Development of Efficient Backward Wave Oscillators for Submillimeter Applications

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I. Introduction

Calabazas Creek Research, Inc. is funded by the National Aeronautics and Space Administration to develop efficient, light-weight, backward wave oscillators (BWOs) for applications from 300 GHz to 1 THz. These devices are needed as local oscillator (LO) sources in heterodyne receivers. Very low noise heterodyne receivers are needed at submillimeter wavelengths for low-background radioastronomy observations and remote sensing of comets, Earth and other planetary atmospheres. Above 100 GHz, only BWOs have broad tunability (over 100 GHz) and high output power (~1 mW); however, they are heavy (over 20 kg), consume a lot of power (270 W), required water cooling, and have poor output mode purity. Figure 1 shows a BWO of this design inside its magnet at the Jet Propulsion Laboratory in Pasadena, CA.

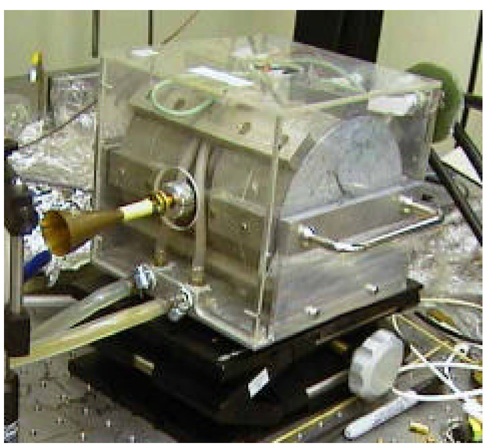


Figure 1. Current state of the art BWO in operation at JPL. The BWO is located inside the cylindrical permanent magnet structure.

Many important molecules play a key role in the energy balance, chemistry, and dynamics of interstellar molecular clouds, planetary atmospheres, and cometary coma. High resolution observations of these species are needed to understand the structure and evolution of the galactic and nearby extragalactic interstellar medium. Heterodyne instruments are required for these observations at ground-based observatories such as the Caltech Submillimeter Observatory, airborne observatories such as the upcoming NASA SOFIA (a 747 aircraft with a 2.5 m telescope), and the ESA Far Infrared and Submillimeter Telescope mission. Currently there are no compact, low-power, broadband LO sources, even above a few hundred GHz. Such a source would enable new science missions and enhance the science return of a given mission as well as expedite the laboratory development of the receiver system.

The technical objectives of the current program are as follows:

- Incorporate a depressed collector to improve the efficiency and eliminate water cooling,
- Improve the electron gun and configuration of the slow wave structure to increase interaction efficiency and reduce body current,
- Improve the output coupling to increase mode purity,
- Reduce the magnet system size and weight,
- incorporate in improved mounting system to facilitate BWO installation and alignment.

In this paper, the various design improvements for the BWO will be covered. Efficiency improvements to the electron gun, slow wave structure and collector will be covered in Section II. In Section III, the design of the output mode coupler will be addressed. Conclusions are given in Section V.

II. Efficiency Improvements

The purpose of the depressed collector is to recover energy from the spent electron beam emerging from the slow wave circuit. Because the electronic efficiency of the BWO is very low, on the order of 1%, a significant amount of the original beam energy is available for recovery. A schematic diagram of the BWO is shown in Figure 1.

A rectangular electron beam is emitted from the cathode in the presence of a high magnetic field. The beam interacting with the slow wave structure is ‘carved out’ by the beam scraper section. This is an innovative approach to beam generation for a series of parallel slow wave structures. The beam scraper is manufactured as part of the slow wave structure which assures precise alignment between the fins of the scraper and the pintles of the slow wave structures. The beam is precisely shaped for optimum interaction and is relatively insensitive to misalignment of the cathode with respect to the circuit. The slow wave structures are currently separated by only 34 microns, yet the positioning of the cathode has only a minor effect on optimum performance.

Unfortunately, it is precisely this characteristic that limits the amount of beam energy that can be recovered by a depressed collector alone. Electron beam energy intercepted by the beam scraper becomes body current and is unavailable for energy recovery. To reduce the amount of energy lost to the body, the circuit can be modified to use four parallel slow wave structures rather than the existing five. In addition, the electron beam can be reduced in size and the separation between slow wave structures increased to 50 microns. To reduce the beam voltage, the periodicity of the slow wave structures can be shortened such that the maximum voltage requirement will be 4000 volts instead of 6000 volts.

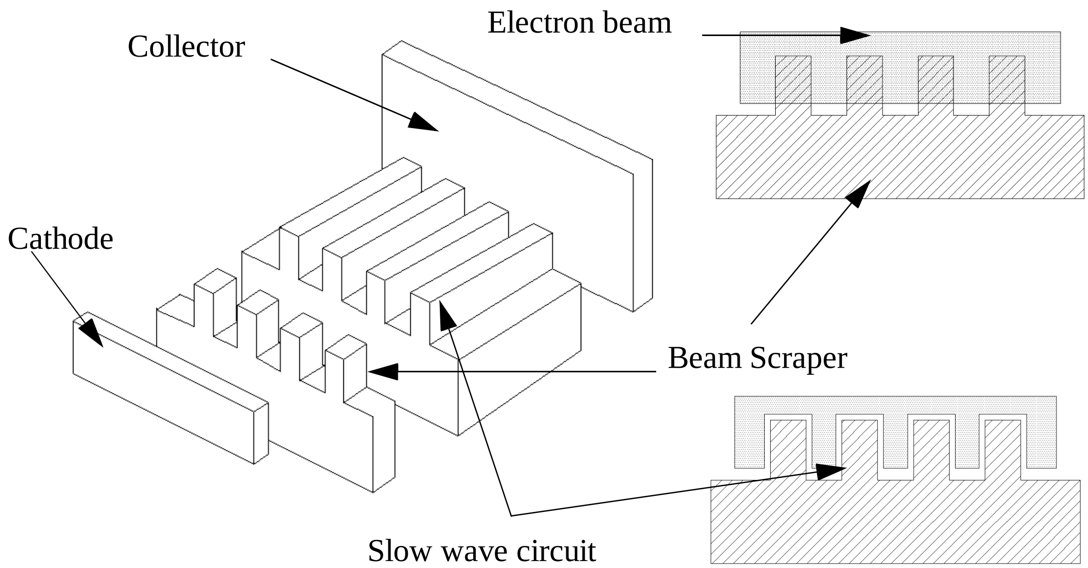


Figure 1. Basic configuration of the existing BWO design

Three-dimensional beam simulations were performed to generate a precise energy balance for the existing tube. The final disposition of the original beam power is provided in the following energy balance:

• Beam scraper	17%
• Conversion to RF	1%
• Interception by slow wave structure	5%
• Collector	77%

Simulation results indicate that approximately 3% of the power deposited on the collector cannot be recovered because of velocity spread in the beam.

The next major power loss, however, is the energy intercepted by the beam scraper. Reducing the beam size and modifications to the slow wave structure can reduce the power lost to the beam scraper by approximately 30%. Additional power savings is achieved by the reduction in beam voltage, because the beam current should not change significantly. The estimated input power requirements with a depressed collector for 600

GHz operation would be 15 W and for 700 GHz operation would be 36 W.

Several alternative depressed collector implementations have been explored. The configuration shown in Figure 2 consists of a flat ceramic insulator brazed between two tungsten or molybdenum plates. Issues related to this configuration are the thermal conduction through the ceramic, the possible increase in secondary emission of tungsten or moly over copper, and the stresses generated in the ceramic by steep temperature gradients. The heat is incident on the collector over a very small region (70 x 300 microns).

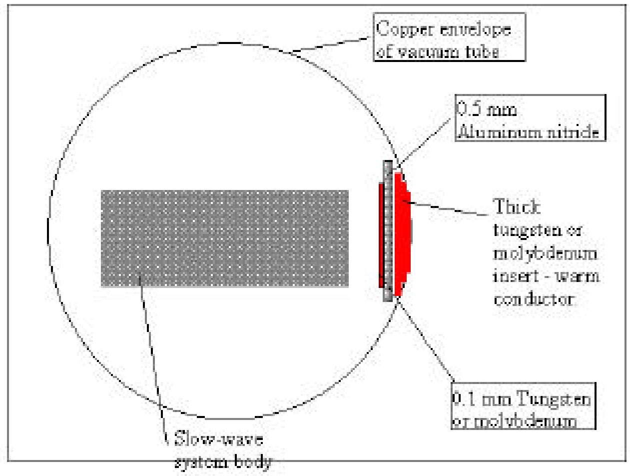


Figure 2. Alternative implementation of depressed collector

Combining all the improvements collector and circuit improvements would reduce the input power from the present 270 watts down to approximately 15 watts. The estimated input power versus incremental improvements to the BWO is shown in Table 1. The improvements are listed in order of increasing technical difficulty in implementation.

Table 1: Estimated Input Power versus Incremental Improvements

Modification	Input Power (W)
Current Design	270
Depressed Collector	80
Reduced Beam Voltage	50
Circuit Modifications	40
Cathode Grid	15

III. Output Coupler

Experience at the Jet Propulsion Laboratory indicates that the output mode purity from the current BWO is relatively low. These observations were confirmed by analysis. This means that a significant proportion of the output power is unusable, effectively reducing the output efficiency of the device. The RF power is coupled from the slow wave structures through a 30 micron gap in the circuit. The rectangular waveguide at the slow wave structure is 30 microns high and 2.4 mm wide in the existing BWOs. The waveguide transitions to a final height of 1.2 mm in a distance of 8 mm. The principle source of the poor mode purity appears to be the coupling from the slow wave circuit to the 30 micron by 2.4 mm waveguide. The waveguide at the slow wave structure is extremely overmoded and excited by an electric field that extends over approximately one eighth of the waveguide width. More than 30 waveguide modes can propagate; however, only 5 or 6 will couple to the excitation field in the slow wave structure. Decomposition of the electric field within the waveguide indicates that only 25% of the power will be coupled into the fundamental waveguide mode.

An obvious way to improve this situation is to reduce the width of the waveguide at the slow wave structure. This will result in power being excited in only the fundamental mode, which will quadruple the usable output power over that of the current design. The new slow wave circuit design has a total width of 230 microns, while the wavelength at 600 GHz is approximately 500 microns. This implies that the waveguide width can be reduced to approximately 260 microns, which will support only the fundamental rectangular waveguide mode at the low frequency end of BWO operation.

It is desirable to have a Gaussian output from the tube due to the low loss and relatively large dimensions of quasi-optical components used to guide and transform the Gaussian beam mode. Several options were considered for generation of the Gaussian mode. Corrugate horns are very efficient generators (98%) of the Gaussian mode but are difficult to manufacture. Rectangular horns are easier to construct but have lower efficiency (84-88%). Potter horns have higher efficiency (96%) but over a narrow bandwidth.

In Potter dual-mode horn designs, the hybrid mode mix (TE_{11}/TM_{11}) necessary for efficient coupling to the Gaussian mode is generated by a sudden transition in the circular guide. While this is an effective way to generate the required mode mix it suffers from several deficiencies. First, this transition introduces a mismatch which requires compensated. Second, the transition must occur in a region that is cutoff to all modes higher than the TM_{11} mode. This means that if a large wavelength aperture is desired, the transition must be followed by a taper which can introduce unwanted mode conversion in addition to adding excess electrical length. The combination of the transition and separate taper result in a design with limited bandwidth.

We have developed a new approach to generate the hybrid mode by use of a computer optimized, non-linear smooth variation in the wall radius (Figure 3). This shape combines the necessary mode conversion as part of the taper to the desired output apertrue. Since there is no abrupt transitions in the wall radius, the frequency sensitivity is reduced. A comparison of the efficiency and return loss of this new design (normalized to nominal frequency) was done against designs published by Potter[1] and Pickett[2]. As can be seen in Figure 4, the non-linear design approach has the advantage of higher peak coupling efficiency (>99%), larger bandwidth and improved return loss than the other horn designs while also having a larger aperture area. The polarization coupling factor is also higher than the comparison designs which are shown in Table 2. The waveguide modal amplitudes at the aperture were calculated by a multi-mode analysis code (*Cascade*[3]) and the coupling of the waveguide modes to the fundamental Gaussian mode by means of the Gauss-Laguerre beam-mode analysis technique[4].

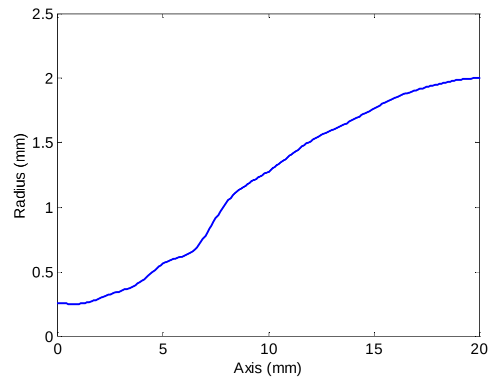


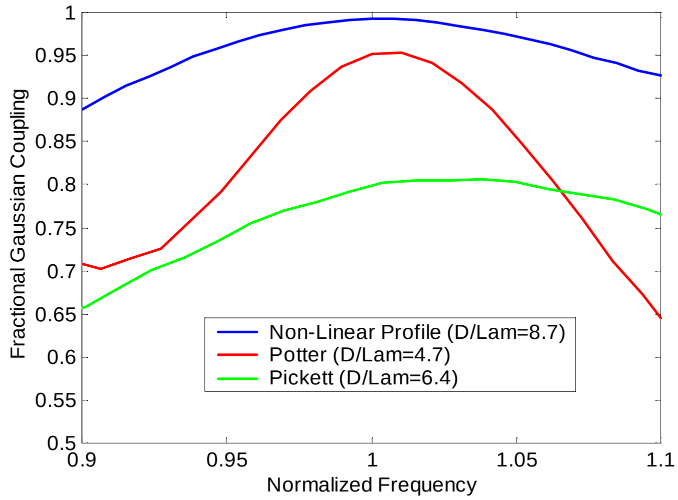
Figure 3. Non-linear wall variation used to generate hybrid mode.

Table 2: Polarization Coupling Factor

Design Type	ε_{pol}
Non-Linear	0.999
Potter	0.986
Pickett	0.933

Coupling from the rectangular waveguide circuit output to the circular, Gaussian mode horn is done through a sudden rectangular to circular transition with matching transformer sections. The return loss of this component is greater than -30 dB across the output band.

(a)



(b)

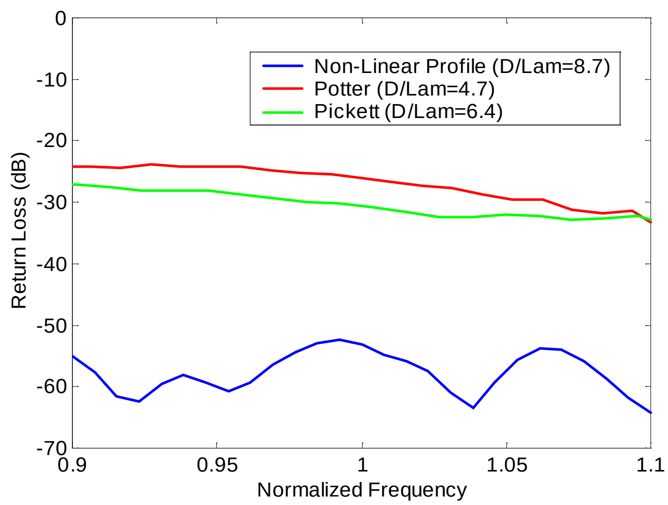


Figure 4. Comparison of Gaussian coupling and return loss for non-linear taper profile and other published designs. (a) Fractional Gaussian coupling versus normalized frequency. (b) Return loss versus normalized frequency.

IV. Conclusions

This proposed effort will address each the drawbacks of existing BWOs using modern innovations in tube and magnet technology which have already been demonstrated. Successful development will result in devices that require significantly less input power (as low as 15W), have reduced weight (8 Kg or less), require much less cooling, and provide significantly improved mode purity. In addition, the power supply for the BWO tube will be smaller and less complicated. Such an LO source would have a significant impact for researchers developing low-noise mixers for heterodyne instruments. It would greatly facilitate the laboratory development of these sensors. This would reduce development costs and time for heterodyne receivers for NASA observational programs. In addition, the potential reduction in required input power to 10 W would allow these sources to be used directly in instruments for aircraft platforms (such as SOFIA), long-duration balloon platforms, and even space missions

1. P.D. Potter, "A New Horn Antenna with Suppressed Sidelobes and Equal Beamwidths," *Microwave J.,* pp 71-78, June 1963.

2. H. Pickett, J. Hardy, and J. Farhoomand, "Characterization of a Dual-Mode Horn for Submillimeter Wavelengths," IEEE Trans. MTT, Vol MTT-32, No. 8, pp 936-937, August 1984.

3. W. Vogler, J. Neilson, and L.Ives, "CASCADE - An Advanced Computational Tool for Rapid Waveguide and Circuit Design," 1998 Microwave Vacuum Electron Devices Conference, Monterey, CA May 1998, page 3E.4

4. P. Goldsmith, *Quasioptical Systems*, IEEE press, pp. 158-160.