Development of Backward Wave Oscillators for Terahertz Applications

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Introduction

Calabazas Creek Research, Inc. (CCR) is developing advanced backward wave oscillators (BWOs) operating from 300 GHz to more than 1 THz. The BWOs will be used by the National Aeronautics and Space Administration as local oscillator sources in heterodyne receivers for low-background astronomy observations and remote sensing. Above 100 GHz, only BWOs have broad tunability (over 100 GHz) and high output power (~1 mW). The current program will reduce the weight, improve the efficiency, and extend the operating range of these devices.

CCR is working with Sandia National Laboratory to utilize advanced masking and etching techniques to reduce manufacturing cost and achieve unprecedented feature sizes. This will allow significant reduction in the periodicity of the BWO circuit, reducing the operating voltage and extending the operating frequency to more than 1 THz. Twenty six circuits can be made on a single 6 cm diameter wafer, significantly reducing the cost and improving reliability. The circuits will be manufactured using the LIGA process, and the results will determine what frequency range can be achieved. The current 600-700 GHz BWO requires feature sizes of approximately 20 microns, while LIGA is capable of producing feature sizes on the order of 5 microns. This indicates that frequencies approaching 2 THz may be achieveable. Circuits up to 1.9 THz are being manufactured for evaluation.

The output coupling into waveguide was redesigned to increase the amount of usable power by a factor of 5 in the 600-700 GHz BWO. Similar designs are now in progress to extend these techniques to the higher frequency BWOs. CCR is also investigating alternative coupling schemes to eliminate the requirement for waveguide output.

The current BWO utilizes an external permanent magnet to provide the 1.1 T field required for beam confinement. Recent research on W-Band sources developed techniques to confine electron beams using periodic permanent magnets within the vacuum envelope[1]. Research is underway to determine if such techniques can be applied to the BWOs. If successful, the weight of the BWO system would be reduced from approximately 20 Kg to a few hundred grams with a similar reduction in size.

Finally, the prototype BWOs will incorporate a single stage depressed collector for energy recovery from the spent electron beam. Simulations indicate that approximately 80% of the energy can be recovered, significantly increasing the device efficiency. This will reduce the electrical power requirement and eliminate water cooling.

Circuit Design

Calabazas Creek Research is using Microwave Studio to model the BWO circuit. The configuration of the BWO circuit is shown in Figure 1. Initially, the existing 600- to 700-GHz circuit was modeled in an attempt to duplicate the performance of the BWOs at the Jet Propulsion Laboratory (JPL). In parallel with the Microwave Studio simulations, which use a finite difference mesh, an analytical code was developed that allows simulation of circuits in seconds of CPU time, rather than the tens to hundreds of minutes required for Microwave Studio.

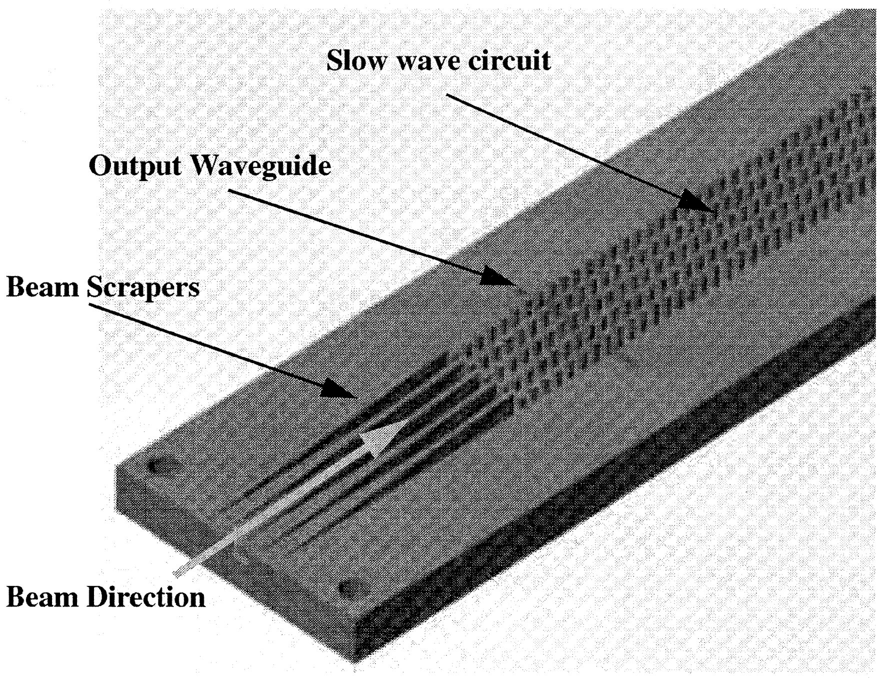


Figure 1. Layout of BWO circuit. The beam scrapers carves grooves in the rectangular electron beam for the slow wave structures downstream. The RF power is extracted through the base into rectangular waveguide.

The BWO circuit is periodic, so it is only necessary to model several periods. The geometry simulated is shown in Figure 2. The electron beam moves in the Z-direction, and there are five parallel rows of BWO posts, or pintles.

These efforts were successful in matching experimental measurements. Figure 3 compares the Microwave Studio analysis of the existing BWO with measured results at JPL. The agreement looks very good with the exception of two experimental points, which appear to be anomalous. The agreement is extremely good over the upper half of the band from 650 GHz to 700 GHz. The agreement with the measured results provides confidence in the accuracy of the model, which can then be used to calculate the magnitude of the electric fields, shown in Figure 4.

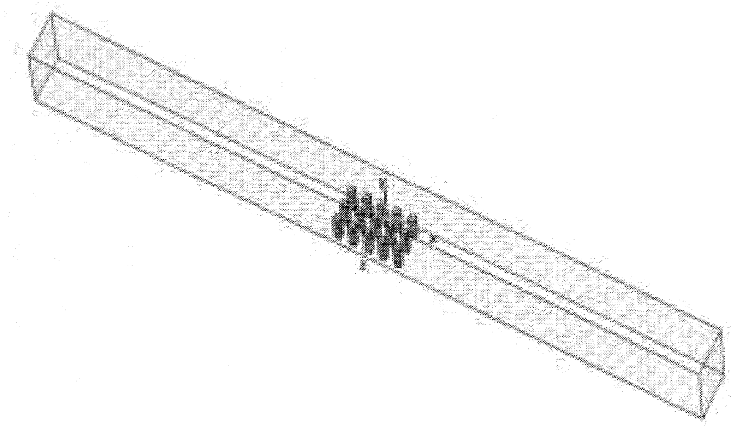


Figure 2. Periodic structure used in the Microwave Studio simulations. The enclosing box represents the size of the existing beam tunnel.

The model also allows analysis of potential competing modes. The simulation modeled the first five modes in the operating band. The predicted behavior of these modes in shown in Figure 5.

When the model was correctly predicting the observed performance, it was used to examine the effect of proposed changes in the circuit and beam tunnel configuration. The existing beam tunnel is 300μ high and 2,400μ wide. Apparently, the width was chosen for convenience by the current BWO manufacturer (Istok Co.) to facilitate manufacture. Using LIGA for manufacture allows simplification of the design to provide better performance. One of the first modifications proposed was to reduce the width of the beam tunnel from 2,400μ to 600μ. The new output coupler is approximately 600μ wide. It was necessary to determine if this change negatively impacts BWO operation. Figure 6 shows a comparison in the dispersion for this change as compared to the original design and measured results. The figure shows the proposed modification does not have a significant impact on BWO performance.

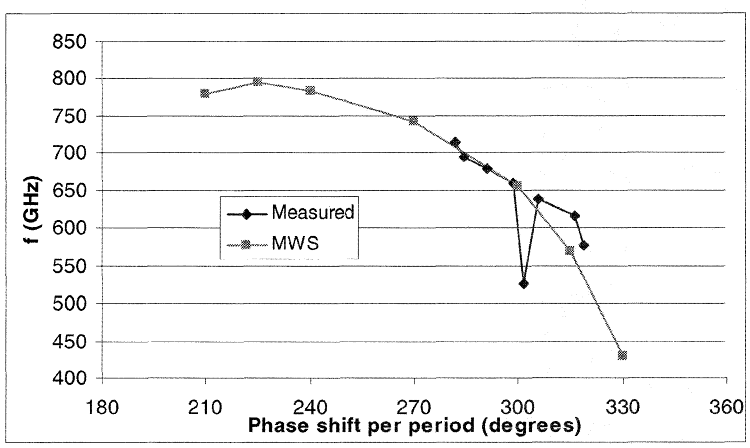


Figure 3. Comparison of measured and simulated dispersion of the 600- to 700-GHz BWO. Measured data is from NASA/JPL.

The interaction of the circuit with the electron beam is important to understand. As modifications are made to the circuit for higher frequency operation, there must be sufficient beam current density near the slow wave structure to initiate RF generation. As the frequency is increased, the required current density increases. Because the cathodes for the program are already purchased, it was necessary to determine how high in frequency they can operate. This will probably be the limitation in frequency until other cathodes are developed, because the LIGA process can produce circuit structures very high in frequency.

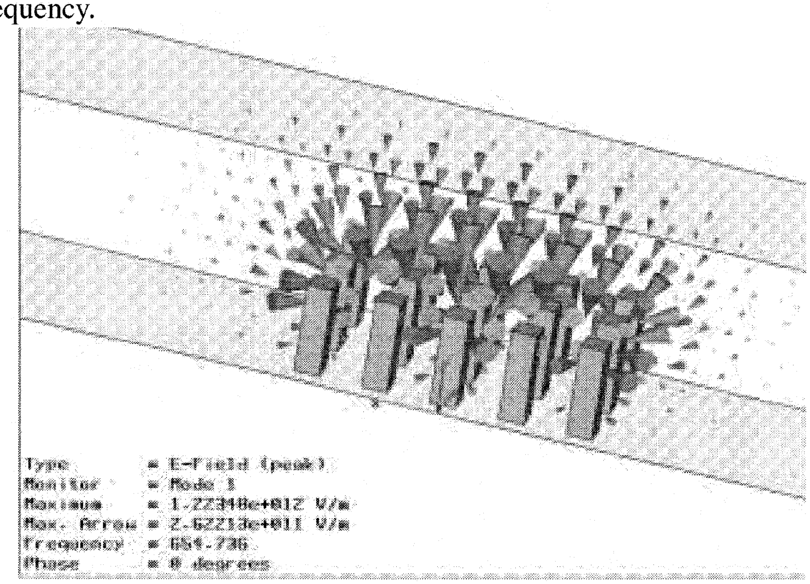


Figure 4. Arrow plot of the electric field strength at a phase shift per period of 300 degrees, f = 654 GHz. The size of the arrow is proportional to the electric field strength.

The relationship between the sheet electron beam and the circuit is shown in Figure 7, which is a cross section of the BWO looking in the Z-direction. The beam passes over the top and partially between the rows of pintles.

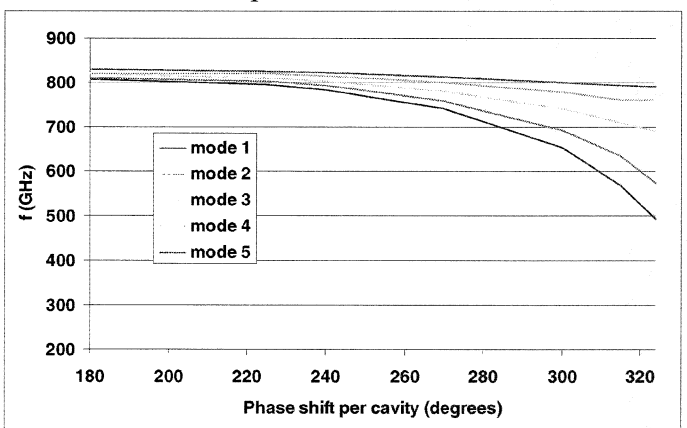
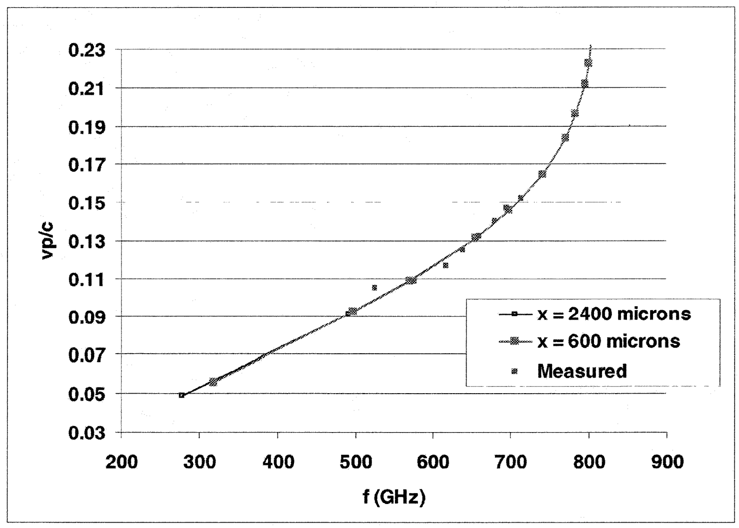


Figure 5. First five modes of the 600- to 700-GHz BWO

A plot of the electric field at various y-positions is shown in Figure 8. The peak fields occur at the tops of the pintles but significant field also extends into the region between the rows of pintles. this provides increased coupling to the electron beam.

When the magnitude of the fields is calculated, one can simulate impedance. The impedance is used to determine the ability of the electron beam to initiate oscillation. The impedance for both the existing BWO and a BWO with the reduction in beam tunnel width from 2400μ to 600μ were calculated. The greatest difference between the x = 2400μ



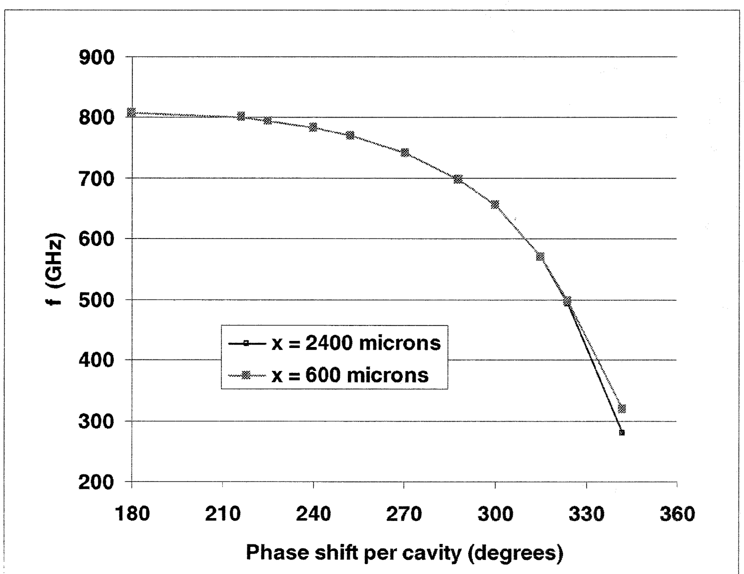


Figure 6. Top figure is simulated phase velocity versus frequency. Lower plot is comparison of frequency versus phase shift.

and 600μ cases is the behavior of the higher order modes. For the standard case, the next group of modes occurs much higher in frequency (approximately 10 THz). Reducing the x-dimension to 600μ causes this mode to shift down in frequency significantly (approximately 1 THz).

This reduction also places this mode in the vicinity of the second harmonic frequency of the operating mode, which might be problematic. To investigate this occurrence, the impedance at a phase shift of 270 degrees as calculated for the first branch of these higher modes occurring at about 1500 GHz. We determined that the impedance is significantly lower than the operating mode frequency, which means the desired mode should oscillate at a lower current than the higher order mode.

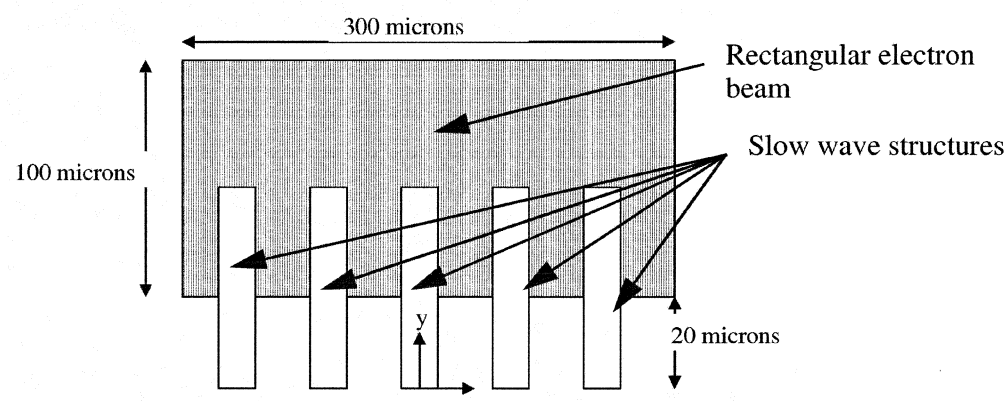


Figure 7. Schematic showing circuit coordinate system and electron beam.

Simulations are in progress to optimize the geometrical configuration for the 600-700 GHz BWO. Preliminary results indicate that the current spacing between rows of pintles (34µ) might not be optimal. In fact, the field structure appears more uniform with a spacing of about 10µ. Keep in mind, however, the requirement for beam transmission between rows. Reduced spacing may cause problems with beam alignment.

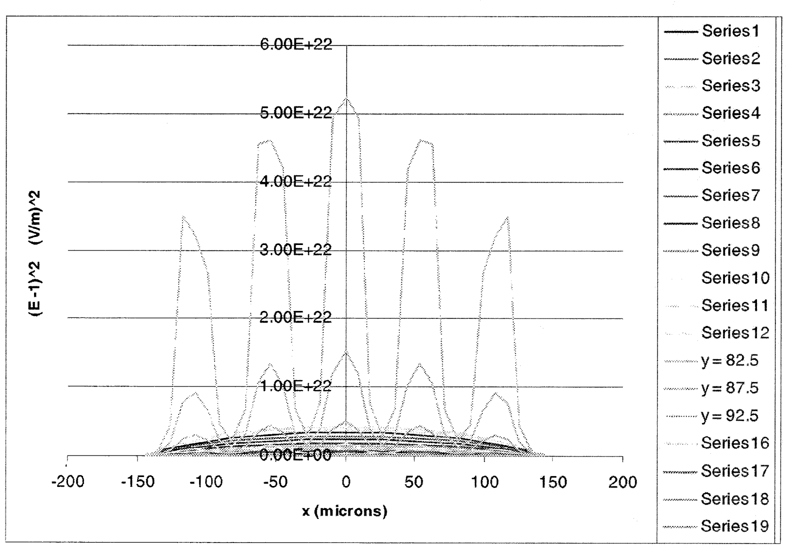


Figure 8. $|E_{-1}|^2$ as a function of x at several y locations for Beta L = 300 degrees (655 GHz) for standard case.

Higher frequency circuits were designed up to 1.9 THz. In theory, the circuit can be simply scaled by the frequency. Unfortunately, this requires an increase in the beam current density to get equivalent coupling. Several cathodes are already procured, so the design must be analyzed to determine how high in frequency the design can go and still use these existing cathodes. If necessary, higher current density cathodes can be procured; however, high emission current density also means reduced lifetime. There is also a 2- to 3-month delivery schedule for additional cathodes.

The higher frequency circuit configurations were designed and transmitted to Sandia National Laboratory, where the wafer will be made using the LIGA process. The lithographic process was initiated and 26 circuits are scheduled for delivery in July 2002 operating from 530 GHz to 1.9 THz.

Output Coupler

The existing BWOs couple the output power from the circuit directly into overmoded rectangular waveguide. Calculations and measurements indicate that less than 10% of the RF power is coupled into the fundamental waveguide mode. Consequently, only a small fraction of the output power is usable by downstream instrumentation. The program investigated modifications to the output coupling scheme to reduce generation of spurious modes and radiate the power in a pure Gaussian mode.

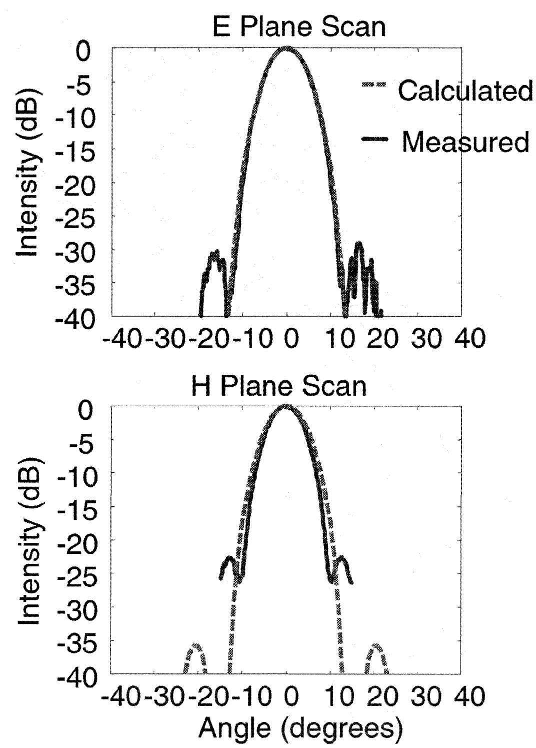


Figure 9. Measured performance of scaled output horn

The waveguide dimension were reduced at the slow wave circuit to only transmit the fundamental TE_{10} rectangular mode. A 2 micron iris was incorporated to match the waveguide to the RF circuit. A series of step transformers convert the TE_{10} rectangular mode into a TE_{11} circular mode in round waveguide. A non-linear horn is employed to generate a combination of TE_{11} and TE_{12} modes which, when combined together after a phasing section, radiate a 95% pure Gaussian free space wave.

A scaled version was built and tested at W-Band. Results of the measurements are shown in Figure 9. The spurious side lobes shown in the H-plane scan have since been eliminate following correction to the design code. A 600-700 GHz version of the output coupling system was manufactured and tested successfully at JPL.

Output Window

The current output windows consist of thin film glass mounted to stainless steel weld flanges. The new output design utilizes a dual mode horn to generate a Gaussian mode, so the guide wavelength is no longer the same. Fused silica is being investigated to provide half guide wavelength windows. Calculation indicate that the maximum VSWR in the operating band should be less than 1.4:1, which is considerably better than in the existing BWOs. It is anticipated that this will lead to reduced reflected power and better performance of the device.

Depressed Collector

The interaction efficiency of BWOs is typically less than a few percent, so most of the electron beam energy is dissipated in the collector. A single stage depressed collector was designed to recover this energy and improve the overall efficiency of the device. The power reduction also allows elimination of the water cooling required for the existing BWOs. A simulation of the depressed collector is shown in Figure 10. Electrons from the cathode pass through the slow wave circuit, across an insulating gap, and into a cavity designed to contain reflected and true secondary electrons. The cavity material is graphite to reduce the number of secondary and reflected electrons generate. Simulations indicate that approximately 85% of the beam power can be recovered. This will reduce the maximum power required for the BWO from 270 W to less than 50 W.

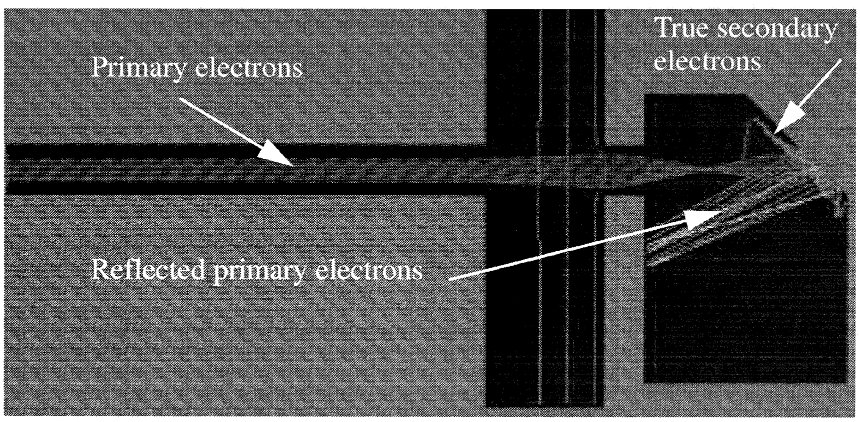


Figure 10. Simulation of sheet electron beam with single stage depressed collector. Primary electrons, reflected primary electrons, and true secondary electrons are indicated. Simulation is at 5,000 Volts, 30 mA.

Reduction of Magnet Size and Weight

Techniques are currently being developed to integrate permanent magnet focusing into W-band klystrons. This work is funded by the U.S. Air Force through the Multidisciplinary University Research Initiative (MURI), and CCR is involved with this program. The magnet research is being performed at the Stanford Linear Accelerator Laboratory.

Basically, permanent magnets and iron pole pieces are incorporated directly into the LIGA-produced structure to place the parts extremely close to the electron beam. This proximity reduces the magnetic field required and dramatically reduces size and weight.

CCR is investigating a similar technique for the BWOs. Because the BWOs use a sheet electron beam, permanent "wiggler" focusing is being considered. Preliminary calculations indicate that sufficient field strength can be generated using wiggler focusing adjacent to the electron beam and within the vacuum envelope. This procedure reduces the total weight of the BWO and magnet from 15 to 20 kG to less than 0.5 kG.

Implementation of permanent magnet, wiggler focusing requires a different type of electron gun. The current gun is totally immersed in the 1.1 T field, which provides the required focusing. Immersion will not be possible with permanent magnet, wiggler focusing, because the magnetic field will not extend into the gun region. Consequently, it is necessary to design an electrostatically focused, convergent gun. CCR currently has a Department of Energy SBIR grant to develop a sheet beam gun for an X-band klystron, so the actual gun design will not be a major task. Mechanical design of such a gun with the small size required could, however, be a significant development effort. One alternative being considered is a field emitter array (FEA) cathode. FEA cathodes do not require a heater and are theoretically capable of very high current densities—higher than available with the existing cathodes.

BWO Construction and Test

A solid model of the 600-700 GHz beam line assembly is shown in Figure 11. The main body assembly is approximately 2 cm X 2 cm X 4 cm and will be enclosed within a copper or glass vacuum envelope. The basic assembly is designed for compatibility with several of the LIGA circuits being manufactured. The output waveguide/ Gaussian mode antenna and window are frequency dependent, so these items must be designed for each particular frequency band. All circuits will have the same base structure so they will be interchangeable within the BWO body section. When the basic configuration is designed, it should be fairly straightforward to install various circuits and output components into a standard BWO body. This capability will reduce the design effort, manufacturing costs, and reliability while facilitating rebuilds.

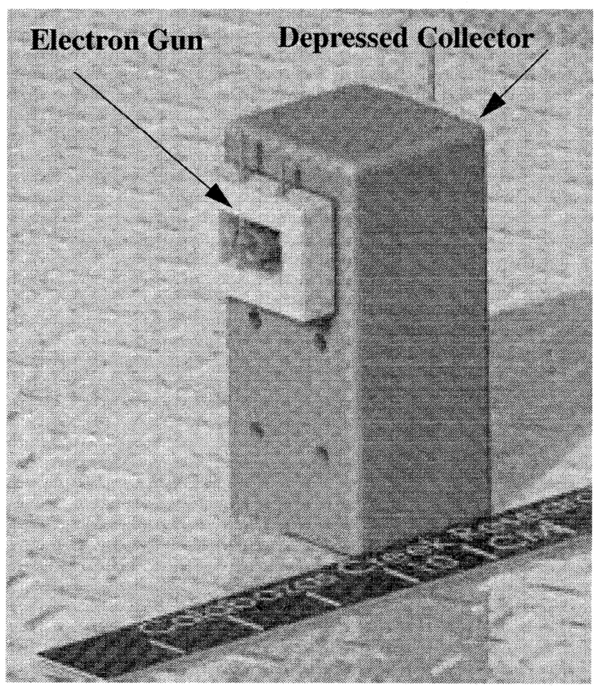


Figure 11. 600-700 GHz Beam Line Assembly.

The cathodes, magnet, power supplies, are completed. The LIGA circuits are currently being manufactured with delivery scheduled for early July. Drawings for the remaining parts, including the window, body, collector, electrical feedthroughs, and vacuum envelope are in progress. It is anticipated that final assembly of the prototype 600-700 GHz BWO will begin in July with completion in August. Testing will begin as soon as the prototype is completed.

Following successful test of the 600-700 GHz BWO, construction will begin for the next BWO in the frequency series which will operate from 650-900 GHz. Additional BWOs will be built and tested as time and funding allow.

Program Summary

A complete, theoretical understanding of the BWO circuit and interaction with the electron beam are essentially complete. This understanding will facilitate optimization of BWO performance and extension of the design to higher frequency, output power, and efficiency. Additional analysis is planned to improve understanding of RF coupling from the slow wave structure into the output waveguide slot.

Analysis to date, coupled with dramatic advances in micro-electro-mechanical systems and FEA cathodes, provides many possibilities for improvements in BWO performance, reduction in weight and power requirements, and reduction in size and weight.

1. Glenn Schietrum, A. Burke, G. Caryotakis, A. Haase, L. Song, "W-Band Klystron Research," Pulsed Power Plasma Science 2001, 28thy IEEE Intern. Conf. Plasma Sci., June 2001, Las Vegas, NV.

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