STTR Phase I Project Description

1 Identification and Significance of the Innovation

Powerful and economical THz sources are key to realizing the full potential of this emerging wavelength regime. In Phase I of the STTR TeraVision Inc. proposes to partner with the University of Arizona in utilizing carbon nanotube technology together with leading edge micromachining to develop THz sources and amplifiers scaled from proven traveling-wave tube designs. These tubes can be configured to serve as high power signal sources or low noise amplifiers, with package sizes of the order of 10x10x10 cm. The availability of such sources and amplifiers will help make THz imaging systems a reality and unleash a wide variety of applications.

As THz detector technology has recently become more widely available, the number of potential THz applications has skyrocketed. Potential THz applications range from the standoff detection of explosives and chemical and biological agents, to the measurement of in vivo tissue water content, fat content, blood glucose and cholesterol contents and the diagnosis of cancer. In dentistry, THz imaging may provide a powerful alternative to X-rays. In the food processing industry, THz waves will help detect E-coli and other poisonous bacteria as well as small imperfections in packaging. THz spectroscopic imaging can help Law-enforcement with the detection of prohibited substances and counterfeit bank notes.

Yet, despite all the exciting laboratory work, very few commercial products have made it to market. Naturally occurring sources have very limited THz power output, and artificial sources to date (far infrared lasers, femtosecond lasers, free electron lasers, synchrotron particle accelerators etc.) have proven inadequate (too bulky, not efficient enough, too expensive) for most Terahertz applications.

2 Background and Phase I Technical Objectives

Traveling wave tubes (TWT's) are a proven technology to frequencies of $\sim$100 GHz. Indeed, these devices can be found in the majority of communications satellites, ground-based and airborne radars, and a variety of remote sensing systems. Our goal in Phase I is to complete a thorough design study for manufacturing TWT based oscillators and amplifiers for operation in the THz frequency regime. The critical components of a TWT are the cathode, beam focusing optics, slow-wave structure, and collimating magnetic field. In the Phase I design study we will:

1. Investigate the use of carbon nano-tube technology to provide the electron source.
2. Use state-of-the-art software tools to optimize
    - the design of electrostatic focusing optics to reduce the electron beam diameter to the required size (10-50 microns) for THz applications
    - the interaction impedance between electron beam and the electromagnetic field in the slow-wave structure.
3. Use the micromachining facilities at the University of Arizona to fabricate prototype slow-wave structures.
4. Use the electron microscope test-bed system at the University of Arizona to verify performance of slow-wave structures.
5. Use modeling and test results to investigate the feasibility of realizing commercial 368 GHz and 1.5 THz TWT amplifiers and oscillators.

The Phase I report will include both modeling and experimental results and provide a clear path to commercial applications.

3 Phase I Research Plan

3.1 *Traveling Wave Tube Amplifiers: Principle of Operation*

Traveling wave tube amplifiers are currently in use from below 1 GHz to 100 GHz and are capable of generating power levels from watts to megawatts. They are used in a wide variety of applications; including radar, communications satellites, and electronic countermeasure systems. Amplification occurs through an interaction between an electron beam and a nearby radio frequency (RF) circuit carrying the signal to be amplified. Through the interaction some of the kinetic energy of the electrons in the beam is transformed into RF radiation. For this to occur the velocity of the RF signal flowing through the circuit must be slowed down to match the speed of the electrons in the beam. The possibility of such an interaction was recognized as early as 1933 (Haeff 1933, Lindenblad 1940) and later Kompfner (1942) were the first to describe using a helical transmission line wrapped around an electron beam as a tube architecture that meets these requirements. The helix serves as the slow-wave structure that matches the axial propagation velocity of the RF signal to that of the electron beam. The basic design of such a TWT is shown in Figure 1 (Gilmour 1994). Today slow-wave structures composed of coupled cavities also serve this purpose.

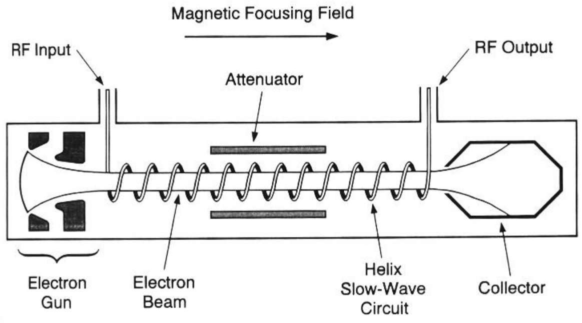


Figure 1: *Schematic of an experimental helical traveling wave tube (TWT), from Gilmour (1994).*

When an electron beam is injected along the axis of the helix, axial electric field components of the RF signal accelerate some electrons while decelerating others. This interaction causes the electrons in the beam to bunch-up. As an electron bunch travels down the center of the helix each interaction with the RF signal increases the charge density in a given bunch. The fields produced by the bunching electrons in the beam will induce corresponding electric currents in the helix, adding constructively to the electric field of the signal it is carrying. As the beam-wave interaction continues, the induced waveform rapidly becomes larger than the initial signal and amplification occurs (Gilmour 1994). A diagram illustrating the relationship between electron bunch charge density and RF circuit voltage with distance along the tube axis is shown in Figure 2 (Hess 1960).

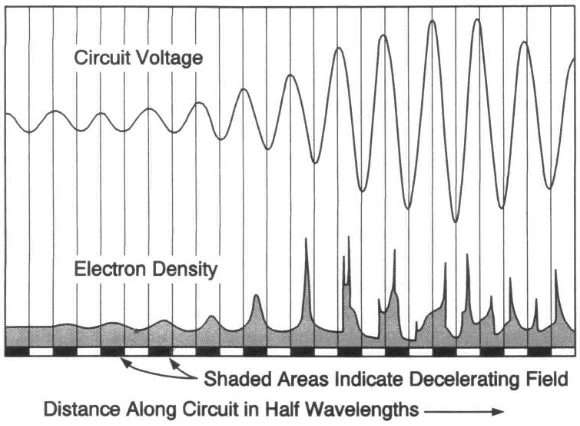


Figure 2: *Illustration of the interaction between electron beam and RF signal in a TWT, resulting in RF amplification. Adapted from Hess (1960) in Gilmour (1994).*

Note that near the end of the tube the charge density in an electron bunch becomes large enough for space-charge forces to begin to disperse it, leading to destructive interference and field saturation. Today the two most common types of slow-wave structures used are the venerable helix and coupled waveguide cavities. The helical design can generate tens to hundred of watts over as much as two octaves of frequency. The coupled-cavity type TWT is narrower band (10-20%), but is capable of producing megawatts of power.

3.1.1 THz Slow-wave Structures

The practical high frequency limit of TWT's was continuously pushed to higher frequencies until the early 1990's when high frequency, high electron mobility transistors (HEMTs) became available. Today, HEMT-based amplifiers have been built to 200 GHz, beyond which limitations in photolithographic processing make them extremely difficult (or impossible) to produce. The high frequency limit of TWTs is set principally by losses in the slow-wave structure. Using modern machining and photolithographic techniques TWT operation to several THz should be possible. This plus the fact that TWTs have been shown to be capable of very low-noise operation (<0.2 dB, Hammer and Wen 1964) provides a strong incentive to push TWT technology to higher and higher frequencies.

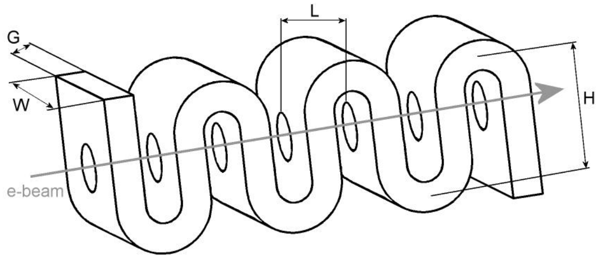


Figure 3: *3D rendering of the geometry of a meandering waveguide slow-wave structure.*

The implementation of a helical slow-wave structure becomes more difficult with frequency. Meandering waveguides have been successfully used at high frequencies as an alternative slow-wave structure (Figure 3). Here interaction between beam and wave is maintained by periodically folding the waveguide back into the beam path. Sharp corners in the bends should be avoided in order to reduce reflections which reduce gain. The waveguide cross section should be retained in the bends for the same reason. Electron-signal interaction occurs where the particle beam passes through the waveguide. The degree of electron-beam interaction that takes place at each encounter is described by the gain parameter C, given by (Pierce 1950):

$$C = \left(\frac{Z_\circ}{4\, V_\circ / I_\circ} \right)^{1/3} \qquad (1)$$

where $Z_\circ$ is the interaction impedance and $V_\circ/I_\circ$ is the beam impedance. Waterman (1979) successfully constructed a 46 GHz TWT using the meandering waveguide structure shown in above. For this structure he derives a value of $Z_\circ = 4.65\Omega$. For our proposed investigations we will use a $1/8^{\text{th}}$ scale of Waterman's design implemented in a copper "split-block" (*J. Waterman has agreed to collaborate with us on this project, see Support Letter*). At the design frequency of 368 GHz the characteristic dimensions of the meandering structure are $G = 79.5\ \mu$m, $W = 457\ \mu$m, $L = 177\ \mu$m , and $H = 346\ \mu$m, with a 127μm diameter beam hole. Using the high precision Kern micromilling machine available in the PI's lab at the University of Arizona, we have fabricated this split block structure (see Figure 4) and will test its performance in the near future.

In the initial characterization of the meandering slow-wave structure we will use our electron microscope as the beam source (see Figure 5). We will then replace the electron microscope with a compact, high efficiency beam source that utilizes commercially available power supplies, carbon nanotube cathodes (see section 3.1.2 below), and permanent magnets (for beam confinement). Typical values of beam current and voltage are $V_\circ = 25$ keV and $I_\circ = 1$ mA. Substitution into the above equation then yields a value of $C = 0.0036$. The power gain P_G of a TWT can be expressed as (Gilmour 1994):

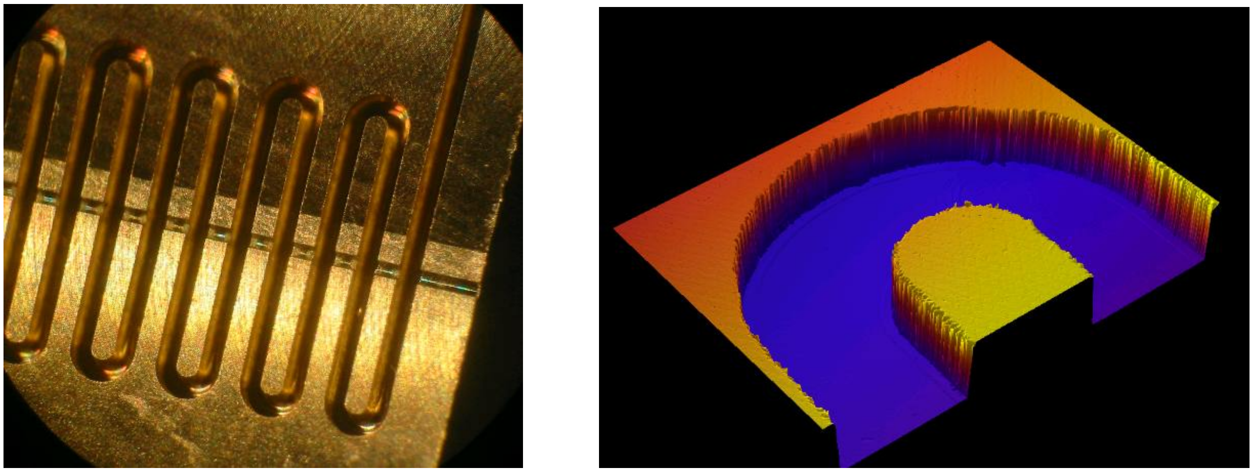


Figure 4: *Left: Microscope image of TWT amplifier slow-wave structure machined in the PI's lab at the University of Arizona. Right: Interferometric Microscope image of the same structure. Measured surface roughness is 120 nm rms waveguide depth is 352 μm.*

$$P_G = 47.3\,CN\,\mathrm{dB}$$

where $N = \text{tube length}/L$. To achieve P_G of 10 dB will require a $N \sim 59$ and an overall tube length of $\sim$ 1 cm.

We have modeled the full length of the slow-wave structure in CST Microwave Studio and found the total loss (including the effects of finite conductivity, surface roughness and leakage through the beam tunnel) to be <2 dB across the operating range of the tube. A snapshot of a computer animation showing the propagation of fields in the slow-wave structure is shown in Figure 6.

Predictions of C, Z_0, and P_G will be tested by real circuits and beams in experiments with the modified SEM. Experimentally-determined coupling impedances will then be used in large-scale TWT simulations (see letter from Raytheon) to design optimized TWT circuit lengths and parameters. Additional gain (up to ~60 dB) can be achieved by increasing the length of the slow-wave structure and/or raising the beam current. As long as the beam can be confined to travel through the beam tunnel and the surface roughness of the slow-wave structure is <3 skin depths, the TWT circuit described here can be scaled directly for operation at THz frequencies, giving it a huge advantage over other devices.

Figure 5: *Amray 1000a scanning electron microscope to be used as an electron beam source in initial TWT measurements.*

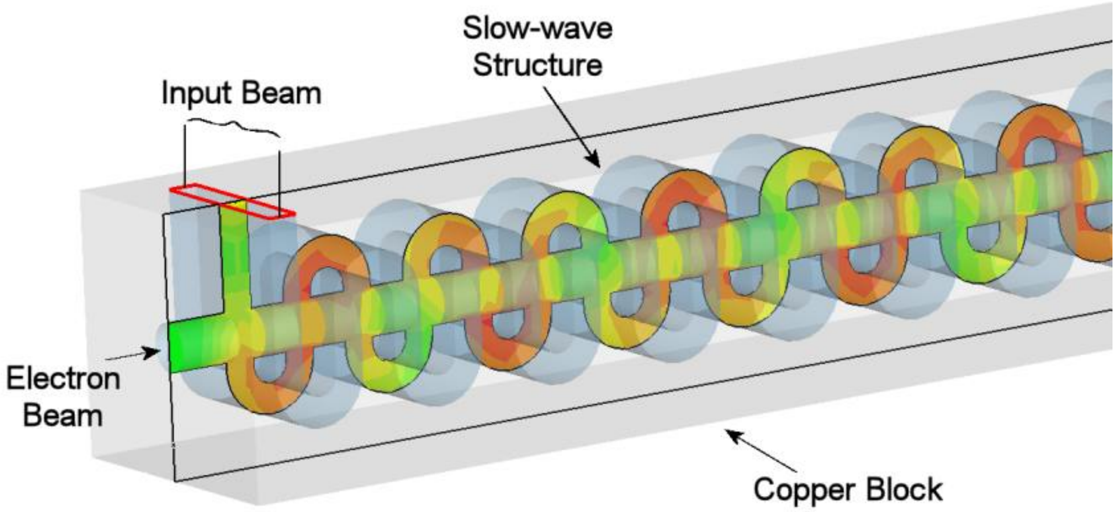


Figure 6: *CST Microwave Studio simulation of the proposed design demonstrates low losses across the full operating range of the TWT.*

3.1.2 Electron Beam Source

The primary goal in Phase I will be to determine the feasibility of producing a practical TWT device at THz frequencies. The electron beam of an SEM is a convenient, flexible tool for experimentally verifying TWT performance. However, a practical TWT must be designed to operate in a compact, efficient, self-contained package. An important task in Phase I will be to design a new cathode based on low-power, low-temperature, carbon nanotube field emitters. Cathodes employing carbon nanotubes have been demonstrated in a Northrop/Grumman TWT at 4.5 GHz and require only 250V of gate voltage. At THz frequencies the size of a unit such as this can be reduced by an order of magnitude, making them very attractive for a wide variety of applications. Carbon nanotubes may have the additional advantage of having exemplary noise performance. In 1964, Hammer & Wen found that high-B fields applied in the vicinity of the cathode reduced the transverse velocity component in the e-beam, significantly improving the noise performance of the TWT. Therefore nonthermionic emitters such as carbon nanotubes may intrinsically provide better noise performance.

Carbon nanotube gated electron sources are now commercially available. One such source manufactured by Applied Nanotech Inc. can generate the DC and AC beam currents of 0.3 and 20 mA respectively. Applied Nanotech has agreed to work with us (*see Support Letter*) to optimize their product for the proposed application. To work with the proposed TWT the emitted electron beam must be focused to a spot size of order 10 microns. We propose to use an einzel electrostatic lens for this purpose (see Figure 7). Chang, Kern, and Murray (1990) have successfully used similar lens configurations to create miniature electron beam microscopes, directly analogous to our application here. Compared to their magnetic counterparts, electrostatic lenses are simple, compact, and take no power. An einzel lens contains 3 elements each with a through hole for the beam. The first and third electrode are at the same voltage as the electron source gate. In our preliminary design the through hole diameter is 1 mm and the third (middle) aperture is at 200V relative to the other electrodes. This geometry and voltage distribution electrostatically focuses a 1 mm electron beam to approximately

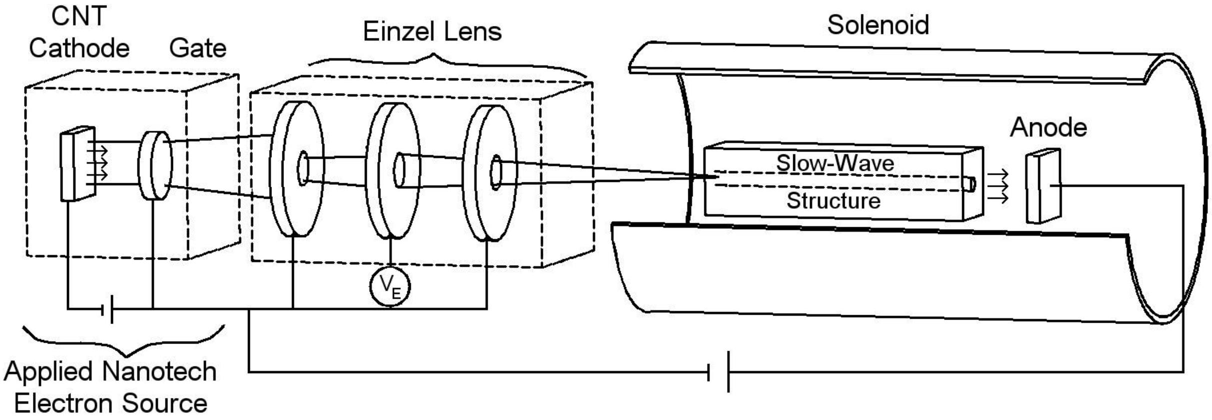


Figure 7: *Electrostatic focusing of an electron beam from a carbon nanotube cathode.*

a few micron spot size over a 10 mm distance. In our TWT application we place this focus just inside the entrance to the beam tunnel in the slow-wave structure. Once in the beam tunnel the solenoid (or permanent magnets) surrounding the slow-wave circuit keeps the beam collimated. In Phase I the design of the electrostatic focusing system will be optimized using commercially available software.

3.1.3 Device Packaging

The TWT itself must operate in a vacuum. A 3D rendering of the conceptual design is shown in Figure 8. Two power supplies are required; one for the cathode itself and another to accelerate the electron beam to the desired velocity (∼0.3c). The power supplies are available commercially from Ultravolt Inc. The gated, carbon nanotube cathode with internal focusing can be purchased from Applied Nanotech Inc., who has agreed to work with us to achieve maximum performance from their devices (*see letter of support from company*). The electron beam is confined to travel in the beam tunnel by immersing it in a magnetic field. For the beam characteristics described above, a magnetic flux density of 400 Gauss is required. Cylindrical, hollow permanent magnets with this flux density are available from several vendors.

The 368 GHz TWT will be designed to be scalable to higher frequencies. As part of the Phase I effort, we will design a 1.5 THz version of the device. Laser micromachining technology is well suited for the fabrication of the required THz waveguide structures. A 1 THz meandering waveguide TWT (Figure 9) was recently machined in the PI's lab using a custom laser chemical etcher (LCE) system. This system will be made available for the proposed effort.

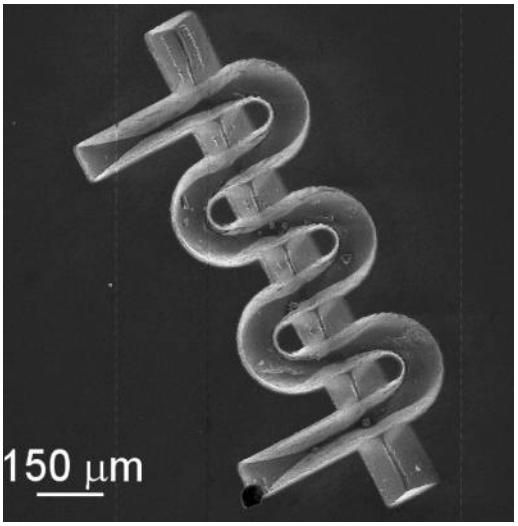


Figure 9: *1 THz meandering waveguide structure laser micromachined in the PI's lab.*

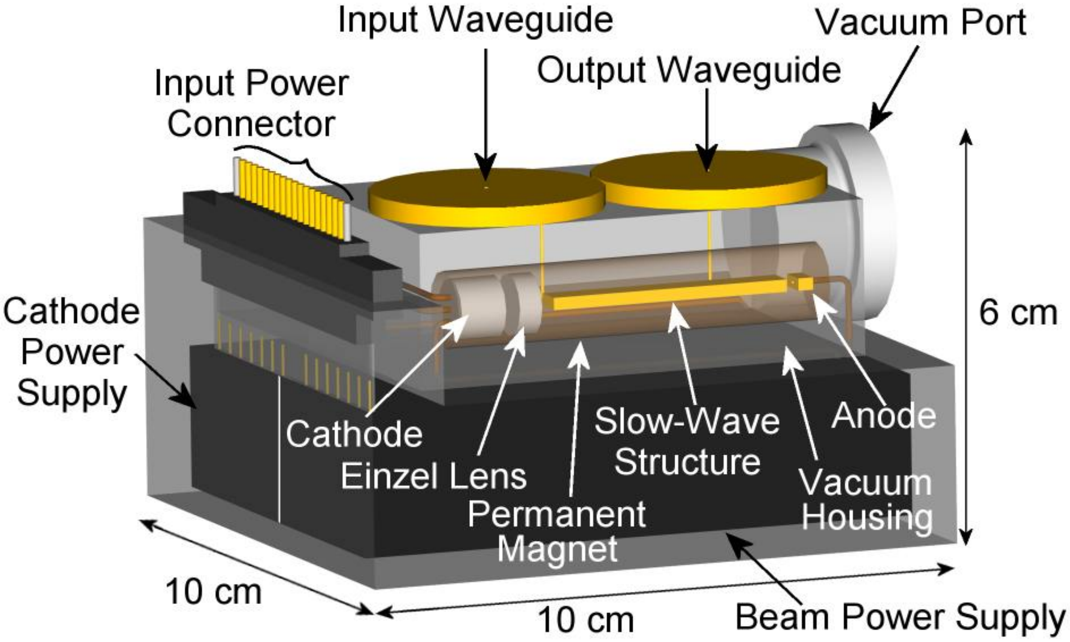


Figure 8: *3D rendering of proposed THz TWT amplifier.*

In the implementation of a new TWT amplifier undesired backward-wave oscillation (BWO) may occur, turning the amplifier into a source of coherent radiation. BWO's can be significantly reduced or eliminated by severing the slow-wave circuit. The two halves of the slow-wave circuit remain reconnected by the electron beam which then induces an amplified version of the input signal in the second half of the circuit. If undesired BWO's are found to be present in the output of the 368 GHz tube, we will add a sever. However, as described above, there are many applications where a clean source of coherent THz radiation is desirable. Therefore, as part of our investigation, we will optimize a tube design to act as an oscillator.

3.2 *Traveling Wave Tube Oscillator*

In the standard BWO implementation some of the forward power is reflected back along the slow-wave structure. In the case of the meandering waveguide, Ohmic losses due to the long pathlengths would have a negative impact on THz performance. However, Bhattacharjee et al. (2004) have shown that recycling some of the forward power directly back to the waveguide input may solve this problem. In their paper the authors both model and test a 45 GHz TWT oscillator based on this approach. In operation the TWTO passband showed that the device had multiple frequency components in its output. Single frequency operation could be achieved by adding enough attenuation in the feedback loop so that only the strongest signal could get through. There was no ability to set the TWTO to provide single line operation at any other frequency. We will investigate the possibility of adding frequency selectivity to the TWTO by placing a micromachined, waveguide bandpass filter in the return path. A 3D schematic of a frequency selective TWTO is shown in Figure 10.

Using this approach, all the available power in the TWTO will be funneled into the frequency of interest until saturation occurs, all others frequencies are suppressed. By adjusting the width of the sidewalls it would be pos-

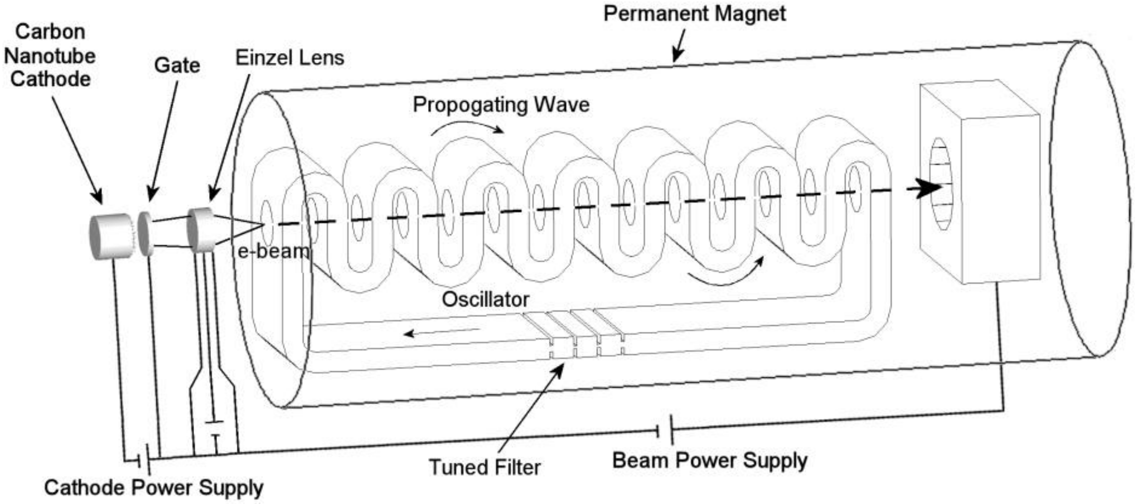


Figure 10: *Schematic of proposed Traveling Wave Tube Oscillator (TWTO)*

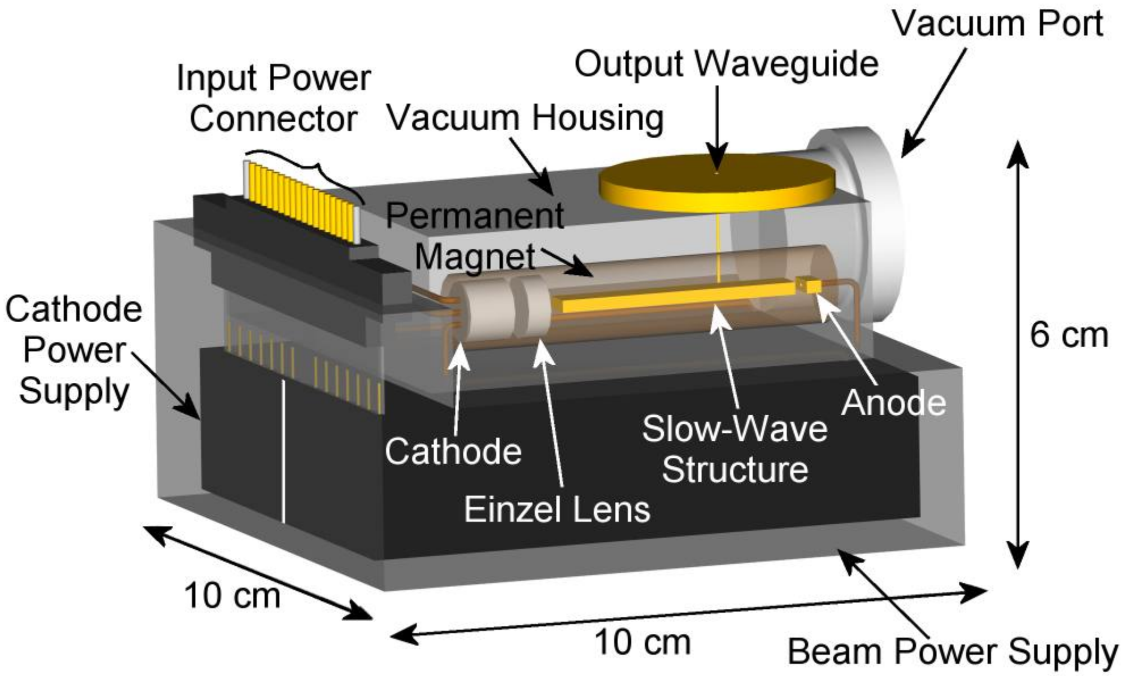


Figure 11: *3D rendering of proposed TWT Oscillator (TWTO).*

sible to tune the filter and TWTO over a significant frequency range, perhaps 20-30%. The efficiencies of TWT amplifiers are often better than 10%. Energy from the oscillator can be extracted from the electron beam using the configuration shown in Figure 11.

Here the output meandering waveguide is designed to provide 10 dB of gain over what emerges from the oscillator. To avoid assembly problems, the entire waveguide circuit can be machined at one time either in copper (using Kern machine) or silicon (using the LCE system). An Example of a 0.65 THz waveguide bandpass filter (Kirby et al. 2003) machined in the PI's lab is shown in Figure 12.

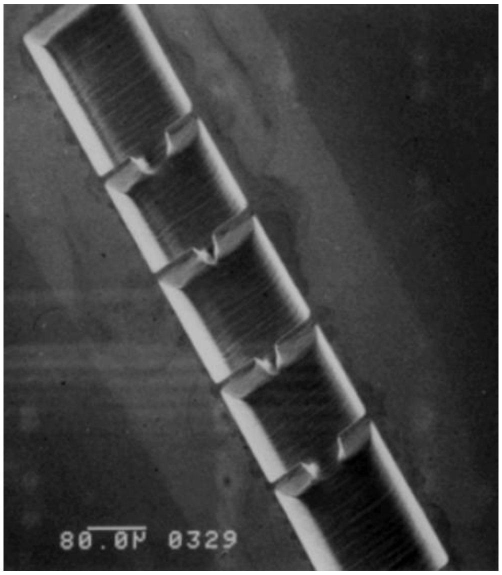


Figure 12: *THz bandpass filters laser micromachined in the PI's lab.*

3.3 *Precision Micromachining*

The TWT slow-wave circuits have structures that are small compared to the design wavelengths. The ability to machine such structures at the required size scale and accuracy has been a major hurdle in scaling well–characterized structures from the microwave to THz spectral regimes. With the aid of funds from the NSF, NASA, and Army Research Office over the past decade, the PI's group at the University of Arizona has established a micromachining capability uniquely suited to making high quality waveguide and quasi-optical components to submicron accuracies. The lab contains two custom-designed laser micromachining systems. One system is optimized for making waveguide devices from ∼0.8 to 5 THz. The second system is used to make similar devices from ∼5 to 30 THz. In these systems the beam from an argon-ion laser is focused onto a silicon wafer residing in a 200 Torr chlorine ambient. The incident laser beam has enough power (typically several watts) to vaporize a small volume ($\leq$1 micron^3) of silicon that reacts with the chlorine to make $SiCl_4$, which remains in the gas phase. Under computer control the laser beam can be steered to create 3D structures such as gratings or meandering waveguides (Drouet d'Aubigny et al. 2004). Once the etching is complete, the etched silicon is gold plated as needed to make it behave like normal waveguide or quasi-optical structures. A picture of one of the laser micromachining systems to be used for the THz portion of the proposed work is shown in Figure 13.

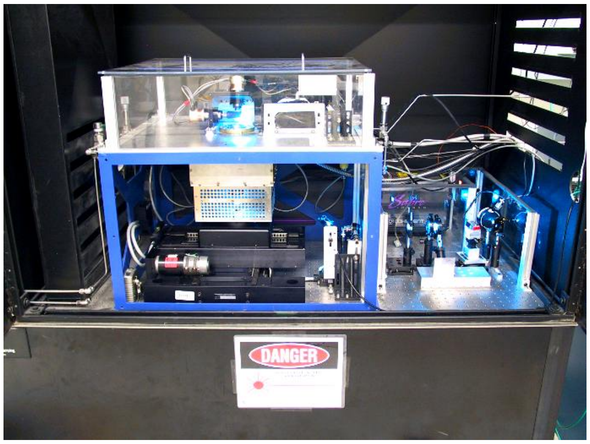


Figure 13: *Laser micro-milling machine in the PI's laboratory, used for fabrication of devices at frequencies >1 THz.*

At frequencies below 1 THz the size of the structures to be etched often require volumetric removal rates beyond the capabilities of the laser micromachining systems. In order to fabricate such structures, the PI's group has recently procured a state-of-the-art micro-milling machine (KERN MMP 2522, see Figure 14) that can machine metallic and ceramic structures to 1 micron precision and accuracy. This system will be used to machine prototype 345 and 368 GHz TWT slow-wave structures for the proposed effort, whereas the laser micromachining system will concentrate on fabrication of 1.5 THz structures.

Figure 14: *Kern micro-milling machine in the PI's laboratory, used for fabricating devices at frequencies < 1 THz.*

The availability of these systems will permit the rapid prototyping and optimization of the gratings and waveguide components needed for this project, from microwave to THz spectral regimes.

3.4 *Plan of Action*

1. TWT Amplifier and Oscillator System Strawman Design (TeraVision Inc.)
2. Design and Modeling of prototype Slow Wave Structure (U of A)
3. Fabrication of 350 GHz Slow Wave Structure Split Blocks (U of A)
4. Design and Fabrication of Anode (TeraVision Inc.)
5. Test in Raytheon SEM (TeraVision U of A)
6. Install Slow Wave Structure in SEM (U of A)
7. Turn Beam On and Measure amplification (U of A)
8. Procurement of Carbon Nanotubes (TeraVision Inc.) - Applied Nanotech Inc. and/or MER
9. Design of Electrostatic Lens (U of A)
10. Electron Beam Characterization (I/V Curve / Beam size / Depth of focus/ power use / duty cycle/ pulse length etc.) (TeraVision Inc.)
11. Design Device Electronics (TeraVision Inc.)
12. Design Vacuum Vessel for Commercial Device (TeraVision Inc). Complete Integrated Package design (TeraVision Inc.)
13. Submit Phase I Report with designs and feasibility studies for manufacturing 368 GHz and 1.5 THz TWT amplifiers and oscillators (TeraVision Inc.)

4 Company Information

4.1 *Mission Statement and Company History*

TeraVision Inc was created in 2002 to bring THz expertise and enabling technologies developed at the University of Arizona and MIT Lincoln Laboratory to market. Soon thereafter, TeraVision Inc. licensed laser etching technology from MIT. More recently, the company has entered into a Technology Transfer Agreement with the University of Arizona for THz technology. Today, TeraVision Inc. maintains close ties to the University of Arizona, and in particular Steward Observatory, the Optical Sciences Center and the Department of Computer and Electrical Engineering. Our proximity to the University allows close collaborations with distinguished researchers and access to the world class facilities of a Research I Institution.

4.2 *Business Strategy*

As a small technology startup, TeraVision Inc.'s strategy is to provide demonstrated THz technology platforms to established key players in three main markets. TeraVision has identified three growing markets where the value of THz technology will justify the initial cost of the new THz sources: Defense, Homeland Security, and Medical Diagnostic. The company is identifying and forming strategic partnerships with key players in those markets like Raytheon for defense and homeland security, General Electric (InVision) for homeland security and parts inspection and General Electric Health Care for medical imaging and diagnostics. TeraVision is already discussing partnership modalities with Raytheon Missile Systems and GE and will be looking at partnering with other market leaders in the near future. By developing the new THz source platform with help and feedback from our end users and future customers, TeraVision expects to have a Phase II prototype that will not only meet the immediate needs of the Department of Defense and the Air Force but will also have a dual use platform technology readily portable to the medical imaging. Eventually as the technology matures and devices become more affordable TeraVision will be ideally placed to serve the needs of other industries where possible THz applications have already been identified and tested in the laboratory.

4.3 *Relationship with Future Research or Research and Development*

The proposed STTR work matches the interests of both TeraVision Inc. and Professor Walker's group at the University of Arizona. TeraVision Inc. sees Phase I of this STTR as an opportunity to demonstrate the basic feasibility of the technology and develop a basic working prototype. Working together with DoD prime contractors like Raytheon, TeraVision Inc. anticipates it will have an early stage commercial technology platform by the end of Phase II. At that point, the platform is expected to not only be immediately applicable to Defense and Homeland Security programs, but also easily adaptable to medical imaging and other industrial applications The present lack of THz sources constitutes a serious impediment for development of large format heterodyne arrays for sub-millimeter Astronomy which are at the core of Professor Walker's research. Professor Walker has received funding from the NSF, NASA and the US Army for the development of new THz detector technology. His group has recently submitted a joint proposal to the NSF with Raytheon Missile Systems to study radically new approaches to THz source technology. The proposed research at the University of Arizona will leverage resources established by previous government funding as well as the new NSF and Raytheon funding, if awarded.

4.4 *Company Size and Revenue*

TeraVision Inc has no revenues and no employees. One of us (Christian d'Aubigny), will join the company's employ if the proposal is awarded. TeraVision Inc. is actively marketing laser micro-fabrication technology and seeking both federal and private funding to develop new THz sources. The proposed work would allow the company to accelerate the development of a prototype source.

5 Commercial Potential

5.1 *Suggested and Demonstrated Use of THz Radiation*

Terahertz technology has potential applications in the military sector for standoff detection of chemical and biological agents and enhancement of satellite communications. In the commercial sector, the technology has applications in the security market (for detection, identification and interrogation of explosives, chemical and biological agents), medicine (measurement of in vivo tissue water content, fat content, blood glucose and cholesterol contents and the diagnosis of cancer), dentistry (as a powerful alternative to x-ray images), pharmaceutics (real time, non-destructive chemical analysis for quality control during drug fabrication), food processing (detection of E-coli and other poisonous bacteria as well as detection of small imperfections in packaging), and Law-enforcement (detection of prohibited substances and of counterfeit bank notes).

5.2 *Supporting Market Data*

5.2.1 *Defense Market*

US Defense electronics market is expected to be worth $181 Billion over the next decade (source: The Forecast International Overview). Practical applications of terahertz wave technology to Department of Defense programs such as the Air Force are numerous. For example, THz wave technology will allow smaller radar antennas to yield more detailed images. Also, THz remote sensing can be used to observe index of refraction inhomogeneities caused by the ionization of air molecules by radioactive materials. In addition, they are sensitive enough to determine whether a nuclear plant is active. Terahertz technology also has potential applications in the military sector for standoff detection of chemical and biological agents. THz satellite communication will expand available bandwidth. Another advantage of THz wave technology is the increased directivity of the beam which will minimize signal interception and radar visibility.

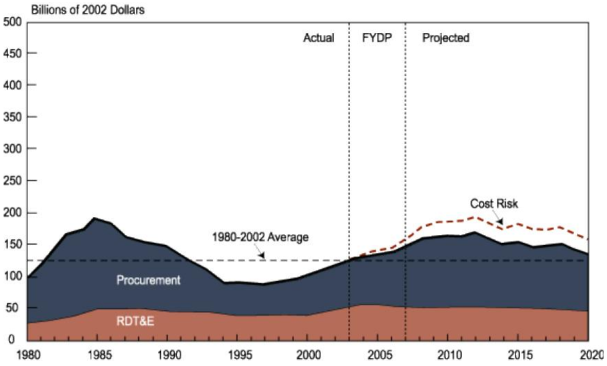


Figure 15: *Source: Congressional Budget Office. FYDP Future Years Defense Program, RDT&E Research Development and Evaluation.*

DoD Prime Contractors: Lockheed-Martin, Boeing, Northrop-Grumman, Raytheon, TRW, Mitre Corporation, United Technologies, Science Applications International.

5.2.2 *Security Market*

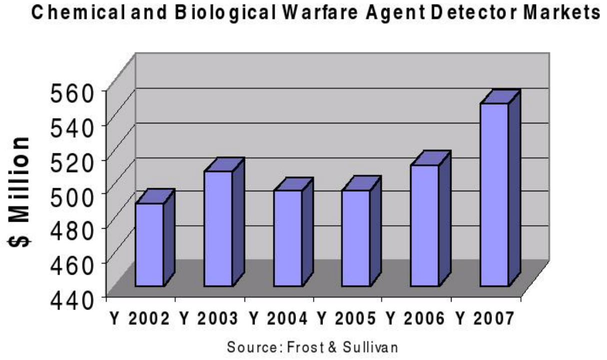
Chemical & Biological Agent Detection Market

Passive and remote detection technologies utilized for the detection of chemical warfare

Agents include: Fourier transform infrared (FTIR), RAMAN infrared (IR) spectroscopy, Active Laser Imaging Detection Ranging (LIDAR), Interrogation (experimental)

Point detection for the field or site monitoring technologies includes: Ion mobility spectrometry (IMS), Field ion spectrometry (FIS) (Russian, coaxial), Gas chromatography (GC), capillary column, Mass spectroscopy

Standoff detection of possible biological aerosols is much more problematic than FTIR for chemical agents, although active lasers (LIDAR) scanning for atmospheric anomalies are already fielded by the U.S. Army. A combination of off-the-shelf instruments is used in the point detection of biological warfare agents: Flow cytometry, Aerodynamic particle sizing, Antigen/antibody reaction, ATP-Luciferase tests, Pyrolytic mass spectroscopy, DNA probes (developmental)


Chemical and Biological Warfare Agent Detector Markets

Source: Frost & Sullivan

Figure 16:

Leading Participants: The leading market participants (in terms of revenue) in the world markets for chemical warfare agent detectors include: Graseby Dynamics, Ltd. Intellitec (formerly Brunswick Defense), Powertronic Systems, Lockheed Martin. The leading market participants (in terms of revenue) in the world markets for biological warfare agent detectors include: Hunting Engineering, Camber Corporation, QTL Biosystems, Intellitec.

Explosives Detection Systems Market

The Transportation Department recently announced plans to use a combination of Explosives Detection Systems (EDS) and much less expensive and easier to deploy trace detection systems (TDS). It is expected that the deployment of EDS systems take place in two phases. In the first wave, freestanding EDS units will be installed in airport terminal lobbies. In a second wave, EDS equipment will be integrated into the airline baggage handling systems. Based on current government procurement plans, the equipment cost for EDS deployment alone is around $**1.5 billion**. The international market opportunity is nearly as large (source: Needham & Company).

Leading Participant: GE InVision Technologies (90% market share)

5.2.3 *Medical Imaging Market*

Due to several advantages over traditional imaging methods, THz radiation has great potential in the field of medical imaging. THz radiation is non-ionizing and its use is intrinsically safer than X-ray. In addition, THz radiation provides more detail than conventional imaging methods such as X-ray and Ultrasound. THz radiation can be used to measure tissue water content and fat tissue content, blood glucose and cholesterol levels. THz imaging can accurately differentiate between malignant and benign skin disease and diagnose skin cancer. This technology is likely to replace expensive and invasive biopsy procedures in use at the present time.

The medical imaging market is forecast to grow 7.6% through 2008. It includes the following modalities and equipment:

- X-Ray Mammography
- Positron Emission Tomography (PET)
- Magnetic Resonance Imaging (MRI)
- Gamma Cameras
- Digital Radiography
- Computed Tomography (CT)
- Picture Archiving and Communications Systems (PACS)
- Osteoporosis Diagnostic Imaging Equipment
- 3D Imaging
- Ultrasound Imaging Equipment

Leading Participants: Agfa Healthcare, Canon Medical Systems, Eastman Kodak, Fujifilm Medical, GE Medical Systems, Philips Medical Systems, Siemens Medical Solutions, Toshiba Medical, Columbia Scientific, B-K Medical, Fischer Imaging, Hologic, Instrumentarium Imaging, Konica Medical Systems, Planmed, Shimadzu Swissray.

5.3 *Intellectual Property*

We plan to seek patents for any new devices developed under this STTR through the University of Arizona.

6 Consultants and Subawards / Subcontracts

TeraVision has also arranged for John Waterman to serve as a consultant for this project. Mr. Waterman's pioneering thesis work at Stanford University focused on high frequency TWT design and fabrication. He then worked at Raytheon on high power millimeter wave TWT. John Waterman now works for Brillian Corporation in an unrelated field, and will be able to provide TeraVision with both theoretical and hands-on help.

7 Equivalent or overlapping Proposals to other federal agencies

1. U.S. Air Force, Air Force Research Lab, Wright-Patterson Air Force Base, Ohio.

   The Air Force STTR Program Manager is Mr. Steve Guilfoos, (800) 222-0336.

   Proposal Submitted on 04/15/2005

AF05-T020 "Novel Terahertz Sources for Advanced Terahertz Power", in STTR solicitation issued 02/01/2005

Nanoklystrons and nanoTWTs and date of solicitation

Novel Sources of Terahertz Power: Nano-Cathode Resonant TWT

The proposed period of performance for this proposal is 10/01/05-06/30/06 actual performance period will depend on funding agency.

P.I. Professor Christopher Walker

Co.I. Christian Drouet d'Aubigny - Commitment 700 Hours (4 person month) over a 9 months period.

While the work proposed here and the US Air Force proposal above are in the same general area of research, their focus are different. The work proposed to the Air Force focuses on making very compact, highly efficient, low power, resonant sources. The work proposed here aims at developing very high current density electron beams, focus and contain them, and design high frequency microwave structures that will amplify or produce very high THz power levels. While the two proposed efforts would benefit from each other, we believe the scope of the work proposed here is significantly different from that proposed to the Air Force.

2. National Science Foundation: Electrical and Communications Systems

   Proposal Title: THz Radiation Production and Amplification Using a New Generation of Electron Beam Devices

   NSF Proposal No.: 0524785

   NSF Program Officer: Kawthar, A. Zaki, ph.703-292-8339

   Total Award Amount: $680,899 Total Award Period Covered: 08/01/05 - 07/31/08

   Location of Project: The University of Arizona

   Person-Months per Year of PI-Walker Committed to the Project: Sumr: 1.0

   PI: Christopher K. Walker

   Co-PI: Christian Drouet d'Aubigny (participation would be reduced to zero, if pending STTR proposals with TeraVision Inc. are selected.)

   The above proposal was submitted by the University of Arizona to the NSF, there was no TeraVision Inc. participation. The proposal outlines a program of fundamental research into generating THz radiation through the Smith-Purcell effect and amplifying THz radiation with TWT's. The research program does not seek to produce a commercial device.