown in Fig. 3, a 10°C rise in cooling water temperature caused a drop in resonant frequency of 1.2 MHz as well as an increase in the Q of the ring.

In order to operate the resonant ring in a repeatable fashion, a flowmeter was installed in each cooling circuit. This also allowed visual inspection of the presence of coolant flow in any circuit. Water flowing in the inner and outer waveguide wall cooling jackets was conducted in different directions in order to equalize the waveguide temperature over the resonator as much as possible.

A port is provided at one of the elbows (of dimensions below cutoff frequency) in order to provide access for a fiber optic arc detector. This allowed correlation of a transmitter shutdown with the existence of an arc in the resonant ring waveguide. The coolant outlet temperature was monitored with a precision quartz thermometer.

III. Experiment Description

The motivation for the restoration of the X-band resonant ring was the need for high-power testing capability during the development of a proposed 1-MW radar transmitter. In particular, the resonator is required to test various sections of the proposed feedhorn (Fig. 4) and associated hardware, including orthomode junctions.

The tests described in this report are intended to simulate one of the four square waveguides that will feed the multimode feedhorn shown in Fig. 5. Under normal operation, each of these guides transports 250 kW, and the output power of these four waveguides is then combined in a larger chamber and launched into the flared horn in a series of waveguide modes. Theoretical analysis of the horn indicates that even though only 25 percent of the total power is present in each of these four square feeding waveguides, the largest electric field will occur in these guides. This can be seen from the following formula, which expresses the maximum electric field (rms) as a function of waveguide dimensions, power level, and frequency for a pure TE_{10} rectangular waveguide mode.

$$E_{\max} = \left(\frac{2\eta P}{ab\widetilde{\beta}}\right)^{1/2} \tag{1}$$

where

P = power level, W

a, b = waveguide dimensions, cm

η = 377 ohms

$\widetilde{\beta} = [1 - (\lambda/2a)^2]^{1/2}$

From the equation, it can be seen that even though the power level goes up by a factor of 4 in the large chamber, this is more than compensated for by the increase in area $(a \times b) = a^2$, and decrease in $\widetilde{\beta}$. The high electric fields in the feeding waveguides are present primarily because these guides operate close to cutoff $(\lambda \rightarrow 2a), \widetilde{\beta} \rightarrow 0$.

For the 1-MW horn, the following parameters are present for the four feeding waveguides: $a = b = 0.8$ in., $P = 250$ kW, and $F = 8.51$ GHz ($\widetilde{\beta} = 0.497$). From this and [1] we get $E_{\max} = 9.6$ kV/cm. For comparison, for the present radar transmitter, $P = 360$ kW, WR 125 waveguide, $E_{\max} = 8$ kV/cm. Thus, it is necessary to demonstrate the capability to operate waveguides at these high power levels, near cutoff, in order to have confidence in the 1-MW feedhorn design.

Since only 7.2-GHz pump power is presently available for the resonant ring, the 0.8-in. square part was scaled to 0.95 in. square. This maintains the same value for $\widetilde{\beta}$; that is, the new section will run as close to cutoff as the original. As a consequence of [1], more power is now needed to simulate the same electric field. In particular:

$$P_{\text{new}} = 250\ \text{kW} \left(\frac{0.95}{0.8}\right)^2 = 352.5\ \text{kW}$$

A two-section transformer from WR 125 to 0.95-in. square waveguides was designed, and a test part consisting of two of these transformers and a straight section of 0.95-in. square guide was electroformed. Two cross-sectional views of the test part are shown in Fig. 5. Measurements of the part indicated a return loss of greater than 30 dB over the operating range of the ring resonator. The following section describes the results of high-power tests made on this component, as well as general observations made when operating the resonator above 400 kW.

IV. General Operational Considerations

Prior to high-power operation of the resonant ring, the waveguide loop was disassembled and cleansed using a liquid copper cleanser. Smaller pieces were cleansed by immersion, and the couplers were cleansed by running moist patches through the waveguide. The flanges were then lapped to ensure flatness and a low resistance connection. A thin layer of silicone vacuum grease was then applied to the flanges to inhibit oxidation. The resonant ring was then reassembled, with attention given to flange alignment. It should be noted that this process was repeated whenever erratic operation accompanied by low gain was encountered. For the testing described in this article, cleaning was performed three times in a period of 28 days of operation (not consecutive). Examination of the waveguide tuners is also in order, especially under conditions of high reflected power into the transmitter along with very low gain. These events indicate a tuner failure, which results in the tuning element (less than 1/2 cubic inch of copper) dissipating power in the several kilowatt range.

During manual high-power operation of the resonant ring, care must be taken not to allow the power reflected to the transmitter to exceed the transmitter protective circuitry shutdown threshold. This is 500 W for the 20-kW, 7.19-GHz transmitter. Operation with less than 50 W of reflected power is much preferred, however, since any increase in input power to the ring will create a corresponding increase in reflected power. Normal operation under 50 W of reflected power usually allows enough time for frequency corrections after a power increase.

Tuning the resonant ring in stages was found to be advantageous. For example, if a power level goal of 300 kW is desired, tuning at 100 and 200 kW before final tuning at 300 kW allows for correction of ring parameters that change with temperature. The goals of tuning the resonant ring are twofold: (1) to minimize the standing wave ratio in the resonator (usually kept above 20 dB); and (2) to minimize reflected power to the transmitter after the first goal has been achieved. This form of tuning is performed in a careful manner, since both of these parameters are interrelated. Experience has shown that tuners A and B (see Fig. 3 [a]–[d]) are most effective in minimizing ring SWR, while tuners C and D have a more pronounced effect in controlling the power reflected to the transmitter.

It may be found that after a period of inactivity, or after cleaning, numerous shutdowns occur before a desired power level may be reliably maintained. This is most probably due to the vaporizing of small contaminant particles inside the waveguide. A dozen shutdowns before attainment of a high power level are common. An upward trend in power levels is indicative of normal ring self-cleaning. Scattered shutdowns normally occur as symptoms of a problem in the resonant ring. The greatest contributor to reliable resonant ring operation at high power levels is the absolute temperature of the coolant water. A flow rate as high as is practical in the waveguide walls is of paramount importance. It was observed that the rise in ambient temperature from morning to afternoon caused severely degraded operation in many instances. A cooling water flow of 4 gal/min on the main ring waveguide and 3 gal/min on the tuners allowed reliable operation at 450 kW, with an outlet water temperature of 39°C.

V. Experimental Results

After several weeks of experiments, a power level in excess of 400 kW was obtained regularly in the resonator. In particular, 400 kW was sustained for over 30 minutes.

Next, the 0.95-in. square test section was inserted into the resonator. The part was cooled by flowing water over it externally at a rate of approximately 3 gal/min. Power levels of 400 kW and 450 kW were sustained for periods of 30 minutes, and a peak level of 463 kW was attained briefly. This level represents the upper limit on the ring power, determined by the available power from the 20-kW transmitter driving the resonator. The power level of 450 kW represents an electric field value of 10.8 kV/cm in the 0.95-in. square section. This electric field level may be scaled to equivalent power levels in the 0.8-in. square waveguide and WR 125 waveguide at 8.51 GHz using [1].

Using [1], 450 kW in 0.95-in. square waveguide at 7.2 GHz represents 652 kW in WR 125 at 8.5 GHz, and 319 kW in 0.8-in. square waveguide at 8.5 GHz, in terms of equivalent electric field.

The results of these tests demonstrate that there is at least a 1-dB margin in the four feeding waveguides of the 1-MW horn under full power conditions. During the resonator tests, the ratio of forward traveling ring power to reverse power was maintained at about 20 dB, so in effect a return loss of about 20 dB is accounted for in these tests. When calculating the margins above, no sharp edges in the horn are accounted for. When the test part was fabricated, all edges were given a 0.03-in. radius except those connecting the WR 125 section to the 1.25-in. by 0.770-in. section, which is the first step in the transformer (see Fig. 8). Without considering the effect of this sharp edge, field values of 9.44 kV/cm are present at this point. Published data [2] indicate that electric field values near this edge may be nearly a factor of two greater than those calculated by [1], so the peak electric field in the test part probably occurs near this edge, not in the 0.95-in. square section. In any event, the 9.44-kV/cm value above is close to the 9.6-kV/cm field that will be present in the 1-MW horn, and the 0.8-in. square section should support 250 kW, even with a single sharp edge present.

VI. Conclusions

Resonant ring tests have been carried out on a reduced-size square waveguide. This square waveguide section represents a scaled version of one of the critical areas in a proposed 1-MW feedhorn. Tests confirm the capability of this section of the horn to withstand power levels in excess of 320 kW. This represents a 1-dB margin over the required level of 250 kW. Future investigations will include tests on an unscaled test part at 8.51 GHz, and should be able to give a margin of 2.6 dB. In addition, the insulating properties of various gases such as SF6 and Freon nitrous oxide will be examined for possible implementation in the DSN 1-MW planetary radar at Goldstone.

References

[1] W. C. Chen and R. Hartop, "Improved Cooling Design for High-Power Waveguide System," *TDA Progress Report 42-63*, vol. March–April 1981, Jet Propulsion Laboratory, Pasadena, California, pp. 104–107, June 15, 1981.

[2] S. B. Cohn, "Rounded Corners in Microwave High-Power Filters," *IRE Trans.*, vol. PGMITT-9, pp. 389–397, September 1961.

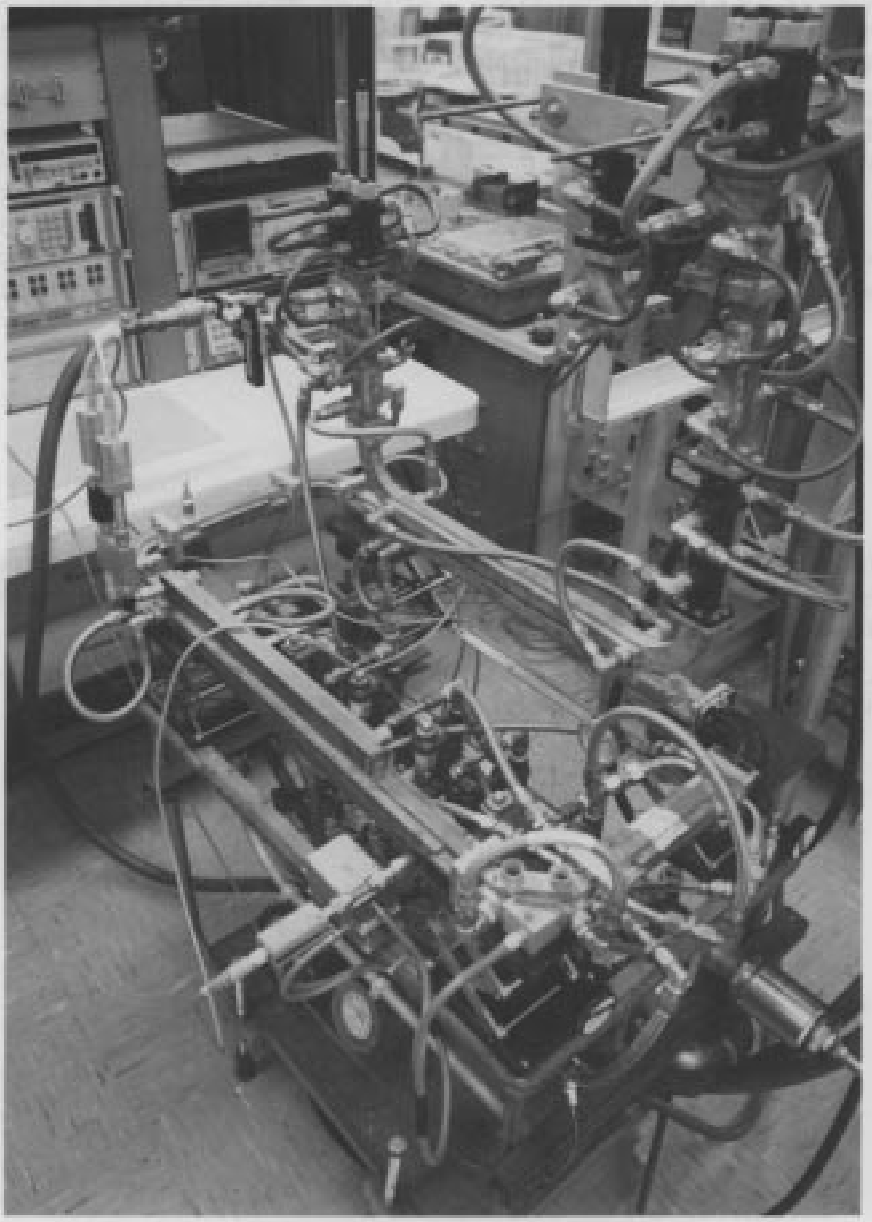

Fig. 1. The 7.2-GHz resonant ring

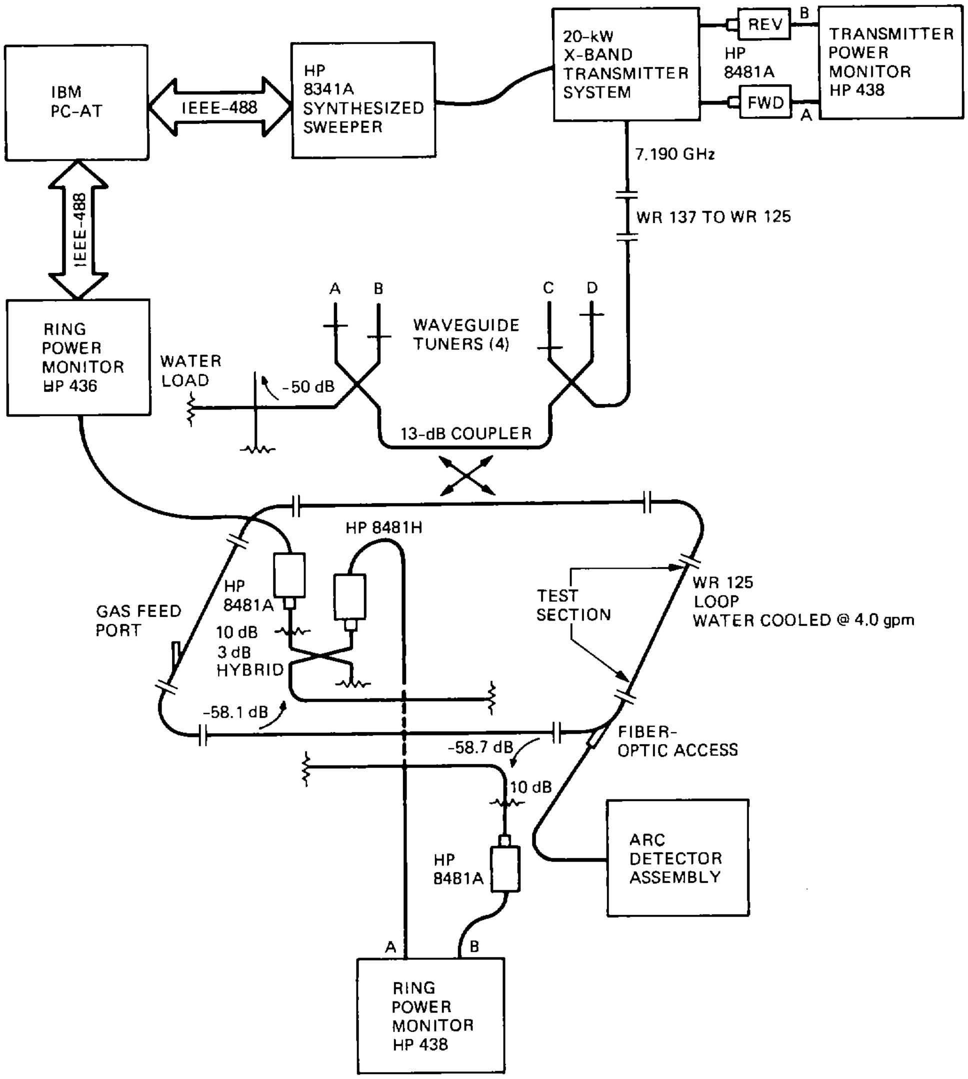

Fig. 2. Experimental configuration used for resonant ring testing

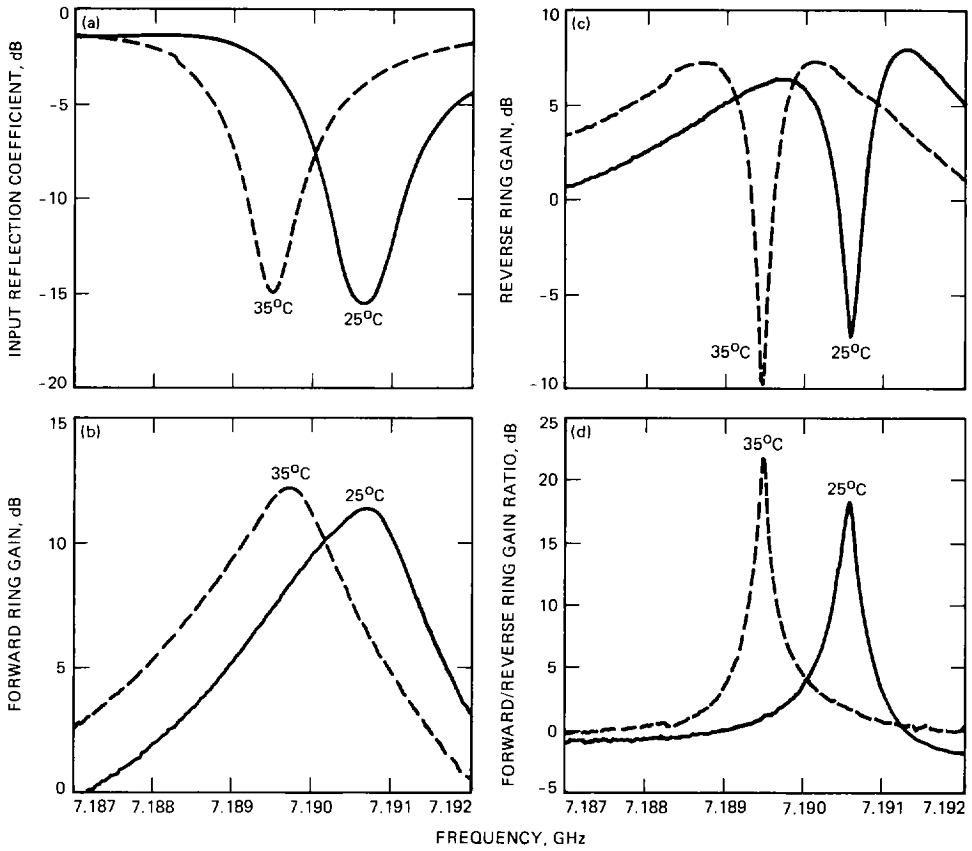

Fig. 3. Resonant ring (a) input reflection; (b) forward gain; (c) reverse gain; and (d) forward/ reverse gain ratio

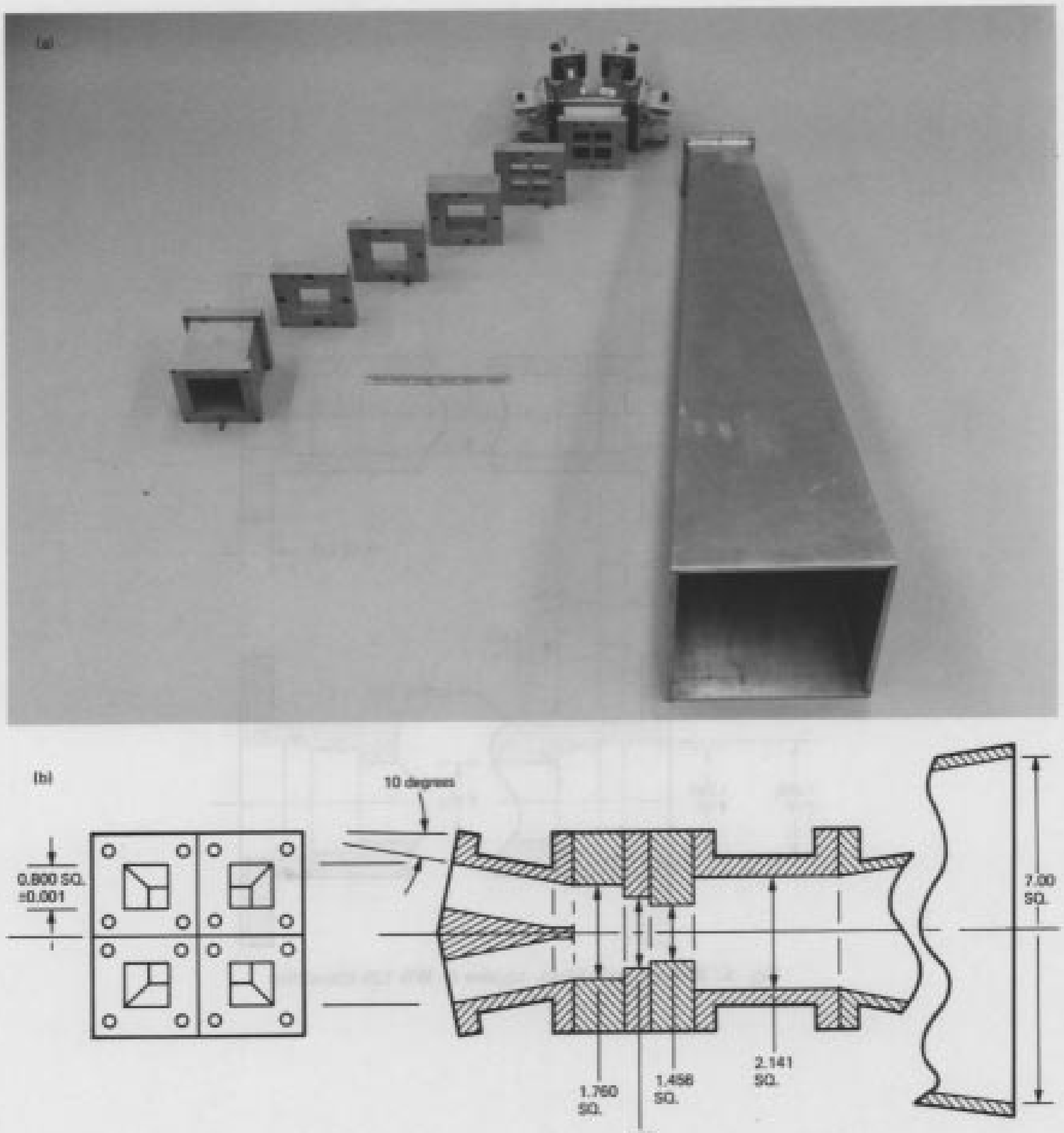

Fig. 4. The 1-MW feedhorn prototype: (a) full view; (b) detail of 1-MW feedhorn input section

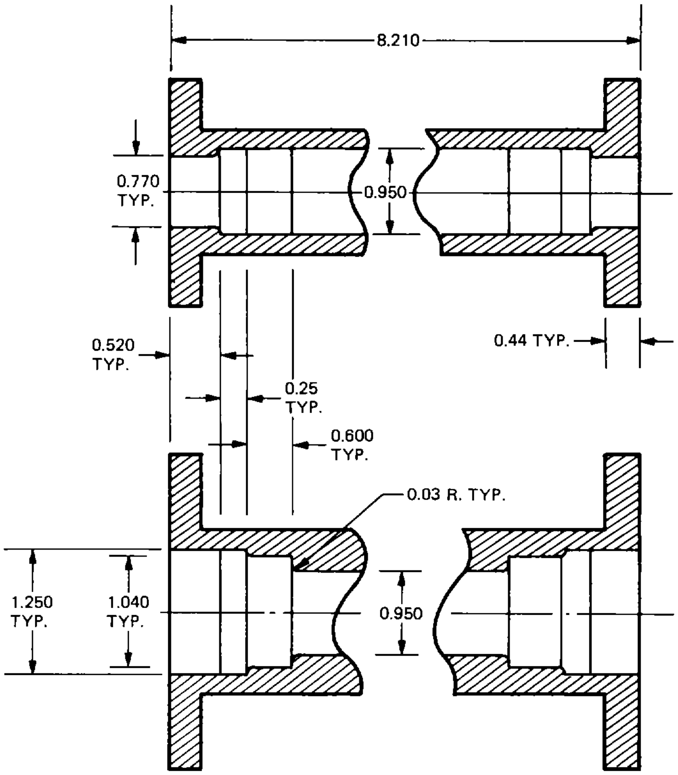

Fig. 5. WR 125 to 0.95-in. square to WR 125 transition