

# OPTICALLY-PUMPED THz LASER TECHNOLOGY

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## Abstract

The recent myriad of advances in THz sources, detectors, and potential applications has brought this region of the spectrum to the attention of its widest audience to date. As applications are developed, the optimal source technology for each application will be requirement dependent. Modern optically-pumped THz laser technology may well be the source of choice for selected applications.

The advent of reliable compact CO<sub>2</sub> laser technology and its widespread commercial application, combined with recent developments in similarly reliable compact THz laser technology, has heralded a new era in optically-pumped THz lasers. This new generation of laser technology is being used on a long-duration space mission on NASA's AURA satellite. Further, this technology has yielded easy-to-operate laboratory THz sources.

The present paper will review the current state of optically-pumped THz laser technology and present some of the longer-term roadmaps available for this technology.

## I. Introduction

During the past ten years the state-of-the-art in CO<sub>2</sub> laser technology has advanced dramatically. These advances have resulted in substantial decrease in size, decrease in cost, and increase in reliability.

This new generation of CO<sub>2</sub> lasers is being used in a wide variety of commercial and scientific applications. Many of these applications require 24/7 operation without service.

Many of the underlying technologies present in this new generation of CO<sub>2</sub> lasers are applicable to optically-pumped THz lasers (OPTL). Accordingly, modern OPTL's not only take advantage of the latest CO<sub>2</sub> laser designs, but also incorporate many of the same design approaches. Also, as CO<sub>2</sub> lasers are an integral component of OPTL's, the improvements in performance of CO<sub>2</sub> lasers improve the performance of OPTL's.

This paper will review OPTL operation concepts, provide a comparison between past and modern OPTL technologies, provide examples of modern OPTL systems, examine a design for a compact OPTL, and review frequency agility technology for OPTL's.

The remainder of this paper will be organized in sections as follows: II – Overview of OPTL Operation; III – Comparison of Past vs Modern OPTL Technology; IV – Examples of Modern OPTL Systems; V – “Shoe Box” Concept OPTL; VI - Frequency Agility Addition to OPTL's; VII – Conclusions, VIII – Acknowledgements, and IX - References.

## II. Overview of OPTL Operation

A generalized schematic representation of an optically-pumped THz laser system is presented in Figure 1. The THz laser cell consists of: a vacuum envelope in which a molecular gas at low pressure is placed, some source of optical feedback (end mirrors), and a method of admitting IR pump radiation and emitting FIR radiation. A grating-tuned CO<sub>2</sub> laser (emission in the 9 - 11 μm range) is typically used to pump the THz laser. This pump radiation is often admitted into the THz cavity through a small input-coupling-hole

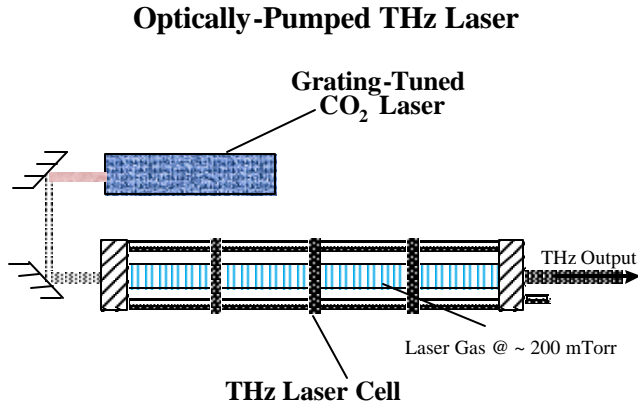


Figure 1: Schematic diagram of a general OPTL system.

in one end mirror. The THz radiation produced in the laser is then typically emitted through either an output-coupling-hole or some sort of uniform output coupler.<sup>1</sup> To understand how this device produces THz radiation, one must examine the quantum-mechanical molecular processes, which take place. The present section provides only a very general overview of these processes; more thorough discussions are available in the literature.<sup>2</sup>

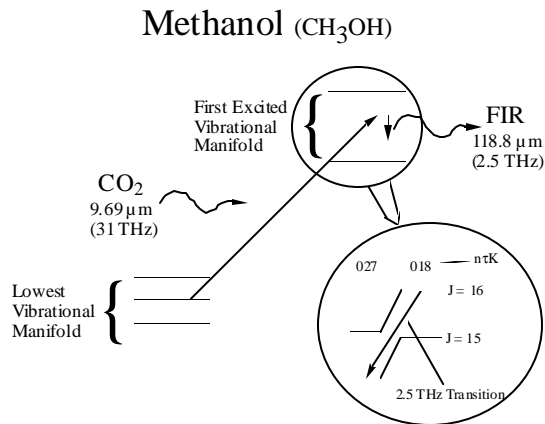


Figure 2: Schematic energy diagram of 2.5 THz methanol laser.

All optically-pumped THz lasers operate on molecular rotational transitions. For purposes of illustration we will consider a specific THz laser example for explanation. A representative diagram of the operation of an

THz laser, operating on the 118.83  $\mu\text{m}$  line in Methanol, is presented in Figure 2, an illustration of the origin of the methanol quantum numbers is presented in Figure 3, and a

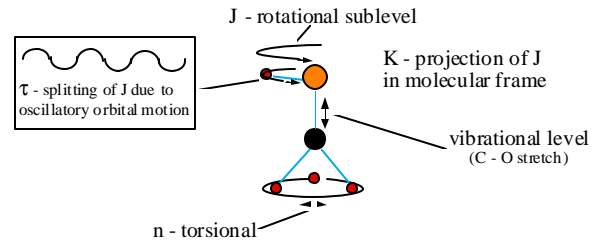


Figure 3: - Illustration of methanol quantum numbers, the top “large” atom is oxygen, the bottom “large” atom is carbon, and the rest are hydrogen.

physical diagram of the lasing process is presented in Figure 4. In the lasing process: 1) an infrared photon with an energy which very closely matches a

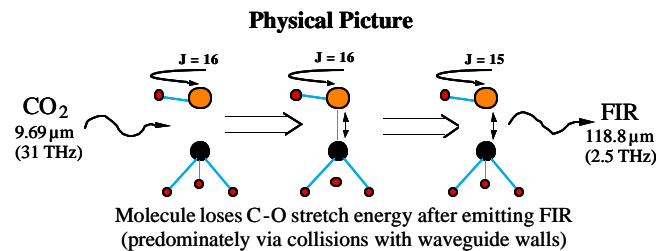


Figure 4: Physical representation of the 2.5 THz lasing process in methanol.

transition from a particular rotational state in the ground vibrational manifold to a rotational state in an excited vibrational manifold is absorbed by a gas molecule, 2) if the conditions are correct this process causes a population inversion between rotational states,\* 3) the inverted rotational transition lases and emits in the THz, 4) the molecule is left in the excited vibrational manifold and must return to the

\* either in the excited manifold due to the pumping, or in the lower manifold due to depletion of the lower state

ground manifold before it can participate in a continuous-wave lasing process again.

The lasing process of Figure 2 is further illustrated in Figure 4. In this example, the 9.69  $\mu\text{m}$  infrared photon excites the C-O stretch mode. The molecule then lases between the J=16 and J=15 rotational levels, emitting a photon at 118.83  $\mu\text{m}$ .

With the large energy difference between the rotational and vibrational energy level separations, one might expect the lasing process to be quite inefficient. This is in fact the case. The majority of the pump radiation is simply converted to heat. The theoretical limit on efficiency for the OPTL is given by the well-known Manley-Rowe limit<sup>3</sup>

$$\varepsilon = \frac{n_{\text{FIR}}}{2n_{\text{IR}}}, \quad (1)$$

where  $\varepsilon$  is the efficiency of converting pump radiation into THz radiation,  $\nu_{\text{FIR}}$  is the frequency of the emitted THz photons, and  $\nu_{\text{IR}}$  is the frequency of the pump photons. So for example, for the 118.83  $\mu\text{m}$  laser line in  $\text{CH}_3\text{OH}$  the efficiency limit is 4%. Typical efficiency for this transition is on the order of 0.2%, and the best efficiency reported<sup>4</sup> is 1% for high power operation, and 0.8% for high-efficiency lower power operation.<sup>5</sup> This example is one of the higher efficiency transitions; typical FIR laser efficiencies are in the range of 0.001 - 0.1 %.

### III. Comparison of Past vs Modern OPTL Technology

In the past, a large number of OPTL's were built by individual research groups, and some were commercially constructed. The systems were typically very large, occupying complete optical tables. The systems integration issues in these traditional OPTL's were often not thoroughly considered. Thus these OPTL's were often "laser jock" specials

requiring detailed knowledge on the part of the operator in order to get acceptable output.

The pump laser technology used in these traditional systems, was typically DC-discharge, flowing gas,  $\text{CO}_2$  laser technology. This technology caused significant limitations in ease-of-use and reliability. These limitations presented themselves to the operator in: gas consumption, periodic replacement of cavity optics (often necessitating complete teardown of the laser head), and poor reliability in general.

The THz lasers used in these traditional systems, were almost entirely flowing gas technologies as well. Again this technology presented a number of logistical issues limiting ease-of-use, and again providing poor reliability.

The traditional OPTL's were often not integrated products, but instead consisted of many standard available component "boxes". Additionally, system sensitivity to thermal and acoustic fluctuations, and pump feedback interactions, were often not well considered in the designs. Operating the resulting OPTL's was often a frustrating experience where only the in-house "laser jock" with the "magic" fingers could get acceptable performance. While many researchers concluded, based this experience, that this behavior was intimate with OPTL technology, this is not the case.

In modern OPTL systems, the latest developments in pump laser technology have been combined with advances in THz laser technology, to create integrated laser appliances.

The move to true integrated systems designs, where the guiding viewpoint of the design effort is away from the "laser jock" view of the system to the appliance view, has had significant impact on usability of OPTL systems.

Pump lasers are now available that are permanently sealed-off. These require no

service and have demonstrated lifetimes > 40,000 hours.

This new pump laser technology replaces DC-discharge excitation of the CO<sub>2</sub> laser with RF excitation (see Figure 5). The RF technology operates at significantly

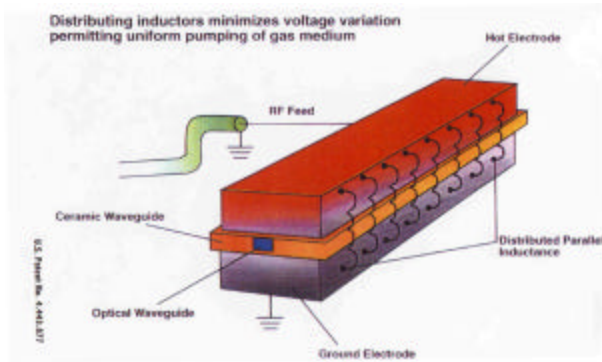


Figure 5: Schematic drawing of the RF excitation technique for modern OPTL pump lasers.

lower voltages (drastically reducing gas dissociation issues) and permits the excitation to couple into the gas through the waveguide material. Thus there is no direct plasma-to-electrode contact and therefore no electrode erosion issues (one of the key lifetime limits in DC-discharge lasers).

In addition to RF excitation, modern pump laser technology uses waveguide

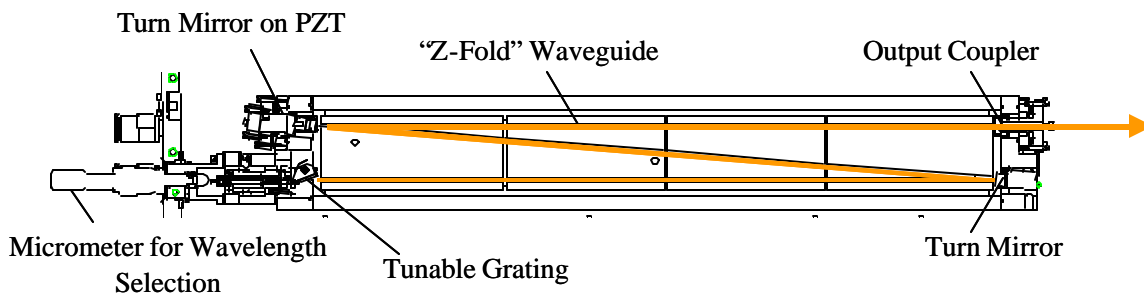


Figure 6: Cutaway view of a folded-cavity RF-excited, waveguide CO<sub>2</sub> laser.

cavity designs (see Figure 6). When teamed with RF excitation and cavity folding techniques, this approach yields a remarkable combination of: excellent mode quality, smallest

size per watt of output, mechanical rigidity (improved immunity to vibration), efficiency, and reliability.

Improvements in THz laser cells have followed a similar development path to that of pump laser technology. Cavity folding has been employed to decrease footprint, and high-vacuum (HV), and in some cases ultra-high-vacuum (UHV), designs have been executed to improve ease-of-use and reliability.

An example HV, folded, THz laser cell is presented in Figure 7. This laser, originally developed for Goddard Space Flight Center for use on the aircraft platform SOFIA, operates sealed-off for days at a time with little degradation in output power.

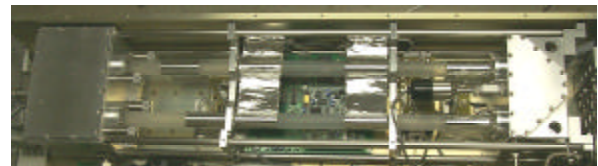


Figure 7: Photograph of a folded THz laser cell originally developed for NASA/Goddard.

An example UHV, folded, THz laser is presented in the photograph of the space-based OPTL laser system shown in Figure 8. This laser system was developed by Coherent-DEOS for Jet Propulsion Laboratory and will fly on the NASA AURA satellite set for launch

in 2003. This laser system has a specified mission duration of 5 years on orbit + 2 years on the ground prior to launch. The laser consumes 120 W of power (including its internal  $\mu$ P), has a

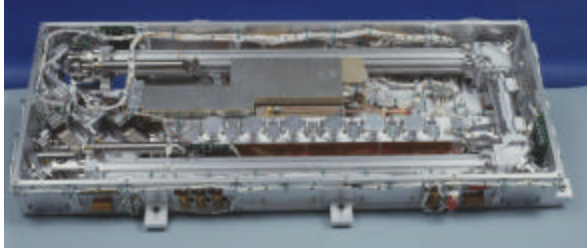


Figure 8: Photograph of the electro-optic section of the space-based 2.5 THz laser.

temperature range of  $-35\text{ C}$  to  $60\text{ C}$ , and has an output of  $> 30\text{ mW}$ . One of the key differences between HV and UHV THz lasers is that the latter utilizes all metal seals, special internal materials, and extreme cleaning of intra-cavity parts, whereas the HV THz laser uses some elastomeric seals and materials with higher vapor pressure and outgassing behavior.

#### IV. Examples of Modern OPTL Systems

There are a fair number of modern, new generation, OPTL's. The present paper will describe a few of these.

##### 1. Coherent-DEOS SIFIR-50 FSW

Figure 9 shows a photograph of the Coherent-DEOS SIFIR-50 FSW OPTL system. This laboratory laser product uses a 50 W pump laser, a folded THz laser, and a pump frequency reference lock to yield reliable, simple operation.

The THz output vs operating wavelength is presented in Figure 10. The abrupt high frequency roll-off is due to the output window material used and the slow low-frequency roll-off is due to the slow waveguide cut-off in the dielectric



Figure 9: Photograph of the SIFIR-50 FSW OPTL.

waveguide used in the THz laser. The drop in the data at  $\sim 235\text{ }\mu\text{m}$  ( $1.3\text{ THz}$ ) is due to the weakness of the pump line at that particular THz line. The operating range presented Figure 10 is  $0.85 - 7.5\text{ THz}$ .

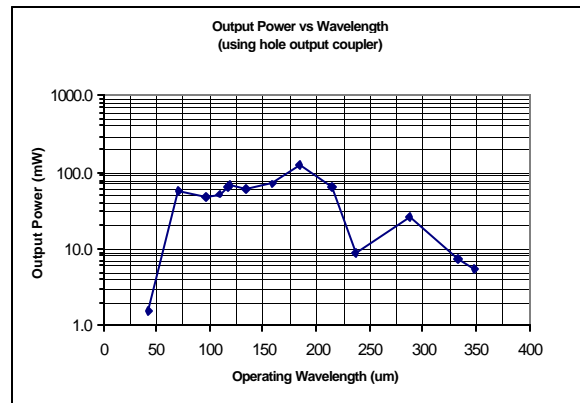


Figure 10: Output power vs wavelength for the SIFIR-50 FSW.

Figure 11 shows the output spatial mode of this laser system at 2.5 THz. This figure is a digital photograph of a liquid crystal image.

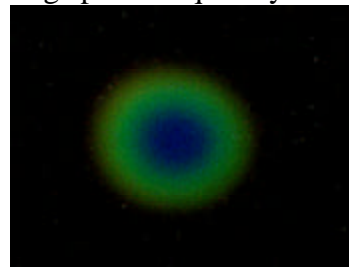


Figure 11: Spatial mode of the output of the SIFIR-50 FSW at 2.5 THz.

## 2. Coherent-DEOS SIFIR-50 DSW

Figure 12 shows a photograph of the Coherent-DEOS SIFIR-50 DSW OPTL system. This laboratory system utilizes the same pump and frequency control



Figure 12: Photograph of the SIFIR-50 DSW OPTL.

technology as found in the previous system but it has two non-folded HV THz laser cells. One of these has been optimized for operation in the 1-5 THz range and the other

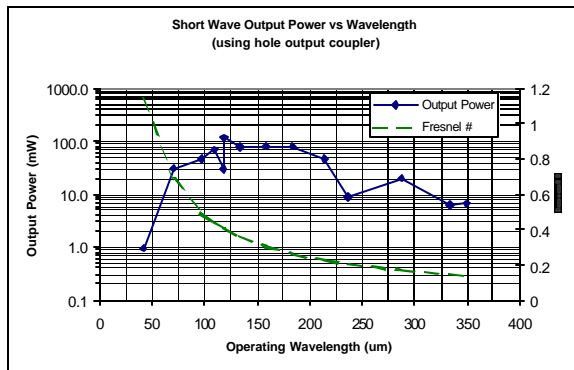


Figure 13: Output power vs wavelength for the short-wave cavity in the SIFIR-50 DSW.

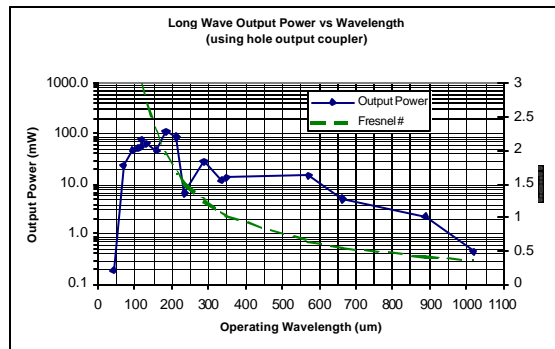


Figure 14: Output power vs wavelength for the long-wave cavity in the SIFIR-50 DSW.

is optimized for operation between 300 GHz and 1 THz.

The output vs wavelength for these two cavities are presented in Figures 13 and 14. The Fresnel number of each of these is also included to illustrate that while the long-wave cavity has substantial output power over the entire range, it is probably not single mode for wavelengths below  $\sim 250 \mu\text{m}$ .

## 3. AURA 2.5 THz Space Laser

Photographs of the 2.5 THz laser local oscillator (LLO) for the NASA AURA satellite are presented in Figures 15 and 16. The LLO is 30 cm x 10 cm x 75 cm, has a mass of 21 kg, operates autonomously, consumes 120 W of prime power, has an output power of  $>30 \text{ mW}$  at 2.5 THz, and has a temperature range of  $-35 \text{ C}$  to  $60 \text{ C}$ .

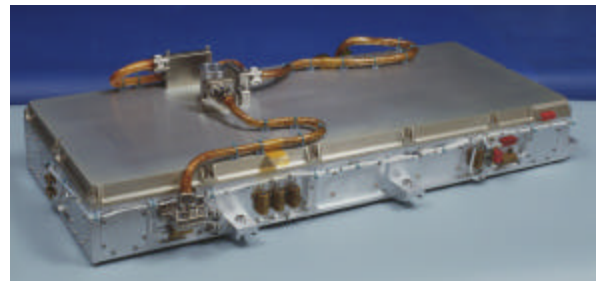


Figure 15: Photograph of the complete flight model LLO.

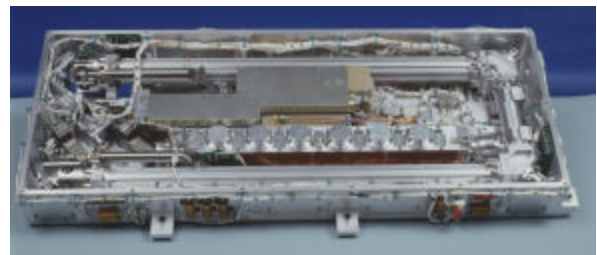


Figure 16: Photograph of the lower section of the LLO. The U-shaped structure around the inside of the right side of this figure is the THz laser cell.

This system represents the true state-of-the-art in high-reliability OPTL technology. The

THz laser is filled and then permanently pinched-off. It is designed to operate in a hostile environment without any possibility for service, for 5 years after being launched into space on a Delta II rocket.

The spatial output mode of the LLO is presented in Figure 17. This data was obtained by scanning a LHe-cooled

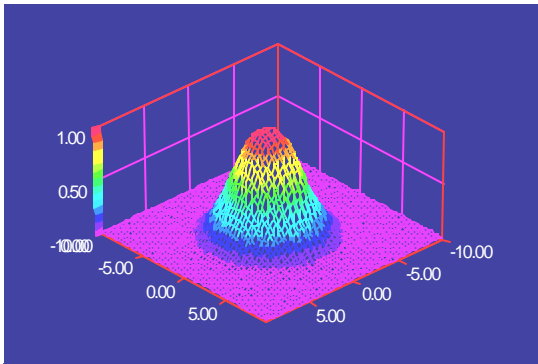


Figure 17: Spatial output mode of the LLO.

bolometer, with a 300  $\mu\text{m}$  input aperture, through the output beam and recording the power vs position.

The dielectric waveguide in the LLO's THz laser is supported within the UHV envelope by a series of energy absorbing wavelets which also serve to

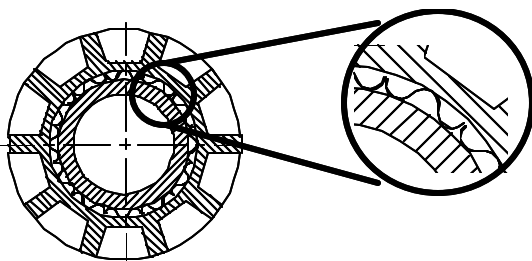


Figure 18: Cut-away section of one of the LLO's THz laser guide sections.

provide a path for heat removal from the THz waveguide to the laser housing. A drawing of this support arrangement is presented in the cut-away section of Figure 18.

#### 4. Laser LO for GREAT

A drawing of the OPTL being developed by DLR for the German Receiver for Astronomy at THz Frequencies (GREAT) is shown in Figure 19. This system utilizes a Coherent-DEOS RF-excited, waveguide pump laser and a transversely-excited THz laser being developed by DLR (see Figure 20).

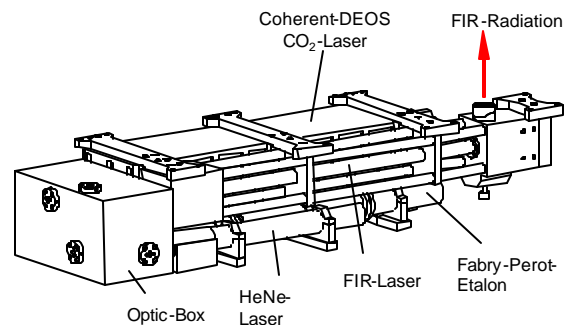


Figure 19: Drawing of the OPTL LO for GREAT.

While the transversely excited THz laser has low efficiency, its very high Q THz resonator is capable of operating even very weak THz laser lines. The SOFIA mission

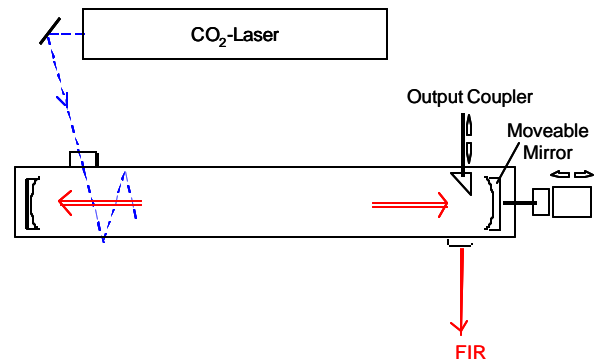


Figure 20: Diagram of the transversely-excited THz laser concept.

on which DLR plans to use this OPTL system on only requires 10's of  $\mu\text{W}$  of LO power and has substantial prime power available. Accordingly, this THz laser design should fulfill the mission requirements quite well.

## 5. THz Laser LO for the South Pole

The Submillimeter-Wave observatory located at the South Pole (Antarctic Submillimeter Telescope and Remote Observatory, AST/RO) is installing a THz receiver for astronomy measurements over the polar winter.

A photograph of the AST/RO facility is presented in Figure 21. A photograph of the OPTL model that is going to be used as the LO for this receiver is shown in Figure 22.



Figure 21: Photograph of the AST/RO facility at the south pole.



Figure 22: Photograph of the Coherent-DEOS SIFIR-50 OPTL. This laser is going to be used as the LO for a THz receiver at the AST/RO facility at the South Pole.

When combined with the HEB mixer being developed by a team from UMass Amherst, NIST Boulder, UMass Lowell, the University of Arizona, and the Smithsonian Astrophysical Observatory, the resulting system, called TREND (Terahertz Receiver with NbN HEB Device), will provide

unprecedented interstellar measurements of NII and CO.

## 6. THz laser for Goddard/SOFIA

Figure 23 presents photographs of the laser developed by Coherent-DEOS for NASA Goddard for use on the airborne platform SOFIA.

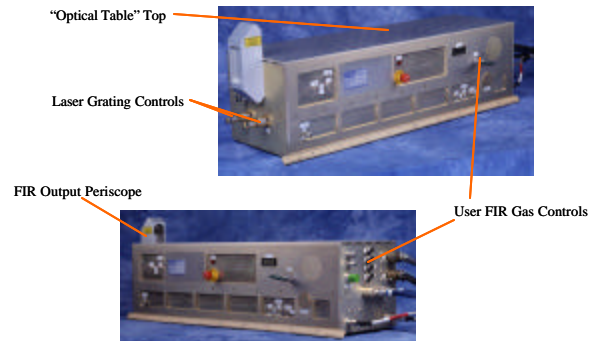


Figure 23: Photographs of the OPTL developed for NASA Goddard for use on SOFIA.

This OPTL utilizes a folded THz laser and a unique absolute frequency lock to provide sub-MHz absolute frequency reproducibility for sub-Doppler THz astronomy. Additionally, it has an integral "optical table top" to provide a convenient mounting location of receivers.

## V. "Shoe Box" Concept OPTL

The recent advances of OPTL technology have made possible heretofore unimagined compact OPTL's. A conceptual design for such a system is presented in Figure 24.

Based on laboratory data, the OPTL shown there would consume  $\sim 60$  W of prime power, and have an output of 10-15 mW. The package size is 18.5" x 6.75" x 6.75" (the size of a large shoe box)

This design uses component designs which have been proven in other OPTL

systems and can support the addition of frequency agility devices. If less efficiency

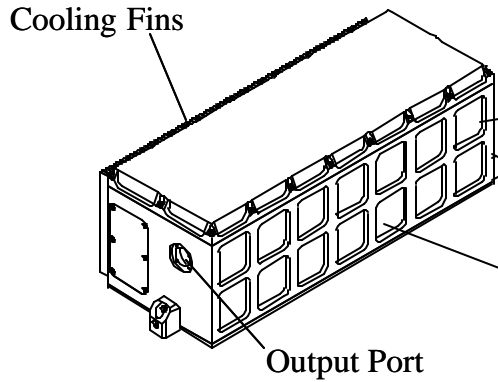


Figure 24: “Shoe Box” OPTL.

is acceptable, the size presented here can be reduced to ~ 2/3 that shown.

## VI. Frequency Agility Addition to OPTL’s

To add instantaneous frequency agility to OPTL’s the recent developments in high-reliability, compact OPTL’s,<sup>5, 6</sup> can be married with recent advances in Schottky-based sideband generators,<sup>7, 8</sup> to yield a reliable, potentially milliwatt-level, tunable THz source.<sup>9</sup>

This source mixes the output from an OPTL with a millimeter-wave (MMW) source in a “Sideband Generator” (SBG). The SBG is an ultra-high-frequency Schottky diode combined with a carefully designed mixer block. The mixer block includes the THz coupling structure and the MMW impedance matching structure.

The output from this device is then externally filtered to remove unwanted non-sideband radiation. This diplexing is usually accomplished with either an etalon diplexer,<sup>10</sup> or a Martin-Puplett diplexer.

A photograph of a THz SBG mixer block and a drawing of this block combined with a Martin-Puplett diplexer, are presented in

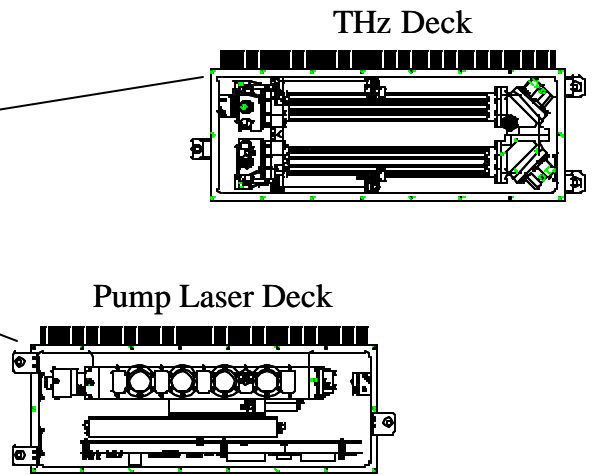


Figure 25.

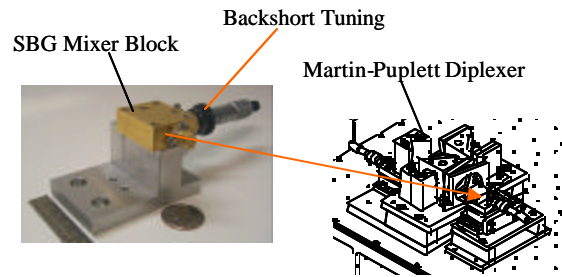


Figure 25: Photograph of a THz SBG block (right hand side) and a drawing of this SBG block combined with a diplexer in a system mounted on top of an OPTL.

Based on the latest MMW matching design (see Figure 26), this approach can add 220 GHz of tuning about any given OPTL line ( $\pm 110$  GHz).

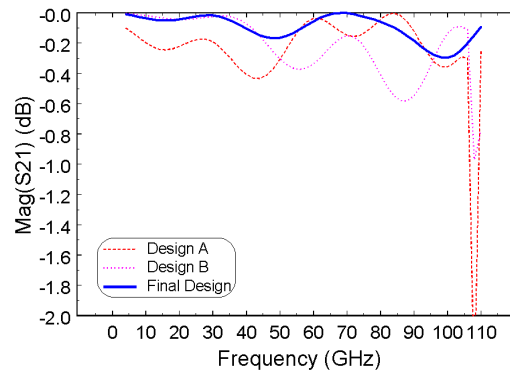


Figure 26:  $S_{21}$  plot for the three most recent MMW matching designs.

## VII. Conclusions

OPTL technology has come a long way in the past few years. What had started as a laboratory curiosity, has now matured into a reliable THz source technology.

Building on the advances in CO<sub>2</sub> laser technology, OPTL's are now in a wide variety of applications.

Based on already proven components, "shoe box" size OPTL's can be constructed, and instantaneous frequency agility can be added to OPTL's.

OPTL's are a mature THz source technology which can fill needs in a wide range of applications.

## VIII. Acknowledgements

The author wishes to thank Heinz-Wilhelm Huebers, of DLR, for information and figures related to the LO for the GREAT system.

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