Sandia National Laboratories

(U) Technology Point Forecast: Terahertz Solid-State Microelectronics

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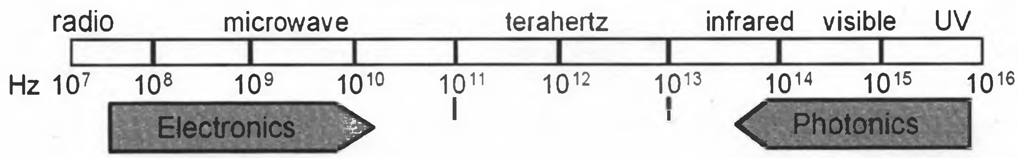
1. (U) Executive Summary

(U) This Point Forecast summarizes recent, ongoing, and projected future progress in research efforts aimed at establishing a solid-state microelectronics based component technology foundation that covers the terahertz portion of the electromagnetic spectrum. Relevant scientific and historical technical background will be introduced. A highly simplified, generic concept of operation in the THz spectrum that has potential relevance to many different national security, defense, and intelligence missions will be outlined, and the component technology requirements discussed. The major technical and scientific hurdles that need to be overcome to establish a useful THz solid-state component foundation will then be presented. The Forecast Analysis assesses the current state-of-the-art and potential future viability of a number of competing THz solid-state microelectronics research directions in meeting anticipated component performance requirements for practical applications. Finally, the world-wide leading research groups and their particular areas of expertise will be listed.

1.1. (U) Summary: Terminology & General Issues

(U) The terahertz (1 THz $= 10^{12}$ cycles per second) portion of the electromagnetic spectrum is loosely defined as electromagnetic waves having frequencies in the range of roughly 0.5 THz to 5 THz. This band of frequencies is also commonly termed *far-infrared* and *sub-millimeter wave* because these frequencies are significantly lower than conventional near- and mid-infrared, and the associated free-space wavelengths are shorter than 1 mm. Some other widespread working definitions of the terahertz spectral range include 0.1 THz to 10 THz and 0.3 THz to 3 THz, the latter because the associated



(U) Figure 1.1: Schematic representation of the electromagnetic frequency spectrum (in units of Hertz, or oscillation cycles per second) from radio (low frequency end) through ultraviolet (high frequency end). The THz spectrum lies between the upper microwaves and the lower infrared. Electronics are the solid-state technology foundation for radio through microwaves, but fail at higher frequencies. Photonics are the solid state technology foundation for ultraviolet down through infrared, but fail at lower frequencies.

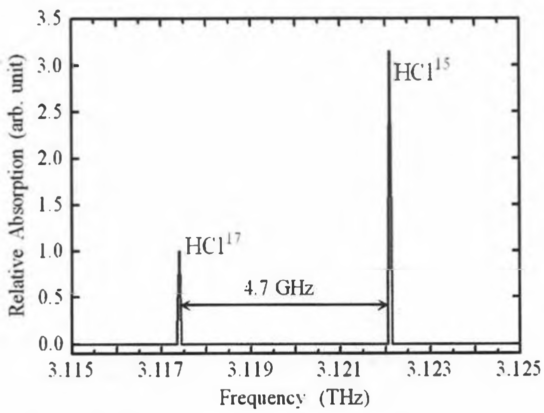
wavelengths are between 0.1 mm to 1 mm. This Point Forecast document will generally use the term "THz spectrum" to mean the range 0.5 THz to 5 THz, which poses the strongest technological challenges to applications of the THz spectrum.

(U) On the electromagnetic frequency spectrum, THz frequencies fall in between microwave/millimeter waves (at lower frequencies) and infrared-to-visible (at higher frequencies). This is depicted schematically in Fig. 1.1. In many ways, this is analogous to THz being the neglected middle child in the family of electromagnetic technologies. Microwaves and, more recently, millimeter waves are used every day in an extremely wide range of applications thanks to a thoroughly established foundation of transistor-based electronics technology for generating, detecting, and processing electromagnetic waves in these frequency bands. Similarly, solid-state photonics technology in the form of semiconductor lasers and photodetector diodes has, over the past two decades, put the infrared/visible spectrum into everyday applications such as CD/DVD players, bar code scanners, and laser pointers. A solid-state component foundation provides the enormous advantages of being large-scale manufacturable, cost-effective, highly compact, fully engineerable, and extremely reliable under practical operating conditions expected in the field, in flight, or in orbit.

(U) Unfortunately, for various fundamental physics reasons (detailed in Sect. 3) it has proven to be extremely difficult to extend electronics speeds up high enough or photonic frequencies down low enough to cover the THz spectrum adequately. Caught in the middle, THz radiation lacks the solid-state microelectronic foundation of its spectral siblings and still relies to a great extent on large-scale tube-based components analogous to using old-fashioned vacuum tubes for radios. This problem is colloquially referred to as the *THz Technology Gap* and is generally blamed for the historical inability to bring THz applications out of the laboratory and into more common use.

1.2. (U) Summary: Examples of Potential Applications

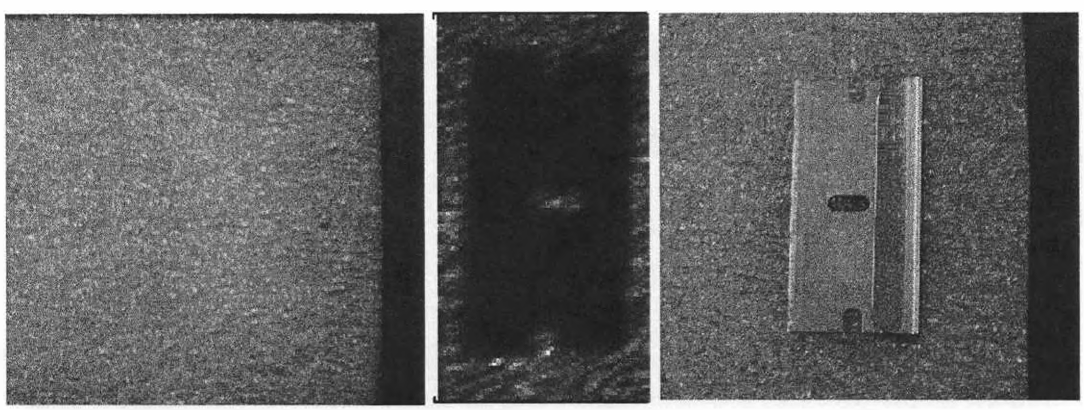
(U) Nevertheless, the impetus to develop a technically practical and economically feasible THz technology infrastructure has arguably never been stronger than it is now. As reviewed by Borak *[1]* and by Lee and Wanke *[2]* the well-known characteristic interactions of THz radiation with various forms of matter have many potential practical implications of direct interest to national security / defense / intelligence missions, fundamental scientific experiments, and medical diagnostics. Commonly cited examples of such applications include:



(U) Figure 1.2: Numerically modeled THz absorption/emission resonances of hydrochloric acid vapor near 3.120 THz. HCl can be positively identified by a distinctive isotopic doublet splitting with a 3:1 spectral weight ratio centered.

• (U) Rapid-but-high precision sensing and identification of chemicals in vapor phase, especially hazardous and/or toxic chemicals and pollutants. This could conceivably be done either locally (*i.e.*, point or portal) or at range (*i.e.*, remote or stand-off), using THz spectral resonances as exemplified in Fig. 1.2.

• (U) Discrete, non-invasive, non-hazardous detection/imaging of weapons concealed



(U) Figure 1.3: Concealed threat imaging of a razor blade hidden under packing foam. The foam is opaque in visible, but transparent to 2.7 THz radiation. Left: packing foam under visible light. Center: Same as left image except under 2.7 THz light. Right: backside visible image of razor blade. Sandia image.

under clothing or hidden in packaging, as demonstrated in Fig. 1.3,

- (U) Sensing of classes of chemical, biological, and nuclear WMD production products,
- (U) Highly secure, high-speed telecommunications difficult to detect or jam, and
- (U) Medical and biological sub-skin diagnostic imaging using non-invasive, non-ionizing radiation.

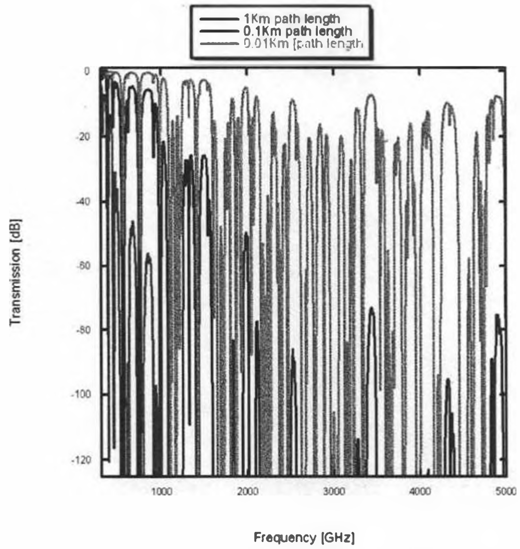
(U) In recent years, laboratories worldwide have carried out straightforward proof-of-principle demonstrations to show feasibility of all these possible applications. However, to get such THz applications out of the laboratory and into common use will require elevating the THz solid-state microelectronic technology base to be on a par with microwave electronics and infrared photonics.

1.3. (U) Summary: Technological Challenges

(U) There are three principal scientific challenges that have historically stymied the development of a THz solid-state microelectronics technology base. They are:

(U) 1) Significant degradation of electronics performance as frequencies go above roughly 0.1 THz. This is primarily due to fundamental electron transit speed limitations discussed more thoroughly in Sect. 3. In particular, electronic amplifier gains and electronic oscillator source powers rapidly fall to practically non-useful levels above a few tenths of THz.

(U) 2) Inability of conventional photonic materials to generate light at frequencies below roughly 10 THz. This is primarily due to the fact that semiconductor energy band



(U) Figure 1.4: Modeled horizontal path transmission attenuation of electromagnetic frequencies up to 5 THz (5000 GHz), using standard sea level atmospheric conditions, calculated at Sandia. At distances approaching 1 km, attenuation can be well in excess of 100 dB.

gaps smaller than the equivalent of 10 THz photon frequency are not known to exist in stable solid-state materials, as discussed more thoroughly in Sect. 3.

(U) 3) Very high atmospheric opacity at THz frequencies. As shown in Fig. 1.4, a "standard" earth atmosphere absorbs THz radiation strongly (albeit unevenly as a function of frequency), severely limiting the distance over which THz waves can propagate through the atmosphere before weakening to undetectable levels. This is primarily due to a strong interaction between water vapor molecules (among other atmospheric constituent molecules) and THz radiation, as discussed more thoroughly in Sect. 3.

(U) Many conceivable applications require propagation of THz radiation through atmosphere. However, Nature perversely arranges things so that the performance of both solid-state electronics and photonics reach a minimal level precisely in the THz frequency band where the atmospheric opacity issue demands the highest level of performance. This conundrum is the heart of the THz Technology Gap problem, and this Point Forecast reviews current research strategies to solve it.

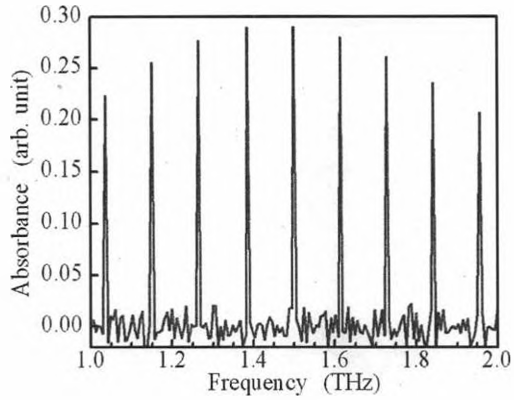
2. (U) Background

2.1. (U) Scientific Background

(U) The main scientific issue that underlies both promising THz applications and technological hurdles is the interaction of THz frequency radiation with matter, in vapor, liquid, or solid phases. This section outlines the important fundamental interactions between THz radiation and molecules in vapor phase, atmosphere, and some solid materials.

2.1.1. (U) Chemical Vapor Sensing

(U) THz frequencies haves long been recognized by chemical spectroscopists as perhaps the best frequency range in the electromagnetic spectrum for high-confidence, high-specificity detection and identification of molecular species in vapor phase. This is because many chemicals, from simple diatomic molecules *[3,4]* to complex macromolecules *[5]* have stronger and more distinctive electromagnetic absorption and emission resonances in the THz than in either microwave or infrared-to-visible ranges. At lower pressures smaller molecules generally have very sharp THz signatures, with Doppler limited widths around 10 MHz, providing significantly enhanced spectral resolution as compared to infrared signatures. While compared to microwave spectroscopy, interaction strengths are generally much larger in the THz since the strength of the interaction increases by greater than the square of the frequency, until reaching a peak located in the THz regime and specified by the molecular mass.



(U) Figure 2.1: THz rotational mode absorption spectrum for the simple rotor molecule carbon monoxide, in vapor phase at low pressure (Sandia measurement)

(U) Most non-centrosymmetric molecules have distinctive sets of resonances between 0.5 to 5 THz that are predominately rotational modes or hybrid rotational-vibrational modes, determined by a molecule's moment-of-inertia. An example for the simple rotor molecule carbon monoxide is shown in Fig. 2.1. The non-centrosymmetric requirement comes from the fact that THz electromagnetic fields interact with a molecule via the molecule's dipole moment, and centrosymmetric molecules generally have zero dipole moment. Since the moment-of-inertia depends on the distribution of mass within the molecule as well as the total mass, a spectrum based on moment-of-inertia will discriminate between molecular species better than any form of spectroscopy based only on mass or only on inter-atomic bond strengths. In fact, at high spectral resolution each molecular signature is unique enough that only a few lines are generally needed to identify a molecule, which is important given the atmospheric propagation properties described below.

(U) An advantage of THz spectroscopy is that analysis of the rotational constants can be performed using fundamental quantum mechanics models. With measured rotational constants, one has an absolute identification of the molecule quantitatively as well as qualitatively. In most cases of interest, molecular absorption/emission cross-sections are also very large in the THz, leading to potentially excellent detection signal-to-noise levels and thus high sensitivity to small concentrations. *[3]* THz spectroscopy techniques can be used to determine quantitatively with very high precision the frequencies, lineshapes, and cross-sections of distinctive THz resonance lines of a target vapor. This information can be used to define the operational parameters of a THz detection system tuned to that specific target molecule.

(U) Since the rotational energy transitions are significantly below the thermal energy scale, the molecules will emit as well as absorb at the rotational transitions. The amount of emission of a fixed number of molecules will depend strongly on the temperature. For gas molecules that are at a higher temperature than the background, such as effluent emitted from a chimney, the characteristic spectral features could be observable passively, which is conceptually and technically simpler than active detection which requires an illumination source. In addition, passive radiometric sensing enables covert monitoring of a potential target. Since the emission lines can be narrow and relatively closely spaced, high resolution spectroscopy is required to take full advantage of THz molecular signatures.

(U) These basic physical facts mean that the THz has enormous potential in the area of remote spectroscopy with unprecedented, unsurpassed species discrimination capability and minimized probability of error due to either missed detection or misidentification. Success in developing the THz for remote vapor detection will create a new modality in remote sensing that stretches frequency agility, complements conventional microwave and infrared detection by providing hitherto inaccessible primary and corroborative spectral information, and decreases operational predictability by deploying a new and unconventional frequency technology that will make counter-detection and interdiction more difficult.

2.1.2. (U) THz Transmission through Atmosphere

(U) The most definitive knowledge of THz transmission through atmosphere comes from Fourier transform spectroscopy (FTS) astronomical observations of THz signals taken at the J. C. Maxwell and Caltech Sub-millimeter Wave Observatories on Mauna Kea, Hawaii in the past 10 years. Because of optimal conditions for THz observations, the data on THz through-atmosphere transmission from Mauna Kea is far more complete and quantitatively reliable than from any other terrestrial point *[6]*. The Mauna Kea data and modeling is thus adopted as the baseline of existing knowledge.

(U) The Mauna Kea conditions for transmission of THz radiation between space and a point on the earth's surface[1] are as optimal as exist. These conditions include:

1.) (U) High elevation -- 4100 m above sea level

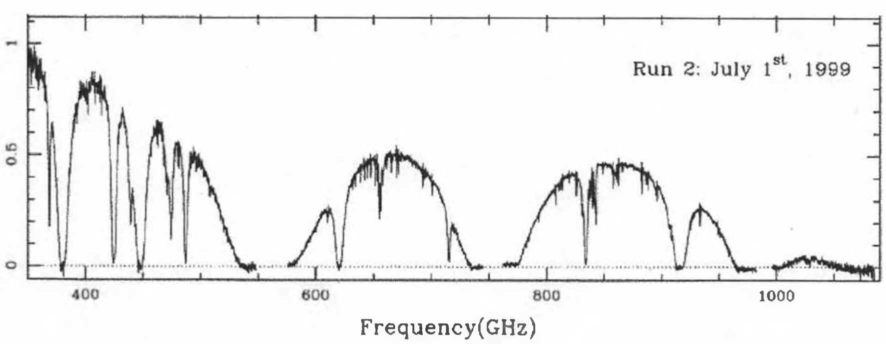
2.) (U) Low humidity -- 0.5 to 1 mm absolute precipitable water vapor, equivalent to 5 to 10% relative humidity near a temperature of 0°C.

3.) (U) Isolation from electromagnetic and chemical pollution.

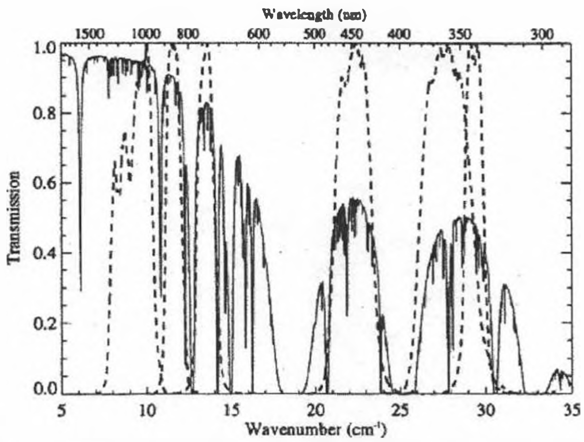
[1]Near zenith angle of 0°, or looking approximately straight up/down

(U) Condition (1) means that pressure broadening of resonance linewidths can be neglected. Condition (2) minimizes water vapor, which is the dominant THz absorbing molecule in the atmosphere. Condition (3) makes Mauna Kea observations immune to interfering electromagnetic signal sources and pollutants.

(U) The initial effort in THz FTS spectroscopy from Mauna Kea by *[6]* has been superseded by the two more recent quantitative experiments of Pardo, *et al.*, *[7]* and Naylor, *et al* . *[8]*. The 0° zenith spectra from the THz emission of the sun are reproduced in Fig. 2.2 (from Ref. 7) and Fig. 2.3 (from Ref. 8). The two sets of data were taken under slightly different weather conditions and use somewhat different corrections to remove instrumental noise and background sky interference. Ultimately, though, the two sets of data agree in frequency window positions to within 5% and in transmission coefficients to within about 1 dB (a reasonable variation for the slightly differing weather conditions), which, for most practical purposes, is an insignificant degree of variation or uncertainty.



(U) Figure 2.2: Power transmission spectrum taken at Mauna Kea from Ref. 5. Transmission coefficient (y-axis) is power fraction transmitted through atmosphere at 0° observation angle. Conditions: temperature = 272 ± 1.5 K, pressure = 620 ± 3 mbar, relative humidity = 12 ± 1%.



(U) Figure 2.3: Power transmission spectrum taken at Mauna Kea from Ref. 6. Note: 33 wavenumbers = 1 THz. Transmission (y-axis) is power percentage transmitted through atmosphere at 0° zenith angle. Conditions: temperature = 280 K, pressure = 625 mbar, absolute humidity = 0.5 mm precipitable water vapor. Dotted lines are the transmission characteristics of bandpass filters used for high-resolution measurements in the transmission windows.

(U) One encouraging fact to note is that the transmission coefficient from space through the atmosphere to Mauna Kea is as high as 0.5 (*i.e.* -3 dB) near the center of the broad windows centered around 0.67 THz and 0.86 THz and can be as much as 0.05 (-13 dB) in the window near 1.03 THz. The definition of a window is, of course, somewhat arbitrary and depends on the bandwidth needs of a particular application. Some closely spaced narrow transmission peaks could be considered parts of a single broad window intercut by a few isolated deep absorption lines. The reverse holds true as well: some broad windows having a few closely spaced absorption resonances inside them could be broken into several discrete windows. Nonetheless, noting this arbitrariness in window definition, a reasonable look at the data of Figs. 1 and 2 show up to a dozen or so useful THz transmission windows between 0.15 THz to 1.1 THz.

(U) Instrumentation difficulties have limited the available data on THz transmission at frequencies above 1.1 THz. Observations done at Atacama, Chile *[9]* showed the existence of two more significant transmission windows, centered near 1.35 THz and 1.5 THz. The poor calibration of that data was insufficient to give a reliable quantitative description of the window transmission parameters, however. Using the best-fit continuum parameters obtained from their measured data up to 1.1 THz together with known molecular absorption lines, Ref. 7 calculated windows at 1.35 and 1.55 THz, both having widths of around 0.15 THz and transmission coefficients comparable to that of the 1.03 THz window. These features were independently reproduced in numerical modeling by [redacted] *[10]* with small differences, for example the window center is near 1.50 THz rather than 1.55 THz. An example of the [redacted] result is cited in Ref. 4 and reproduced in Fig. 2.4. The results of numerical models using the Mauna Kea baseline are expected to be accurate to within 10% in frequency and transmission coefficient.

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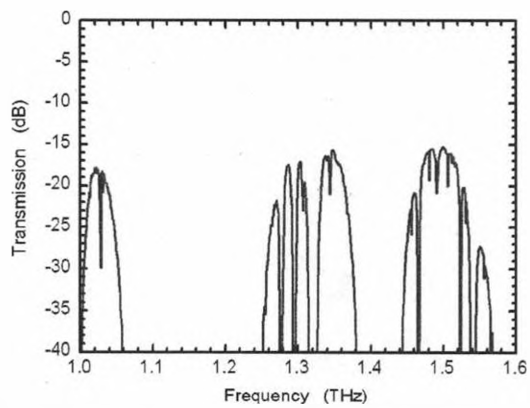
(U) Extending the baseline Mauna Kea knowledge to other terrestrial conditions, particularly closer to sea level, more humid, and more polluted environments, poses



(U) Figure 2.4: Numerically modeled power transmission spectrum from Ref. 8 assuming Mauna Kea atmospheric conditions. Transmission is power percentage transmitted through atmosphere at 0° zenith angle. Conditions: absolute humidity = 1.0 mm precipitable water vapor, temperature = 273 K (0° C), altitude = 4100 m above sea level.

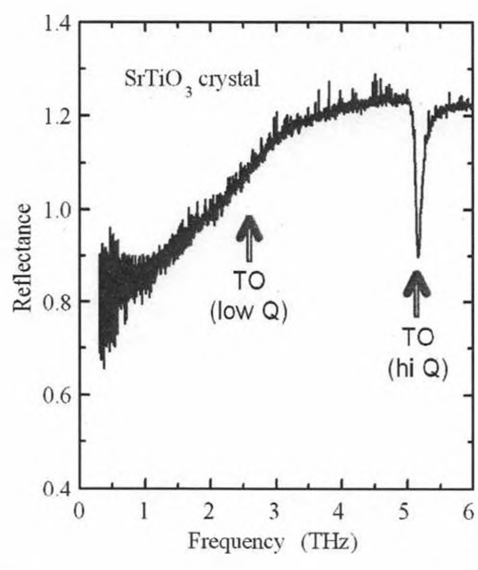
many difficult scientific problems which are not resolved. There is also a lack of quantitative and reliable experimental data, of comparable quality to the baseline data, in more adverse conditions.

(U) From a scientific perspective, the chief difficulties in extending the baseline knowledge to lower altitudes is the complications of pressure broadening and increased water vapor concentration. Water vapor is the dominant absorber of THz radiation in the atmosphere. In the (unrealistic) absence of pressure broadening, the THz atmospheric opacity near H_2O absorption lines would simply scale linearly with absolute precipitable water vapor. Pressure broadening introduces severe nonlinear complications, however. First, the average general atmospheric pressure and the average density of water vapor both increase in an exponential manner with decreasing altitude approaching sea level. Added to this, absorption peak widths widen in a nonlinear manner with increasing pressure. The widening of the absorption peaks causes strong overlaps in the wings of nearby absorption lines. This coupling between absorption wings makes the continuum absorption stronger and hence drags down the transmission coefficients in the propagation windows observed at high altitude, with nonlinear frequency, pressure, and temperature dependencies. Since the continuum absorption becomes strong, accounting for it becomes more sensitive to the specific functional form used to model it.

(U) The real problem in developing an accurate model of pressure broadening is the lack of precise knowledge about absorption lineshapes, particularly in the wings far from the center of the absorption resonance. Under baseline Mauna Kea conditions, pressure broadening is small enough that the assumption of a Lorentzian lineshape is sufficiently accurate for all realistic purposes. However, near sea level the use of a Lorentzian is insufficient to describe the increasing overlap of absorption tails. Unfortunately, accurate measurements of absorption lineshapes far from resonance centers are difficult and usually neglected, and so there exists little reliable data to use as a guide.

2.1.3. (U) THz Transmission through Solids

(U) The transmission of THz radiation through solid materials is a complex issue because of the very wide variety of types of solids and the many different ways solid materials can interact with THz electromagnetic fields. It turns out that some solid phase chemicals, such as certain drugs (legal and illegal), *[11]* some types of explosives, *[12]* biological materials, *[5]* and many classes of crystals can be identified by their THz absorption resonance signatures, similar to vapor phase chemical identification. An



(U) Figure 2.5: THz reflection spectrum of a strontium titanate crystal, taken at Sandia. The crystal can be identified by two THz features: a low quality factor (Q) transverse optical (TO) phonon around 2.5 THz and a high Q TO phonon near 5 THz.

example is shown in Fig. 2.5.

(U) It also turns out that several common clothing and packaging materials that are completely opaque to infrared-to-visible radiation are at least partially transparent to THz frequencies. *[13]* These materials also tend to be transparent to microwave frequencies, but the centimeter wavelengths of micr owaves make imaging with high enough resolution to identify a threat shape (*e.g.* gun or knife) impossible. By contrast, the sub-millimeter wavelengths of THz radiation can give sufficiently high imaging resolution to clearly distinguish shapes. Furthermore, the photon energy of THz electromagnetic radiation is far below atomic or molecular ionization levels, so that such imaging can in principle be done without the associated health hazards of X-rays . This has led to understandable excitement in the potential use of THz radiation for non-invasive concealed weapon / threat / contraband detection. (See Fig. 1.3)

(U) While a broadly detailed description of THz interaction with solid materials is far beyond the scope of this Point Forecast, a few generic principles can be reviewed. First and most generally useful, metals are highly reflective *(i.e.* very low emissivity) in the THz, as they are anywhere in the electromagnetic spectrum below ultraviolet frequencies. This is of practical importance in wave guide, mirror, and antenna design as highly conductive metals such as aluminum. copper, and gold are still the best way to guide and focus THz electromagnetic waves. In addition, in THz imaging metallic objects often form high contrast regions against highly absorptive or transmissive background materials, both in active imaging which depends on reflection and in passive imaging which depends on emissivity contrast.

(U) In general, materials with a significant liquid or vapor phase water content are highly absorptive in the THz. As mentioned in Sect. 2.1.2., water vapor is the atmospheric constituent that most strongly absorbs THz radiation because its strong dipole moment and set of fundamental rotation modes couple very strongly to THz frequencies. In liquid water the H_2O molecules retain sufficient rotational degrees of freedom to continue strongly absorbing THz radiation, and their spectral absorption resonances broaden and overlap to form a strong continuum background absorption.

(U) "Dry" dielectric materials typically do not absorb or reflect THz radiation strongly, though they may scatter THz radiation significantly depending on details of material morphology at the 0.1 to 1 millimeter length scale. The main exception to this rule-of-thumb are those materials that have strong resonant inter-atomic or lattice vibrational modes in the THz. Such vibrational modes are found in many oxide crystals and organic solids and can be used as a spectral fingerprint to identify the solid material. However, these solid-phase vibrational modes have broad spectral linewidths, so they are not as definitive as vapor phase rotational mode spectral signatures and can contribute to a strong background continuum absorption as well.

2.2. (U) THz Technology Background

(U) For most of the past roughly 30-40 years, THz technology has been developed primarily by radioastronomers. This happened as a logical upward frequency extension of earlier radio-frequency and microwave radioastronomy. In particular, astronomical interest in THz increased when two things were recognized: 1.) chemicals in vapor phase, whether from planetary atmospheres or deep-space gas clouds, could be identified more reliably using collections of spectral signatures in THz thermal absorption/emission spectra than using any other part of the electromagnetic spectrum, and 2.) the spectrum of thermally radiated power from cold planetary atmospheres and gas clouds (typically at absolute temperatures of 20 K to 100 K) peak s in the THz, rather than microwave or infrared. This means that if the problem of THz absorption by earth's atmosphere can be bypassed, through the use of high-altitude ground-based radiotelescopes, airborne radiotelescopes, or satellites, a tremendous amount of information about the molecular constituents of the earth's upper atmospheric layers and a wide variety of astronomical objects can be gleaned via THz radioastronomy. In fact, over the past decade NASA the NSF (via the National Radio-Astronomy Observatory (NRAO)), and the European Space Agency (ESA) have invested significant resources into THz radioastronomy via telescopes on Mauna Kea in Hawaii, the South Pole, the Atacama plane in Chile, on custom-modified aircraft (the NASA/ESA SOFIA project), and satellites (NASA's Aura EOS satellite).

2.2.1. (U) Tube-based THz Sources

(U) A continuous-wave, coherent source of THz frequency radiation is typically required for active illumination, laboratory spectroscopy, or as a local oscillator for very high sensitivity heterodyne-based THz detection. From decades of radioastronomy-driven research, the workhorse sources of such THz radiation have been tube-based oscillators. These oscillators use evacuated or low-pressure gas filled tubes, often around 1 meter in length, to generate THz radiation either using electron beams or optical excitation of the rotational modes of a known gas. By far the two most dominant THz tube sources in use today are backward-wave oscillators (BWOs) *[14]* and CO_2-pumped molecular gas lasers (MGLs). *[15]*

(U) BWOs generate coherent THz radiation by firing a radio-frequency modulated, collimated high energy (few keV) electron beam in an evacuated tube through a parallel high magnetic field (typically a few Teslas). Electron orbits in the magnetic field generate THz radiation, which propagates outward from the tube in a direction opposite to the electron beam, hence the name. The THz frequency emitted can be tuned continuously over roughly an octave for a given BWO by adjusting the electron beam energy and the strength of the magnetic field. BWOs can typically generate a few mWs of average power at a few tenths of THz, falling to < 1 mW at 1 to 2 THz.

(U) MGLs generate coherent THz radiation by using a CO_2 laser (at approximately 30 THz) to optically excite a low-pressure molecular gas into a high-energy rotational state inside a resonant cavity tube. The excited molecular state decays by emitting stimulated emission of resonant THz photons into the cavity, producing a THz laser of well-defined frequency. The THz frequency emitted cannot be tuned continuously, but can be changed discretely over the available resonant frequencies of the molecular gas species used by changing the exact CO_2 excitation frequency and the molecular gas tube cavity length. MGLs can typically generate several to tens of mWs of average power anywhere from a few tenths of THz up to several THz.

(U) As with the days of tube-based radios, all tube-based THz sources suffer from intrinsic problems that make them unreliable or difficult to operate. These include:

• (U) Stringent requirements for mechanical stability and structural integrity of the tube(s), associated optical components, and the necessary component alignments under varying operating conditions of changing temperature, humidity, vibrations, etc. This makes such sources both fragile and finicky.

• (U) Large size and weight – BWOs and MGLs are typically of order 1 m in length and weigh between 25 to 100 kg.

• (U) Requirement for high operating voltages and powers – a kilovolt power supply is required for a BWO, and MGLs typically require 100 W of operating power. Thus a large power supply must be used as well.

(U) This is not to say that such THz sources cannot be engine ered an built to withstand rigorous applications such as flight or satellite operation. The best example is a 2.5 THz MGL built for the NASA Aura EOS satellite *[16]* launched successfully in 2004 and operating today as a local oscillator for remote sensing of OH^- radical concentrations in the earth's atmospheric limb. The downside is that development of that one MGL for launch and satellite-qualified operation is estimated to have cost around $8M. *[17]*

(U) The remainder of this forecast article will not address tube-based sources because of their relative maturity and innate difficulties in using tube-based sources outside controlled laboratory conditions. It is the opinion of the author that a widely accepted terahertz component technology must be built upon a solid-state, rather than a tube-based, foundation.

2.2.2. (U) Solid-state THz Detectors

(U) Solid-state THz detectors of several different types have been used for several decades now. There are two main categories of THz detectors in common use, both developed in radioastronomy-driven research over the past few decades. These are:

1) (U) Direct detectors – these detect incident THz radiation power, usually without frequency discrimination, and generate a voltage or current output proportional to the power detected. A typical THz direct detector is a bolometer, which by definition absorbs electromagnetic power to generate a slight increase in detector temperature, then outputs an electrical signal proportional to that temperature increase and hence proportional to the electromagnetic power absorbed.

2) (U) Heterodyne detectors – these detect the power incident in a THz signal at a specific frequency relative to a known local oscillator (LO) frequency and generate a frequency output at the absolute difference between the signal and the LO frequencies. The output difference frequency power is proportional to the incident signal power at a fixed an known LO power. A typical heterodyne detector is a mixer.

(U) Commercial off-the-shelf (COTS) direct detectors that work as THz detectors are available from a number of vendors. Such detectors are typically bolometers that use doped semiconductors, high-resistivity metal films, a pyroelectric material, or an absorbing gas mixture. All of these absorbing materials operate on the general principal of producing a change in electrical signal (voltage or current) upon being locally heated by a small amount of absorbed THz electromagnetic radiation power. They are thus electromagnetic power detectors that respond to the absolute magnitude squared of the electromagnetic field, not to the field, frequency, or phase of the electromagnetic wave. A large temperature-coefficient of resistance or pyroelectric coefficient is desired so as to produce a large change in detector electrical signal for a small amount of absorbed radiation power.

(U) The sensitivity of bolometers is specified by noise-equivalent power (NEP), with a smaller NEP indicating higher sensitivity and thus superior low-signal performance. Room temperature COTS bolometers can be found with NEPs in the range of 10^{-9} to 10^{-10} W/Hz$^{1/2}$, while cooled or cryogenic COTS bolometers have NEPs in the range of 10^{-12} to 10^{-15} W/Hz$^{1/2}$. As an example of a simple signal-to-noise sensitivity calculation, suppose one wants to detect a THz signal at video-rate speeds (*i.e.*, update signals at approximately 100 Hz rate). Then, a bolometer having NEP of 10^{-10} W/Hz$^{1/2}$ would reach a signal-to-noise ratio of unity (*i.e.*, the smallest signal power detectable) at a signal power level of 10^{-10} W/Hz$^{1/2}$ x $(100\ \text{Hz})^{1/2} = 10^{-9}$ W = 1 nW. Note that the faster the desired detection rate or bandwidth, the larger the minimum detectable power will be, so the worse the sensitivity. In general, more sensitive bolometers or direct THz detectors of any kind require cryogenic cooling to near or below 4 K temperature. These bolometers are usually relatively slow detectors, requiring 10 to 100 ms of integration time, making them marginal for video-rate detection and not useful for detecting fast transients, modulations, or single-shot pulses. Also, bolometers give no information about the frequency content of an incoming signal. Frequency information must be acquired separately, either using a frequency band filter or some sort of interferometer placed before the detector input.

(U) Heterodyne-detection THz mixers in use today include Schottky diodes, metal-insulator-metal (MIM) diodes, varactors, different forms of tunnel diodes, and superconductors. All such mixers rely on a strong non-linear characteristic in their current-voltage relation, and all require a known, coherent THz LO source to pump the mixer and define a central frequency. Although commonly used in the THz scientific community and available from various vendors, unlike bolometers THz mixers can not really be considered COTS items. Almost all THz mixers are specific custom-designed and custom-built devices.

(U) The sensitivity of a THz heterodyne mixer receiver is a more complicated issue than the sensitivity of a direct detector. A mixer's sensitivity is conventionally given as a noise temperature, T_N, in units of degrees Kelvin (K), rather than a NEP. Physically interpreted, if a heterodyne receiver input were looking at a signal from 0 K blackbody (*i.e.* absolute zero temperature, or equivalently zero input power in the frequency band of interest), the receiver's output signal power would be the same as that of an ideal (noiseless) receiver looking at an input signal from a blackbody at temperature T_N. All heterodyne mixers require a minimum LO input power to achieve an optimal operating point of minimum T_N. For THz semiconductor diodes this LO power is typically several mWs, while for THz superconductor mixers this LO power is typically tenths of μWs to a few μWs.

(U) When detecting signals near a center frequency f, T_N rises with increasing f. The quantum limit on mixer noise temperature, due to photon fluctuations, is approximately hf/k, where h is Planck's constant and k is Boltzmann's constant (up to a factor of 2 depending on whether the receiver is sensitive to single- or double-side band noise). In practice, good THz mixer receivers have $T_N \sim 10$ to 100 hf/k assuming optimal LO power requirements are met.

(U) In terms of mixer signal-to-noise there are two typical cases:

1.) (U) Assume a mixer receiver with noise temperature T_N is functioning as a radiometer; that is, looking at the signal within a bandwidth Δf (*i.e.*, spectral resolution of Δf)around a central frequency f from a blackbody radiator of temperature T_{BB}.

(U) The relevant noise power P_{Noise} generated by the receiver is:

$$P_{Noise} = kT_N \sqrt{\frac{\Delta f}{\tau}} \quad (2.1a)$$

where k is Boltzmann's constant and τ is the integration time constant. This assumes that the noise characteristics are Poisson distributed, so random fluctuations are reduced as $1/\sqrt{n}$ where n is the number of "samples," which in this case is proportional to the integration time.

(U) The signal power P_{Sig} received from the blackbody is:

$$P_{Sig} = \left(\frac{c}{f}\right)^2 B(f, T_{BB})\Delta f \quad (2.1b)$$

where c is the speed of light and $B(f,T)$ is the Planck blackbody radiation function.

(U) The signal-to-noise is thus:

$$SNR = \frac{(c/f)^2 B(f, T_{BB})}{kT_N}\sqrt{\Delta f \tau} \quad (2.1c)$$

(U) There are some factors of ½ or 2 that get thrown in depending on whether the receiver is polarization sensitive, alternating between looking at the signal and looking at a calibrated source (*i.e.*, a Dickey radiometer), or sensitive to single or double side bands

(U) To be concrete, a mixer receiver with $T_N = 10{,}000$ K (typical of a Schottky diode driven with several mWs of LO power) can detect a $T_{BB} = 100$ K blackbody at $f = 2.5$ THz, $\Delta f = 10$ MHz, and $\tau = 10$ ms with $SNR \approx 10$ dB.

2.) (U) Assume a mixer receiver with noise temperature T_N is functioning as a coherent receiver; that is, receiving a signal that is frequency and phase referenced to the mixer's local oscillator (LO). This would be the case for some radar, telecommunications, and actively illuminated imaging applications.

(U) The relevant noise power is then:

$$P_{Noise} = \frac{kT_N}{\tau} \quad (2.2a)$$

where τ is the integration time. (It helps if you think of a Joule as a spectral power density: a Watt/Hz.)

(U) The signal-to-noise is just the ratio of the received coherent power to (2a):

$$SNR = P_{Sig}\,\tau / kT_N \quad (2.2b)$$

(U) To be concrete, if one wants a minimum $SNR = 10$ dB for detection of a coherent signal in a video-rate integration time $\tau = 10$ ms using a mixer receiver with $T_N = 10{,}000$ K, the minimal detectable signal power is then:

$$P_{Sig}^{min} = 10\ P_{Noise} = 1.4 \times 10^{-16}\ \mathrm{W} \quad (2.2c)$$

Up to a factor of two depending on whether the noise is single- or double-side band (both are used, often without specifying which one).

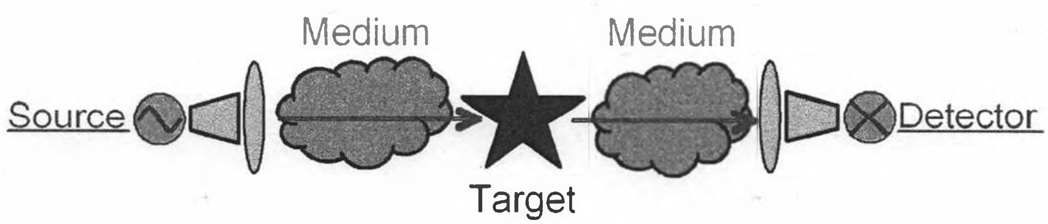
(U) Except for direct detectors cooled to near absolute zero, heterodyne mixer detection is generally more sensitive than direct detection and gives high precision signal frequency information as well as signal power information. The disadvantages of heterodyne detection are that it requires a significantly more complicated circuit (including an LO source and associated high frequency signal circuitry), is far more difficult to scale into detector arrays, and can cover only a relatively narrow frequency range of up to several GHz around the central LO frequency. For these reasons, heterodyne detection is used primarily to recover very weak signals at known frequencies and not to do broadband spectral surveys or focal-plane array imaging.

3. (U) Scenario Study

3.1. (U) Fundamental Concept of Operation and Criterion

(U) The following Scenario Study and Technology Forecast Analysis are based on an simplified and idealized concept of operation that lies at the heart of the vast majority of conceived THz applications. It must be not ed that the various different example THz applications mentioned in Sect. 1.2. each have their own specific component performance requirements that can differ dramatically from application to application. It is not the purpose of this report to con centrate on or specify any one particular application. Nonetheless, the concept of operation for nearly all THz communications, spectroscopy, chemical sensing, imaging, threat detection, *etc.* applications share the following stripped-down but fundamental operational concept, illustrated in Fig. 3.1.

(U) Basically, all such applications require a THz signal source, transmit the THz signal through a medium (usually atmosphere, but possibly vacuum) to interact with a target (*e.g.*, a chemical vapor cell, an object to be imaged, etc.), and then transmit the signal through a medium to a THz receiver that may be either a direct or heterodyne detector. In the case of heterodyne detection a coherent THz source would be coupled directly to the detector as a local oscillator, and the THz signal source could be either



(U) Figure 3.1: Illustration of the fundamental concept of operation of most THz applications. Solid-state microelectronic Source and Detector components are the subject of the Forecast Analysis.

from the same or other coherent source (as in the case of a transceiver), or from a passive thermally emitting body. From a THz component point-of-view, whether such a concept of operation can work depends chiefly on whether the THz signal power output by the signal source and the THz sensitivity of the detector are sufficiently high so that the attenuated signal arriving at the detector can be measured with a signal-to-noise ratio greater than unity. Hence the principal performance parameter to be considered for a solid-state source is its power, and of a solid-state detector is its sensitivity as quantified by its noise equivalent power or noise temperature. Quite generally, the over-arching future path or direction of a solid-state THz component technology will depend mostly on the following power/sensitivity criterion:

$$\frac{\alpha P_{\mathrm{Source}}}{P_{\mathrm{Detector}}^{\min}} \geq 1 \quad (3.1)$$

where P_{Source} is the power emitted by the THz signal source, α is the fraction of the signal power that makes it to the detector (*i.e.*, the attenuation coefficient that depends on path length, absorption and scattering of the medium and target, antenna size, *etc.*), and $P_{\mathrm{Detector}}^{\min}$ is the minimum power detectable by the THz detector, as determined by the calculations described in Sect. 2.2.2.

(U) There are other THz component criteria that are less fundamental than the power/sensitivity ratio summarized in Eq. 3.1 and tend to be highly application specific. These include: operating temperature (room or ambient temperature preferred), frequency tunability and coverage range, frequency precision and stability, and modulation speed. The more important of these will also be addressed.

(U) The two major directions for solid-state THz component applications discussed in the following sections differ primarily in what level of attenuation α can be handled by the power available in solid-state sources and the sensitivity available in solid-state detectors.

3.2. (U) Local Detection Scenario

(U) For THz applications that require transmission along a horizontal path through earth's atmosphere at near sea level altitudes, atmospheric opacity, as discussed in Sect. 2.1.2., is such that α in Eq. 3.1 can easily be in the range 10^{-10} to 10^{-100} per km of signal propagation distance, depending on exact frequency and weather conditions. The attenuation value increases strongly with increasing humidity.

(U) Thus, the first application scenario considered is the case where THz solid-state components cannot produce sufficient source power and/or detector sensitivity to satisfy Eq. 3.1 for α in the range of 10^{-10} to 10^{-100}. This means that THz solid-state components do not develop to the point that the technology can detect a THz signal transmitted over a distance on the order of 1 km through air in typical weather conditions. In such a scenario THz applications using solid-state components would be limited to local applications where transmission is only over distances of order < 1 m up to possibly 10 m. This includes applications where THz signals are confined to small low pressure gas cells, so-called point detection applications.

(U) There are several local THz detection applications of interest to security, defense, intelligence, and industrial concerns. Some examples include:

• (U) Point detection of hazardous or toxic chemical vapors – where the gas mixture to be tested is sucked into a low-pressure gas spectroscopy cell,

• (U) Non-destructive evaluation of mechanical, structural, and chemical defects in materials as varied as ceramics, plastics, and pharmaceuticals,

• (U) Non-invasive detection / imaging of weapons or threats concealed behind clothing or packaging materials.

(U) Most, though not all, such applications use an active THz coherent illumination source. For point detection of chemicals in a gas cell, attenuation of a THz signal is not a significant issue. For local applications that require transmission through a material, the attenuation coefficient α is typically $\geq 10^{-7}$, assuming the material is not unusually thick and is not metallic nor has significant water content.

(U) From this, the required solid-state source power and detector sensitivity performance parameters may be estimated for general local application scenarios. Using a value of $\alpha = 10^{-6}$, Eq. 3.1 then requires the ratio $P_{Source}/P^{min}_{Detector} > 10^{6}$. From the discussion in Sect. 2.2.2., COTS direct detector bolometers that operate at or near room temperature are available that can have $P^{min}_{Detector} = 10^{-9}$ W assuming video-rate detection speeds. This means the required coherent source power is in the range 10^{-3} W, or the order of 1 mW. In practice a coherent source power of 1 to 10 mW is considered highly desirable to maintain a cushion against system inefficiencies. While a phase-locked heterodyne detector can detect significantly smaller signal powers, it turns out most room temperature THz mixer detectors require a local oscillator input power near 10 mW to function at the optimal point of minimum noise temperature. Thus for local THz detection application scenarios using currently available solid-state THz detectors, a THz source should generate power in the 1 to 10 mW range independent of direct or heterodyne detection. While this power level is available from traditional tube-based THz sources as mentioned in Sect. 2.2.1, it currently lies in the upper range limit of current state-of-the-art solid-state THz microelectronic sources.

3.2.1. (U) Projected Path Forward for Local Detection Scenario

(U) From the analysis above, developing THz solid-state components for local detection applications to a point which will achieve wide functional acceptability will require increasing the available $P_{\text{Source}}/P^{\text{min}}_{\text{Detector}}$ ratio by a factor of 2 to 10 using room-temperature operating components. At the same time, other practical considerations such as frequency range coverage, speed, and tunability will be important technical acceptability considerations depending on the specific application. The ability of current research strategies to achieve this factor of ten improvement will be discussed in Sect. 4.

(U) For most local detection application scenarios, the performance of many COTS THz direct detectors and custom heterodyne receivers is already mostly acceptable. Sensitivity in terms of room-temperature or near room-temperature noise equivalent power or noise temperature is generally adequate in this case. Technological. improvements that are now being researched include faster response time without increasing noise equivalent power for THz direct detectors, lowering LO power requirements without increasing noise temperature for THz heterodyne detectors, making one- and two-dimensional focal plane imaging arrays out of detectors, and integrating THz detectors with solid-state sources to make THz integrated circuits. Descriptions of these efforts will be reviewed in Sect. 4. There is high confidence that significant technical advances in this area will be achieved over the next ~5 years that will dramatically improve acceptance of THz technology for local detection applications.

(U) The main exception to the preceding paragraph is in the application of non-invasive imaging of concealed weapons worn by people under clothing. Because of illumination angle and speckle problems that arise from using a coherent THz source as active illumination for imaging, researchers in this field are investigating purely passive imaging by looking for emissivity contrast between a metal weapon and the human body.*[18]* To achieve the sensitivity needed for such thermally-based images requires cryogenically cooled THz detectors.

(U) Real room for improvement is expected to come in source power. As reviewed in Sect. 4, current solid-state technologies such as multipliers and quantum cascade lasers now come close to achieving the estimated 10 μW to 10 mW power range needed for most local detection applications. Multipliers cover the lower end of the THz spectrum, typically giving mWs below 0.5 THz dropping to 10 μW above 1 THz and < 1 μW above 2 THz. Quantum cascade lasers cover the upper end of the THz spectrum, giving tens of mWs around 4 to 5 THz, dropping to mWs at 2 to 3 THz and << 1 mW below 2 THz. Quantum cascade lasers also require cryogenic cooling, with optimal operating temperature of < 30 K and maximum operating temperature approaching 180 K at this time.

(U) It is highly likely that improvements in coherent THz source power to achieve the desired factor of ten improvement in $P_{\mathrm{Source}}/P^{\mathrm{min}}_{\mathrm{Detector}}$ ratio will come about in the near-to-mid term future (*i.e.* within six years). By itself, a power improvement will somewhat enhance acceptance of THz solid-state technology for local detection applications, but other major technological challenges must also be solved before acceptability of THz technology for local detection applications will become widespread. These challenges include:

1) (U) Extending frequency coverage range of all types of coherent sources, such as increasing the upper frequency range of multipliers to > 2 THz with > 10 μW of power, and lowering the lower frequency range of quantum cascade lasers to < 1.5 THz with > 10 μW of power,

2) (U) Increasing the maximum operating temperature of quantum cascade laser sources to room temperature or at least to a temperature that can be achieved using COTS field-deployable electronic cryo-coolers, *i.e.* around 250 K.

3) (U) Increasing detector speed or bandwidth without sacrificing sensitivity.

(U) These improvements are likely to occur over a mid-to-long term time scale of greater than four to six years.

3.3. (U) Remote Detection Scenario

(U) For THz applications that require transmission along a horizontal path through earth's atmosphere at near sea level altitudes, atmospheric opacity, as discussed in Sect. 2.1.2., is such that α in Eq. 3.1 can easily be in the range 10^{-10} to 10^{-100} per km of signal propagation distance, depending on exact frequency and weather conditions. The attenuation value increases strongly with increasing humidity and is very frequency dependent as well.

(U) Thus, the second application scenario considered is the case where THz solid-state components evolve to the point that they have sufficient source power and/or detector sensitivity to satisfy Eq. 3.1 for $\alpha \leq 10^{-10}$, *i.e.*, for remote THz detection applications at horizontal ranges of roughly 1 km under highly favorable atmospheric conditions, or under one of the following two somewhat easier remote THz detection cases. The first is remote detection along a vertical path, such as sea level up ~ 1 km altitude, or from a high altitude (~ 1 km above sea level) point up to space. In this case α can be substantially $> 10^{-10}$ because atmospheric density and water vapor content decrease approximately exponentially with increasing altitude above sea level. The second is remote detection in orbit or space, *i.e.*, between satellites or monitoring upper atmosphere situations from an orbiting satellite. In this case atmospheric attenuation is negligible and only signal divergence over a given distance and collection optic efficiency enters into the attenuation. In such a case, a well-designed antenna system can make α as high as 10^{-1} to 10^{-3}.

(U) Realistically, there is no point considering situations where $\alpha \leq 10^{-15}$. Barring some completely unforeseen radical breakthrough in THz technology, overcoming such extraordinary attenuation levels is basically impossible. Thus, even assuming a highly optimistic prediction of the evolution of THz source and detector component performance, remote THz detection applications through atmosphere will be limited to at nor more roughly 1 km range and only in certain frequency windows and under highly favorable weather conditions.

(U) There are several remote THz detection applications of interest to security, defense, intelligence, and industrial concerns. Some examples include:

- (U) Remote detection and identification of hazardous or toxic chemical vapors – where the gas mixture to be tested is at some significant distance from the detection apparatus,
- (U) Remote detection and identification of materials associated with WMD production,
- (U) Remote chemical assaying of hot gas plumes,
- (U) Imaging radar (*e.g.*, synthetic aperture radars) with high directionality and image resolution
- (U) Short range, secure, high-data-rate wireless telecommunication.

(U) Pretty much all radar and communications applications use heterodyne detection since they involve a coherent transmission or illumination source that may as well also be used as a local oscillator. In addition, because of the extremely large attenuation involved in atmospheric remote THz detection, most other remote THz detection applications also use the more sensitive heterodyne detection over direct detections methods even if trying to detect incoherent signals such as passive thermal emissions. Thus a large part of THz remote detection technology is the development of solid-state coherent THz sources suitable as local oscillators for THz heterodyne detectors.

(U) From the estimates of α for through-atmosphere remote THz detection, the required solid-state source power and detector sensitivity performance parameters may be estimated for general remote application scenarios. Using a best-case value of $\alpha = 10^{-10}$, Eq. 3.1 then requires the ratio $P_{\text{Source}}/P^{\text{min}}_{\text{Detector}} > 10^{10}$. From the discussion in Sect. 2.2.2., cryogenic direct detector bolometers are available that can have $P^{\text{min}}_{\text{Detector}} = 10^{-12}$ to 10^{-13} W assuming video-rate detection speeds. This means the required source power is in the range 10^{-3} to 10^{-2} W, or 1 to 10 mW. Because such powers are at the limit of state-of-the-art coherent solid-state THz sources, cryogenic direct detectors can just barely detect an active coherent signal even under best-case through-atmosphere remote conditions. Passive thermal THz signal emitters, which typically emit nanoWatts or less of power, cannot be detected remotely through atmosphere by current THz direct detectors.

(U) Heterodyne detectors, especially cryogenically cooled superconducting mixers, pumped to optimal minimum noise temperature by a local oscillator, can detect coherent signal powers two to three orders-of-magnitude smaller than direct detectors, meaning they could overcome an attenuation as high as $\alpha = 10^{-13}$ using a 10 mW coherent signal source. Such an attenuation represents a slightly sub-optimal but still far-from-worst-case transmission through about 1 km of standard atmosphere. Following the calculations of Sect. 2.2.2., heterodyne detection is still insufficient for passive thermal signal detection even under best-case atmospheric conditions. Thus the state of solid-state THz source and detector components needs to advance significantly before a remote THz detection application becomes practical.

(U) A proprietary Sandia analysis of a practical THz synthetic aperture radar (SAR) application from an airborne platform to ground level estimates that a coherent THz source power of 50 to 100 W would be required to build a radar image at typical operational ranges.

3.3.1. (U) Projected Path Forward for Remote Detection Scenario

(U) From the analysis above, developing THz solid-state components for remote through-atmosphere detection applications to a functionally acceptable point will require substantially increasing the available $P_{\text{Source}}/P^{\text{min}}_{\text{Detector}}$ ratio by several orders-of-magnitude for coherent active detection under anything but idealized best-case atmospheric scenarios and much more for passive thermal detection. At this time. the power/sensitivity challenge is so large that other practical considerations such as room-temperature operation of components and frequency range coverage are secondary to the simple power/sensitivity ratio issue. The ability of current research strategies to achieve such improvements will be discussed in Sect. 4.

(U) In terms of detectors, there is only a little room left for improvement in terms of sensitivity. As mentioned in Sect. 2.2.2., THz heterodyne mixers are currently within roughly one to two order-of-magnitude of the fundamental quantum limit on noise temperature. Research strategies aimed at closing in on the quantum limit all involve nanotechnology superconducting mixer designs that require cryogenic cooling to liquid helium temperature (4 K) and below, as reviewed in Sect. 4. Over the medium term (4-6 years) future, it is reasonably likely that laboratory-based cryogenic heterodyne THz detectors will come within a factor of 2 to 3 of the quantum limit on noise temperature. It is highly unlikely that a significant improvement in noise temperature can be made with a room-temperature operating detector in the foreseeable future.

(U) The frontier of THz direct detector research is on approaching the physical limit of single THz photon detection. Single photon detection requires a noise equivalent power less than about 10^{-20} W/Hz$^{1/2}$. This noise figure and single THz photon detection has been claimed in at least one case,*[19]* using very slow integration times of a few minutes. THz photons have only a few meV of energy, so that single THz photon detection will always require cryogenic cooling of a detector to milliKelvin. Thus while the confidence level is reasonable for achieving ultimate single photon THz detection capability with integration times of a few seconds rather than minutes within the next 4 to 6 years, such sensitivity will likely have little impact on practical acceptance of remote THz detection applications outside of high-altitude ground-based radioastronomy.

(U) Room for significant improvement in coherent solid-state THz source power to overcome the remote through-atmosphere application challenge also looks to be constrained at this time and limited to cryogenic source components, similar to detectors. Currently, the only solid-state THz source that looks like it could achieve substantially greater than 10 mW of power is the quantum cascade laser. As reviewed in Sect. 4, quantum cascade lasers have been reported that output > 50 mW of average power at various specific frequencies between 3 to 5 THz. Over the short term future (1 to 4 years), it is likely to expect quantum cascade lasers to breach the 100 mW average power barrier. Over the medium to long term future (4 to 6+ years), several hundred mW to almost 1 W average power could be expected with medium confidence from quantum cascade lasers. However, it is unlikely that quantum cascade lasers will, by themselves, ever significantly exceed the 1 W threshold because of intractable thermal management problems at high THz powers. Exceeding 1 W may require development of high power THz amplifiers or emitting arrays of quantum cascade lasers coupled either through a power combiner or driven to emit coherently. There is currently little to no active research in these areas, however.

(U) At this time, no other solid-state coherent THz source technology being investigated appears capable of 100 mW average THz power output in the foreseeable future. Some fast-pulse photomixing technologies have claimed kW of total instantaneous peak THz power spread over a fairly broad output band of several MHz, but these peak powers correspond to microWatts of continuous average power. However, very high peak power pulsed sources may have usefulness in certain specific applications, such as radar, that naturally use pulsed rather than continuous wave electromagnetic fields.

(U) This section will review the major THz solid-state source and detector technologies being researched and developed world-wide. Included will be brief descriptions of the technology, projections of their future evolution on the short, medium, and long term time horizons, and specific technical breakthrough milestones to watch out for.

4. (U) Technology Forecast Analysis

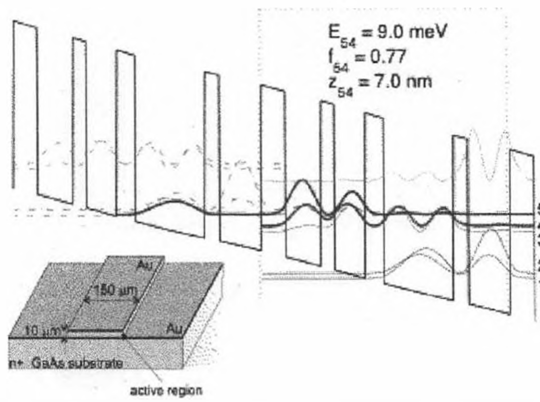
4.1. (U) THz Solid-state Sources

(U) This section will discuss major current research areas in THz solid-state coherent source components. Included will be quantum cascade lasers, multipliers, photomixers, and other potential but less well-developed approaches.

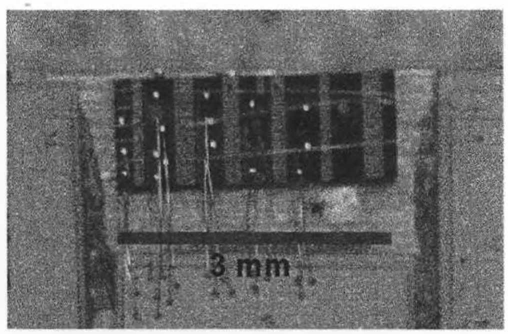
4.1.1. (U) Quantum Cascade Lasers

(U) The first major advance in THz devices is the recent invention of III-V semiconductor THz quantum cascade lasers (QCLs), *[20,21]* in which Sandia has played a significant role. THz QCLs have opened an exciting new door to compact, robust sources generating continuous-waved and long-pulsed at frequencies above about 1.5 THz. In contrast to typical semiconductor lasers which operate as bipolar devices, QCLs are unipolar devices in which lasing occurs via electronic transitions between states all within the conduction band (*i.e.* intraband transitions). An example of a conduction band diagram of a QCL is shown in Fig 4.1. The laser frequency is primarily determined by the energy separation of the states involved in the lasing transition, which is set by the layer thickness and alloy composition of the compound semiconductor quantum wells and barriers making up the structure. Since the frequency of the light depends on layering geometry as well as material composition and device geometry, a very wide range of frequencies can be accessed within the same material system allowing devices to be fabricated using mature group III-V semiconductor alloy systems.

(U) QCLs are extremely frequency stable and are currently the *only* solid-state sources capable of delivering > 10 mW continuous wave power above ~ 2 THz. This power is technologically crucial because, as discussed in Sects. 3.2 and 3.3, powers significantly greater than 1 mW LO power are needed to operate many semiconductor heterodyne mixers at their minimum noise point to achieve optimal sensitivity, and 10 mW is the absolute smallest power at which remote detection through atmosphere is even potentially realistic. QCLs can be made very compact, (< 1 mm dimension) as shown in Fig. 4.1 inset and Fig. 4.2, and very reliable, especially compared to currently used laboratory-based electron-tube or gas-tu be THz sources which have dimensions 1 meter, weigh 50 kg, and require constant maintenance. QCLs' intrinsically narrow linewidths, relatively high powers, and potential tunability (already demonstrated



(U) Figure 4.1: Conduction band diagram of electron wave functions in five sub-bands of a QCL structure. 9.0 meV photons (2.2 THz) are emitted when an electron drops from level 5 to level 4. Inset: sketch of typical dimensions of a finished QCL.



(U) Figure 4.2: Photograph of six QCLs made at Sandia, viewed from above, mounted on a cold head. The gold stripes are the top electrodes. THz light comes from the top edge facet of the chip. (Sandia image) in the mid-infrared) make them excellent sources for spectroscopic identification of hazardous or toxic chemical vapors.

(U) The main drawback of most QCLs is the need to operate them at cryogenic temperatures. However, very recent progress has shown continuous-wave lasing in a fundamental THz QCL at temperatures of 178 K,*[22]* which is in the range of solid-state electronic cryocoolers. Continuing research will almost certainly lead to higher operating temperatures. Also, because QCLs are very small, a single cryocooler can cool many QCLs, as in Fig. 4.2. More intriguing is a very recent report of coherent THz radiation generated via difference frequency generation from two monolithically integrated mid-infrared QCLs operating at room temperature. *[23]* Only 0.3 μW of average THz power was output, but operation at room temperature represents a seminal breakthrough.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that QCLs will achieve:

- (U) Frequency coverage below 1.5 THz
- (U) Maximum average power approaching 100 mW in a fundamental laser
- (U) Maximum operating temperature above 200 K for a fundamental frequency laser
- (U) 1 μW average power in a room-temperature difference-frequency laser

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that QCLs will achieve:

- (U) Frequency coverage down to 1.0 THz

• (U) Maximum average power exceeding 100 mW in a fundamental laser

• (U) Maximum operating temperature above 230 K for a fundamental frequency laser

• (U) 10 μW average power in a room-temperature difference-frequency laser

• (U) Electronic frequency tunability up to 10 GHz around a central THz frequency

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that QCLs will achieve:

• (U) Frequency coverage below 1.0 THz

• (U) Maximum average power approaching 1 W in a fundamental laser

• (U) 1 mW average power in a room-temperature difference-frequency laser

• (U) Power combining ability among multiple QCLs

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz QCLs into many practical applications:

• (U) Room temperature operation of a fundamental laser

• (U) ≥ 10 mW average power in room temperature operation of any single laser

• (U) ≥ 1 W average power in room temperature operation of any power combined lasers

• (U) DC-to-THz power conversion efficiency exceeding 1%

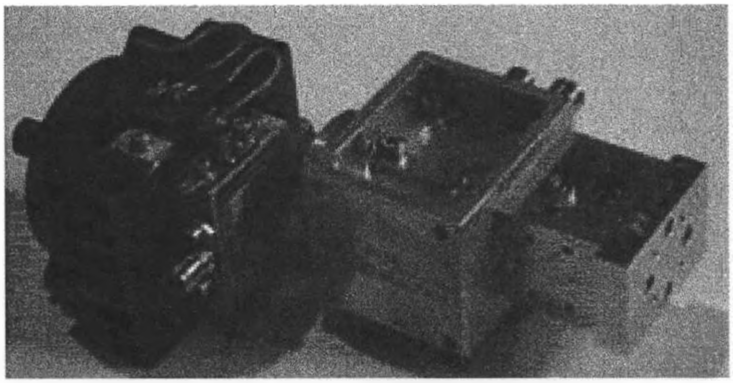
4.1.2. (U) Multiplier Chains

(U) Perhaps the most advanced solid-state coherent THz source technology for frequencies below to just above 1 THz is non-linear harmonic multiplication. The basic principle behind harmonic multiplication is that a non-linear electronic component, usually a diode or a varactor, can output phase-coherent integer harmonics of a coherent input frequency. The simplest and most widely used example is a quadratic nonlinearity, where a non-linear component outputs signals proportional to the absolute square of an input electric field, according to:

$$E_{\text{out}} \propto \left| E_{\text{in}} \cos(\omega t) \right|^2 = \tfrac{1}{2} E_{\text{in}}^2 + \tfrac{1}{2} E_{\text{in}}^2 \cos(2\omega t) \quad (4.1)$$

For this basic quadratic linearity, the output consists of both a rectified (DC) field and a second harmonic field oscillating at twice the input frequency. Such frequency doublers are very commonly used, as well as triplers and, less commonly, quadruplers and quintuplers. *[24]*

(U) A THz multiplier typically consists of an ambient temperature diode or varactor embedded into a block waveguide circuit with integrated amplifiers, resonators, and filters designed to isolate the desired harmonic from other undesired harmonics that may be generated. See Fig. 4.3. The fundamental input is usually supplied by a COTS high power microwave synthesizer, typically at input frequencies between 20 GHz to 100 GHz and powers between 10 W to 100 W. The conversion efficiency of harmonic generation is measured as the ratio of output power at the desired harmonic frequency to input power at the fundamental and is typically as high as 10% for a single-stage doubler or tripler, dropping to 1 % or less for a single-stage higher order multiplier.



(U) Figure 4.3: Image of a Virginia Diodes. Inc. harmonic multiplier block (from www.virginiadiodes.com) This unit takes fundamental input near 18 GHz and outputs about 10 μW at 1.26 to 1.31 THz.

(U) To generate outputs at hundreds of GHz up to one or two THz, several stages of multipliers are cascaded. For example, a fundamental input of 50 GHz might be doubled to 100 GHz in the first stage, amplified, then tripled and doubled again to generate an output of 0.6 GHz. At the lower frequency intermediate stages, *i.e.*, below 400 GHz, it is now common practice to insert millimeter-wave integrated circuit amplifiers to regenerate and amplify the desired harmonic signal before the next multiplication state.

(U) In terms of output power, multipliers can supply up to tens of mW average power at a sharply defined frequency up to roughly 0.5 THz. From 0.5 THz up to roughly 1 THz output power drops to the range of 1 mW. Near 1 THz multiplier systems can supply tens to a few hundred μW, falling to sub μW above 2 THz. The drop in output power with increasing output frequency is a reflection of the decreasing multiplier efficiency at higher and higher multiplication factors. In principle higher output power can be generated simply by raising the input power. However, two practical limits prevent arbitrarily increasing input power. The first is heat generation. Much of the wasted power not converted into a harmonic is dissipated as heat. As a consequence, at the low conversion efficiencies associated with high multiplication factors, thermal management becomes a significant engineering issue. The second is rectification. As shown in Eq. 4.1, most harmonic generation produces a rectified DC field across the non-linear component such as a diode. At high input powers this rectified field will self-bias the diode, and at high enough input powers this self-bias field can approach the breakdown field of the diode at which the diode ceases to operate.

(U) Multipliers have the following general advantages and disadvantages over competing coherent solid-state THz source technologies. Advantages include:

• (U) Operation at room or ambient temperatures. Also coolable for better performance if desired.

• (U) Relatively compact and light weight, typically a complete multiplier system occupies ~ 10 cubic inches of volume and weighs ~ 10 lbs.

• (U) Excellent frequency characteristics. Intrinsic linewidth is defined by the multiplication factor times the linewidth of the fundamental input source, which can by < 1 Hz, resulting in output instrumental linewidths of only about 10 Hz up to 1 THz. This is also continuously tunable over a good range (many tens of GHz) by tuning the input microwave synthesizer, limited by the waveguide cut-off and resonant characteristics of the waveguide circuit used.

• (U) Useful powers below ~ 2 THz. Powers of order of 10 mW up to 0.5 THz, 1 mW up to 1 THz, and tens of μW below 2 THz.

(U) Disadvantages include:

• (U) Conversion efficiency difficulties make it very difficult to scale power up at frequencies above ~ 2 THz.

• (U) Thermal management: multiplier systems can run fairly hot and require active cooling in many cases.

(U) Current research and development in mulitpliers revolves around engineering ways to increase average power output at frequencies from 1.5 to 3 THz. There are two main strategies being pursued. The first involves developing new or improved non-linear components with stronger non-linear characteristics that will deliver higher conversion efficiency. The second involves spreading input power over several conventional non-linear components to reduce the input power per component to tolerable levels, then using waveguided power combining techniques to coherently combine the output powers from each component.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that multipliers will achieve:

• (U) Frequency coverage above 2 THz with maximum average power around 1 μW

• (U) Continuous electronic tunability in full waveguide bands up to 2 THz.

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that multipliers will achieve:

• (U) Frequency coverage up to 3 THz with maximum average power around 1 μW

• (U) Average power around 10 μW near 2.5 THz

• (U) Average power around 1 mW near 1 THz

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that multipliers will achieve:

• (U) Frequency coverage up to 4 THz

• (U) Conversion efficienciew exceeding 1% in triplers and quadruplers laser

• (U) Waveguide based power combiners capable of handling tens of mW

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz multipliers into many practical applications:

• (U) Conversion efficiency of 10% in a doubler or tripler stage

• (U) $\geq$ 10 mW average power above 1 THz

• (U) $\geq$ 1 mW average power near 2 THz

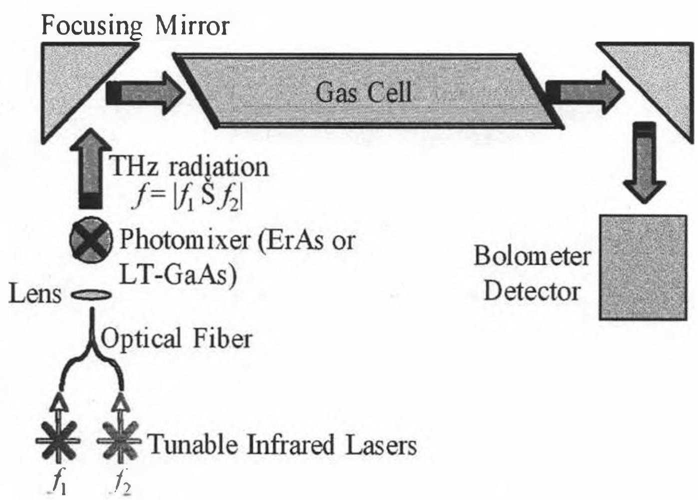
4.1.3. (U) Photomixers

(U) Photomixing down-converters are basically the inverse of harmonic multiplier up-converters. Also relying on a component with a non-linear response to electromagnetic fields, photomixers take two input fields, usually in the infrared, and generate and output signal at a frequency that is at the absolute difference of the two input frequencies. This process is illustrated in Fig. 4.4. For example, for a quadratic non-linear device coupled to two input fields at angular frequencies ω_1 and ω_2, the output is described by:

$$E_{out} \propto \left|E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t)\right|^2 = E_{DC} + A \cos\left[(\omega_1 - \omega_2)t\right] + \ldots \quad (4.2)$$

(U) The difference frequency output is the first term. Also generated are a sum frequency output and harmonic frequencies that are normally much higher than the difference frequency. Because in typical operation ω_1 and ω_2 are close in frequency, the difference frequency output is at a much lower frequency than the inputs, allowing the difference frequency output to be isolated using appropriately constructed low-pass filters. The conversion efficiency of photomixers is defined as the ratio between output power at the difference frequency to the total power of the two input beams. Most photomixers have < 1% conversion efficiency.

(U) There are several classes of non-linear photomixing components used to generate a THz output from infrared input beams. Conceptually the simplest are optoelectronic devices like photoconductive switches and photodiodes. Often made from intentionally



(U) Figure 4.4: Block diagram of a photomixer downconversion system to generate coherent tunable THz radiation for a THz vapor phase spectrometer.

defected semiconductors such as low-temperature grown GaAs (LT-GaAs) or erbium-doped GaAs (Er:GaAs), these can be easily designed to photomix telecommunications carrier frequency lasers (near 1.5 μm wavelength). The advantage of using telecommunications lasers as the input frequencies are that telecomm lasers are fully COTS solid-state products that operate at room temperature, are continuously differentially tunable over a > 1 THz difference frequency range, give significant optical power, are ruggedly packaged, and can be completely coupled via fiber optics rather than free-space.

(U) Photomixers based on such systems can currently generate up to ~ 10 μW of power near 0.3 THz, dropping to 1 μW of power approaching 1 THz, and 0.1 μW of power approaching 2 THz. By differentially tuning the infrared input lasers, these photomixer sources can be continuously tuned over a very broad THz range, often from 0.1 to 1 THz (though with constantly decreasing power). For this reason, these photomixer sources are becoming popular in broadband THz spectroscopy and are now just beginning come on the market as COTS turnkey systems.

(U) Another photomixer approach relies on non-linear crystals such as GaSe, *[25]* where an intrinsic symmetry breaking in the crystal structure gives rise to ferroelectric or piezoelectric behavior with an associated strong optical non-linearity. These crystals are widely used to generate high-power THz pulses via photomixing infrared inputs, rather than a continuous wave THz output. Using pulsed infrared inputs, reports of high instantaneous peak pulse powers of > 100 W to kW have been reported. Because the pulses and duty cycles are short, these peak powers correspond to an average continuous power of order 1 μW. However, there are applications such as radar ranging for which peak pulse power is an important figure of merit.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that photomixers will achieve:

• (U) Reliable COTS turnkey photomixer sources aimed at laboratory chemical spectroscopy

• (U) > 10 μW power at frequencies below 0.5 THz

• (U) near 10 μW power at frequencies up to 1 THz

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that photomixers will achieve:

• (U) Frequency coverage up to 2 THz with maximum average power around 1 μW

• (U) Average power around 10 μW near 1 THz

• (U) Average power around 1 mW near 0.5 THz

• (U) Instantaneous peak powers approaching 1 kW in fast pulsed systems

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that photomixers will achieve:

• (U) Frequency coverage up to 4 THz

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz photomixers into many practical applications:

• (U) Conversion efficiency > 10%

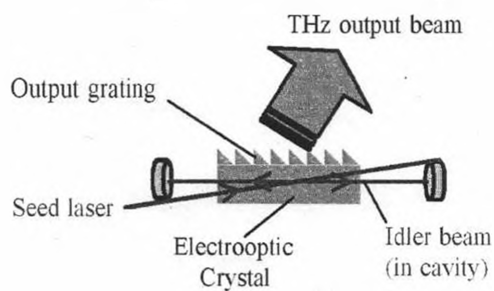
• (U) ≥ 1 mW average power below 1 THz

• (U) ≥ 0.1 mW average power above 1 THz

• (U) Demonstration of a photomixer source useful as a local oscillator with any THz mixer

4.1.4. (U) Optical Parametric THz Oscillators

(U) Closely related to photomixing and useful for generating long-train coherent THz pulses with reasonable average power of a few mW spread over a spectral bandwidth of 10 to 100 MHz, optical parametric generation techniques are being researched and developed. Similar to photomixing, this method relies essentially on optical down-conversion of a high-power infrared laser pulse, usually around 1 μm wavelength, to a THz pulse using the non-linear optical properties of an electro-optic crystal such as lithium niobate. Such crystals can generate sub-harmonics of a single infrared excitation frequency, so unlike photomixing only a single infrared excitation beam is required.



(U) Figure 4.5: Schematic of the basic elements of a THz optical parametric generator. The seed laser is typically a high powered pulsed infrared laser around 1 μm wavelength.

However, optical parametric methods can only generate THz pulse trains, not continuous wave THz radiation.

(U) In a typical optical parametric THz generation system, sketched in Fig. 4.5, an electro-optic crystal, such as lithium niobate, is put inside an optical cavity. A "seed" laser beam around 1 μm wavelength and ~ 20 W average power is injected into the cavity where it refracts inside the crystal, and the refracted beam bounces between the set of mirrors forming the cavity to create the "idler" beam of the system. The interaction of the idler beam with the non-linear crystal generates THz sub-harmonic oscillations in the crystal, which then propagate out of the crystal into free space via a grating coupler etched onto one of the crystal's faces. The frequency of the THz emission can be varied by varying either the wavelength of the idler or the orientation of the non-linear crystal facet relative to the idler beam.

(U) Optical parametric THz generators have been demonstrated primarily for see-through imaging applications, where precise frequency definition or continuous wave operation are not needed. Optical parametric THz generators are not useful as local oscillators for heterodyne receivers because of the pulsed nature of the source. Such generators can be used for spectroscopy, but are ultimately limited in spectroscopic applications by spectral width and brightness considerations. Although some optical parametric THz generators have been shown to produce ~ 1 mW of average THz output power,*[26]* that power is spread over a spectral width of ~ 100 MHz because of the long-pulse nature of the output beam. Because the non-linear crystal must sit in a cavity, optical parametric generation methods cannot be readily adapted to more robust fiber-optic based configurations. Finally, the power required from the seed laser means that the seed laser systems needed are still large, expensive, high-power infrared pulse lasers rather than small, compact semiconductor diode lasers.

(U) As is the case for all THz sources, the research frontier in optical parametric THz generators is primarily in generating greater average power. The main strategies being pursued involve multi-pass cavities,*[27]* amplification by coherent sequential optical impulse seeds,*[28]* and improvement of the non-linear crystal material. Secondary research goals include narrowing the THz emission spectral width and achieving a wider range of continuous tuning.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that optical parametric THz generators will achieve:

- (U) 1 mW of average THz power spread over a spectral band < 100 MHz wide

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that optical parametric THz generators will achieve:

- (U) up to 10 mW average THz power spread over a spectral band < 50 MHz wide
- (U) continuously tunable range of up to 0.5 THz about the center THz frequency

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that optical parametric THz generators will achieve:

- (U) greater than 10 mW average THz power over a spectral band < 20 MHz wide

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of optical parametric THz generators into many practical applications:

- (U) Power approaching 100 mW near 2 THz
- (U) Demonstrated use of a semiconductor diode seed laser
- (U) Spectral band of THz emission < 5 MHz wide
- (U) Complete source with volume < 0.5 cubic meter

4.1.5. (U) Other Potential THz Sources

(U) There are numerous other solid-state THz source technologies that are considerably less well developed than those discussed in Sects. 4.1.1. through 4.1.3. At this time these other source technologies can still be considered laboratory curiosities which require a great deal more fundamental scientific research to flesh out before any realistically assessement of their potential usefulness in a THz technology can be made. Nonetheless, a few of these incipient technologies will be mentioned in this section.

(U) *p-Ge Lasers* – These devices use the cyclotron orbits of doped hole carriers in a Ge crystal placed in a very high magnetic to generate THz radiation. The frequency of the radiation is a function of the cyclotron frequency and hence can be tuned continuously via the magnetic field. Currently these are strictly very low-temperature cryogenic devices since they require a very long mean-free path for holes in Ge, which occurs only at liquid helium temperatures and below, and a very high magnetic field of several

Teslas, which is most easily generated using a liquid helium cooled superconducting magnet. The large magnet infrastructure required renders this type of source fairly large and heavy. To date, average power outputs in the range of 0.1 μW have been reported. *[29]*

(U) *High-T_c Superconductor Oscillators* – A very recent report *[30]* has been made that the internal Josephson junctions that result from the stacked copper-oxide structure of the high-T_c superconductor BSCCO can be made to oscillate coherently and coherent THz radiation. The frequency of the radiation can be tuned within limits by a DC voltage. Average power of around 1 μW was reported. Since this effect depends on strong superconducting properties, it will always be a cryogenic device technology. However, it is conceivable that the operating temperature will increase if layered superconducting materials with higher T_c are discovered.

(U) *GaN Gunn Oscillators* – The Gunn effect, which exploits the scattering of electrons from high mobility to low mobility energy-momentum valleys in III-V semiconductor crystals, is a widely used and highly effective way to generate coherent, high power millimeter-wave radiation up to around 0.2 THz in a room-temperature semiconductor device. Above 0.2 THz, power from Gunn oscillators using traditional III-V materials such as InP and GaAs drops precipitously. There have been theoretical and numerical predictions *[31]* that Gunn oscillators using GaN can sustain high power (order 10 mW) Gunn oscillations up to near 1 THz because of its faster intervalley scattering rate and superior thermal conduction properties. Currently, no experimental demonstration of the Gunn effect in GaN have yet been made. This is thought to be due to limitations on available material quality and thermal load issues. There is no reason to suspect that GaN will not display a Gunn effect as its electronic band structure properties are reasonably well understood. The main question will be whether the power and frequency levels predicted can be realized.

(U) *High-speed Transistor Oscillators* – The maximum gain and oscillation frequency thresholds (f_T and f_{max}) of high-speed electronics transistors rises continuously with time. There have been single-case demonstrations of InP/InGaAs based heterojunction bipolar transistors with an extrapolated f_T approaching 1 THz, *[32]* and reports of Si/SiGe heterojunction bipolar transistors with extrapolated f_T up to 0.5 THz.*[33]* To date, however, self-sustaining oscillator circuits using such transistors have not been widely reported. It is certainly possible, however, that continued advances in transistor speed technology may render transistors as competitive THz sources from 0.5 THz to 1 THz within the next 4 to 6 years.

4.2. (U) THz Solid-state Detectors

(U) This section will discuss major current research areas in THz solid-state detector components, both direct and heterodyne. Included will be diode-type mixers, superconducting mixers, bolometric detectors, and cutting-edge single THz photon detectors.

4.2.1. (U) Diode-type Mixers

(U) The oldest and most highly developed of solid-state heterodyne mixer detectors for THz are diode-type mixers that rely on the non-linear current-voltage relation of a semiconductor diode to generate a difference frequency output between a THz local oscillator and an incoming THz signal. *[34]* The heterodyne detection process is analogous to the photomixing down-conversion process outlined in Sect. 4.1.3, except with two THz inputs (local oscillator and signal) rather than two infrared inputs, and a resulting microwave output rather than a THz output. Diodes for THz mixer detectors are a relatively straightforward evolution of commonly used diodes used for radiofrequency and microwave mixing.

(U) There are two main differences between THz diode mixer detectors and diodes used at radio- and microwave frequencies. First, THz diodes are always some form of unipolar metal-to-semiconductor structure, rather than a bipolar all semiconductor p-n or p-i-n diode structure. The reason for this is that in virtually all semiconductors one polarity of carrier, either electrons or holes, usually has too low a mobility to be able to effectively follow a THz frequency field without phase lag. In the most commonly used III-V semiconductors, electron mobility is ten to a hundred times higher than hole mobility, so electron polarity unipolar device structures are used at THz frequencies.. The second difference is that THz diode mixer devices must be patterned to be very small. Metal anode-to-semiconductor contact diameters must be on the order of 0.25 μm for a diode to function above 2 THz. *[35]* And example is depicted in Fig. 4.6. The reason for this is that the product of parasitic resistance and capacitance (RC) time constant must be kept small enough so that THz signals are not shunted around the diode depletion layer. While parasitic resistance can be reduced by heavily doping the semiconductor surface and careful electrode layout, the only way to reduce capacitance is to minimize the geometric contact area. The requirement for deep sub-micron patterning to make THz diode mixers makes the process slow and expensive and is the main reason such diodes are still custom fabricated devices rather than COTS items.

(U) Figure 4.6: Scanning electron micrograph image of the anode contact of a 2.5 THz Schottky diode. The actual anode-to semiconductor contact diameter is 0.25 µm. From the NASA Jet Propulsion Laboratory at CalTech.

(U)Schottky diodes, comprising a metal anode in contact with a clean, heavily doped high-mobility semiconductor, are still the dominant form of diode used for THz mixer detectors. Schottky diodes are very well understood both theoretic ally and practically, and they have been developed to the point that they are useful for flight and satellite THz missions.

(U) Metal-semiconductor diodes have the great advantage of working at room or ambient temperatures. They can also be designed to be cooled to cryogenic temperature is better performance is need ed. Diodes are intrinsically very broad band; the THz bandwidth they can cover is usually determined by the frequency limitations of the circuit they are embedded in rather than by the diode itself. Operating as heterodyne mixer detectors, diodes have usable but not great sensitivity. Their noise temperatures are around 4,000 K at 1 THz rising to 10,000 K at 2.5 THz. This is of order 100 times the fundamental quantum limit. Diodes also require several mW of very stable, well-defined local oscillator power in order to operate at their lowest noise temperature point. Current research and development of diode THz mixer detectors emphasizes reducing required local oscillator power and reducing noise temperature.

(U) Because Schottky diodes in particular are already highly developed, prognosis for further development beyond small evolutionary steps is not strong. The only possible exception is if modern nanotechnology and nanomaterial methods can be adapted to construct THz diode detectors using cheaper, faster bottom-up assembly methods. Such an advance would drive wider production and acceptance of THz diode mixers.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that diode heterodyne mixers will achieve:

- (U) Noise temperature of < 10,000 K (double side band) at 2.5 THz
- (U) Local oscillator input power requirement of < 5 mW at 2.5 THz

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that diode heterodyne mixers will achieve:

- (U) Noise temperature of 5,000 K to 10,000 K (double side band) at 2.5 THz
- (U) Local oscillator input power requirement of 2 to 4 mW at 2.5 THz

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that diode heterodyne mixers will achieve:

- (U) Noise temperature < 5,000 K (double side band) at 2.5 THz
- (U) Local oscillator input power requirement approaching 1 mW at 2.5 THz
- (U) Frequency coverage to > 4 THz

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz diode heterodyne mixers into many practical applications:

- (U) Noise temperature < 1,000 K at 1 THz and/or < 2,500 K at 2.5 THz
- (U) Local oscillator input power requirement below 0.5 mW at 1 THz or 1 mW at 2.5 THz
- (U) Demonstration of a true THz diode heterodyne mixer with reasonable (*i.e.*, 10,000 K) noise temperature bottom-up fabricated using modern semiconductor nanowire materials without electron beam lithography methods.

4.2.2. (U) Superconducting Mixers

(U) Almost as old and well-established as metal-semiconductor diode heterodyne mixers are THz mixers using superconducting materials and devices. The quantum mechanical nature of superconductors endows them with sensitivity significantly better than possible with conventional semiconductor devices, at the expense of cryogenic cooling. For traditional THz applications in radioastronomy, cryogenic cooling has been an acceptable trade-off for the gain in sensitivity. Also, the energy gap that characterizes the strength of a superconductor's quantum mechanical order corresponds to a photon energy of around 1 THz, making superconductors fast enough to respond to THz frequency radiation. There are two major classes of superconducting heterodyne mixers: superconductor-insulator-superconductor (SIS) tunnel junctions *[36]* and hot-electron bolometeric (HEB) mixers.

(U) SIS tunnel junctions operate on the principle of quantum mechanical tunneling of uncorrelated electrons between two superconductors separated by a classically forbidden, insulating barrier. These junctions explicitly demonstrate the quantum nature of superconductors. Because of the existence of a sharp energy gap in a superconductor well below its superconducting transition temperature, electron tunneling does not occur at voltages below this gap energy but becomes strong at voltages just exceeding this gap energy. As a result, the current-voltage characteristic of an SIS tunnel junction is so highly non-linear that it is regarded as the strongest electronic non-linearity that is known in nature. Because of this unusually strong non-linearity, SIS tunnel junctions have very high conversion efficiency exceeding 10% from THz LO and signal inputs to difference frequency output. This efficiency combined with the highly correlated nature of superconducting current flow, which makes Johnson and shot noise irrelevant, make SIS tunnel junctions extremely sensitive, with noise temperatures within a factor of 2 or 3 of the fundamental quantum limit while requiring only ~ 0.1 μW of local oscillator power.

(U) While the advantages of SIS mixers for sensitivity and low local oscillator power are clear, they have limitations beyond simply the need for cryogenic cooling. Firstly, the circuit characteristic of SIS mixers is primarily capacitive. This makes it difficult to avoid introducing undesired *RC* roll-offs or *RLC* resonances into the whole detection circuit. As a consequence, the capacitance often has to be resonated out with an inductive element that severely limits the detection circuit bandwidth of any circuit using SIS mixers. More significantly, the non-linear behavior of SIS mixers arises explicitly from the quantum mechanical energy gap of the superconducting state. At photon frequencies above the energy gap value, the superconductor behaves as a normal metal and loses its non-linear behavior and hence its ability to mix. In niobium, the most reliable and widely used superconductor for SIS mixers to date, this energy gap limit is 0.7 THz, meaning that niobium based SIS mixers cannot be used as heterodyne mixer detectors for frequencies above 0.7 THz.

(U) Thus the research frontier in SIS mixers is aimed at using superconductor materials with significantly larger energy gaps that will enable heterodyne mixing detection up to higher THz frequencies. The current leading candidate material is niobium nitride (NbN), whose energy gap is almost 2.5 times that of niobium, making heterodyne mixing detection up to 1.7 THz a possibility. *[37]* Another class of candidate materials being explored is the high-T_c oxide superconductor family. These materials may have energy gaps ten times larger than niobium's, increasing the heterodyne mixing detection frequency up to 7 THz in principle. The major hurdle in using such high energy gap materials is the difficulty in fabricating a high quality SIS junction. The characteristics of a NbN based SIS junction, such as low leakage current below the energy gap and strong non-linear behavior at the energy gap, are noticeably worse than what can be done routinely with niobium SIS junctions. The heart of the problem lies in control of the interface properties of the superconductor and finding an appropriate ultra-thin insulator to use as the tunnel junction barrier. The situation is worse for high-T_c oxide superconductors. In that case there has not, to date, been a reproducible demonstration of an SIS tunnel junction. *[38]* This may be because of lack of interface property control with these difficult-to-work-with materials, but there are now theoretical reasons to believe that good SIS tunnel junctions cannot be made with high-T_c oxide superconductor materials.

(U) Superconductor HEB mixers are a relatively recent development that get around several of the limitations of SIS mixers. HEB mixers were developed from superconducting bolometer direct detectors, described in Sect. 4.2.3, but with an extreme engineering trade-off to gain response speed at the expense of sensitivity. As the name implies, HEBs respond bolometrically to input THz radiation. That is, the input local oscillator and signal fields are simply absorbed as power by the HEB device, causing a slight local temperature rise and concomitant change in device resistance. The power response is directly proportional to the magnitude squared of the total electromagnetic field strength at the HEB, making HEBs almost perfect quadratic mixers. By removing the excess heat very quickly, HEBs can respond fast enough to follow THz frequency fields. Heat is removed quickly by making the superconducting HEB element very small, usually a thin film much less than 1 μm in lateral dimension and 1 to 10 nm thick, and strongly heat-sinking it to a thermal reservoir.

(U) Modern HEB mixers have sensitivity and local oscillator power characteristics mid way between Schottky diode and SIS mixers. Like SIS mixers, superconducting

HEB mixers must be cryogenically cooled. They can have noise temperatures below 1,000 K near 1 THz, [39] about a factor of ten better in sensitivity than diode mixers. Of more practical interest, HEBs can achieve this noise temperature using only of order 1 μW of local oscillator power, several orders-of-magnitude better than diode mixers. However, the response speed of most HEB mixers, as measured by the difference frequency bandwidth, is at most only a few GHz, which is more than ten times inferior to the speed of diode mixers. Compared to SIS mixers, HEBs are not as sensitive an require more LO power. However, the circuit response of HEB mixers is mainly resistive, rather than capacitive, making it far simpler to embed HEB mixers into very broadband detection circuits. Also, since HEBs are simply power absorbers, their upper frequency response is not limited by the energy gap of the superconductor material, in contrast to SIS mixers.

(U) The research frontier in HEB mixers emphasizes evolutionary improvements to the sensitivity/speed combination. Materials and device geometries with faster electronic thermal relaxation rates are being explored in the hope that the speed, as measured by the difference frequency bandwidth, can be improved to as much as 10 GHz without significant sacrifice in either noise temperature or required LO power input. To do this, new materials such as NbN [40] and high-T_c oxide superconductors [41] have been researched with promising results. Also, very fast electron thermal relaxation by diffusive or ballistic out-transport of "hot" electrons using nanostructured geometries has been tested.

(U) *Short Term Evolution Assessment* – In the 1 to 4 year time frame, there is high confidence that superconductor heterodyne mixers will achieve:

- (U) Noise temperature of < 3,000 K (double side band) at 2.5 THz in HEB mixers
- (U) Difference frequency bandwidth of 5 GHz in HEB mixers
- (U) Detection frequency > 1 THz in SIS mixers

(U) *Medium Term Evolution Assessment* – In the 4 to 6 year time frame, there is high confidence that superconductor heterodyne mixers will achieve:

- (U) Noise temperature of 2,000 K (double side band) at 2.5 THz in HEB mixers
- (U) Difference frequency bandwidth of 5 to 10 GHz in HEB mixers
- (U) Detection frequency of 1.5 THz in SIS mixers

(U) *Long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable expectation that superconductor heterodyne mixers will achieve:

- (U) Noise temperature of 1,000 K (double side band) at 2.5 THz in HEB mixers
- (U) Operating temperature of 77 K in HEB mixers

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz superconducting heterodyne mixers into many practical applications:

- (U) Noise temperature < 1,000 K at 2.5 THz in HEB mixers
- (U) Difference frequency bandwidth exceeding 10 GHz in HEB mixers

- (U) Demonstration of excellent SIS tunnel junction characteristics using NbN superconductors
- (U) Reproducible demonstration of reasonable SIS tunnel junction characteristics using high-T_c oxide superconductor materials
- (U) Demonstration of using nanotechnology to bottom-up fabricate a superconducting mixer without electron beam lithography methods

4.2.3. (U) Bolometer Direct Detectors

(U) The oldest and most widely used method of detecting THz radiation is by using a bolometer direct detector. A bolometer is basically an electromagnetic power absorber that converts the absorbed power to local heating of the device that, because of a small temperature increase, changes some electrical characteristic of the device. The electrical characteristic is typically but not always the device's resistance R. Another popular electrical characteristic is the pyroelectric coefficient of a pyroelectric material. For simple resistance change bolometers, the change in voltage ΔV generated by a bolometer in response to an incident electromagnetic field of amplitude E is given by:

$$\Delta V = I_{bias}\Delta R = I_{bias}\frac{dR}{dT}\Delta T \propto I_{bias}\frac{dR}{dT}\left\langle |E|^2 \right\rangle \quad (4.2)$$

where I_{bias} is the DC current bias applied to the bolometer, dR/dT is the temperature coefficient of resistance of the bolometer at operating temperature T, ΔT is the change in bolometer temperature upon absorbing electromagnetic power, and the brackets <...> denote an average over the integration time of the detector. The same basic equation governs superconducting HEB mixers described in the previous section except the integration time average is omitted for bolometric mixers.

(U) Since bolometers are simply power detectors, they are insensitive to incident signal frequency and hence are very broadband detectors. As long as they can absorb electromagnetic power and heat up, they will yield a signal. However, because bolometers do not give information about frequency content of an input signal, frequency information must be obtained separately, often with a bandpass filter or interferometric resonator in front of the bolometer detector.

(U) From Eq. 4.2, it is clear that the bolometer's signal strength is directly proportional to its temperature coefficient of resistance dR/dT. For this reason materials chosen for use as bolometers all have large values of dR/dT. For THz direct detector bolometers operating at room temperature, small bandgap semiconductors, such as indium antimonide, or semimetals, such as vanadium oxide, are used. These have dR/dT in the range of 1 to 10 Ohms/K near 300 K temperature. Cryogenic bolometers use either lightly doped semiconductors such as silicon or germanium or superconductors held in their superconducting transition are widely used. These have dR/dT in the range of 100 to 1,000 ohms/K operating at 1.5 K to 10 K temperature.

(U) Bolometer sensitivity and response speed are trade-offs. To generate the largest ΔT for a given incident electromagnetic field strength, it is necessary to thermally isolate the bolometer so that heat builds up in the detector rather than leak out to its environment. However, as long as heat builds up in the detector, the detector is insensitive to changes in the incident field strength. Most direct detector bolometers accomplish thermal isolation by suspending the detecting element from its surroundings using a very thin membrane or thin wires. Generally, bolometers target approximately video-rate response speeds, meaning integration times of order 10 ms to 100 ms. Given such integration times, COTS room-temperature THz direct detector bolometers have sensitivity, as expressed by noise-equivalent power, in the range of 10^{-9} to 10^{-10} $W/Hz^{1/2}$. COTS cryogenic bolometers have noise-equivalent power in the range 10^{-12} to 10^{-14} $W/Hz^{1/2}$. Cryogenic superconducting bolometers have noise-equivalent power around 10^{-12} $W/Hz^{1/2}$ but can be used with < 1 ms integration times.

(U) The research frontier in THz direct detector bolometers is not highly active given the maturity of the technology. Some research continues on improved materials with higher *dR/dT* and micromachining methods for improving thermal isolation. Most current research is in making addressable arrays of bolometers for imaging purposes, either one-dimensional arrays for use with line scanning imaging systems or two-dimensional arrays for use as focal plane arrays imagers.

(U) *__Medium Term Evolution Assessment__* – In the 4 to 6 year time frame, there is high confidence that direct detector bolometers will achieve:

- (U) Noise equivalent power of 10^{-13} $W/Hz^{1/2}$ at room temperature
- (U) Noise equivalent power of 10^{-16} $W/Hz^{1/2}$ at cryogenic temperatures
- (U) Integration times < 10 ms without sacrificing sensitivity

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz bolometer direct into many practical applications:

• (U) Noise-equivalent power of $\leq 10^{-14}$ W/Hz$^{1/2}$ at room temperature

• (U) A kilo-pixel focal plane imaging array with noise-equivalent power $\leq 10^{-12}$ W/Hz$^{1/2}$ at room temperature or 10^{-15} W/Hz$^{1/2}$ at cryogenic temperature

4.2.4. (U) Single THz Photon Detectors

(U) The fundamental quantum limit for THz direct detector sensitivity is single THz photon detection, similar to what can be done at infrared and visible frequencies. This requires achieving a noise-equivalent power of $\leq 10^{-20}$ W/Hz$^{1/2}$. The great challenge compared to infrared and visible photons is that THz photons have only about 1/1000 the energy of infrared and visible photons. Since the few meV energy of THz photons is well below room temperature thermal background (about 25 meV), THz single photon detection must be done using cryogenic cooling. Furthermore, classical power-detecting bolometers cannot reach the level noise-equivalent power desired. Only quantum mechanical coherent systems can have that level of sensitity, and such quantum states only exist below about 1 K temperature.

(U) There is currently one major published claim of THz single photon detection in the literature. *[19]* As a detection element, this uses a "quantum dot," a small pool containing only a few electrons formed by nanostructured electrostatic gates in high-mobility semiconductors, in very high magnetic fields. The quantum dots are small enough for their electrons to have strong quantum wave function coherence at milliKelvin temperatures, and the magnetic field splits the allowed electronic energies into sharp levels with well-defined inter-level energy gaps that can be tuned to absorb specific THz photon frequencies. Evidence of single THz photon detection has shown, but only with integration times of several minutes. The very long integration time and the sophisticated cooling and high magnetic field required makes existing THz single photon detection of interest in long-term fundamental research, but of no immediate importance to acceptance of such ultra-high sensitivity detection methods in any practical application.

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances THz single-photon detection into many any applications:

• (U) Any demonstration of a new method of THz single photon detection.

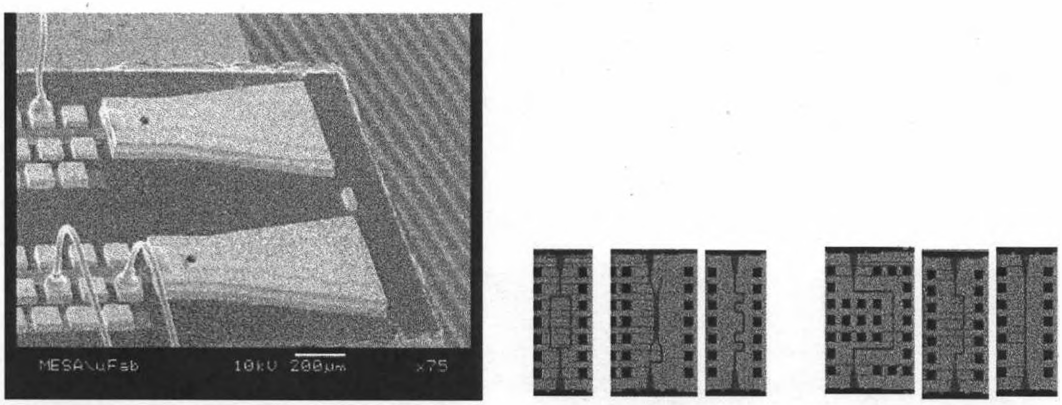
• (U) Demonstration of true THz single-photon detection using integration time of order 1 s or less.

• (U) Demonstration of THz single-photon detection using a de tector operating at temperature of 1.5 K or higher.

4.3. (U) THz Integrated Circuits

(U) There is very recently developed interest in the integration of THz solid-state source, detector, and waveguiding components in what can be regarded as the foundational steps towards a THz Integrated Circuit (THzIC) technology. The goal of these research and development activities is to duplicate the past decade's success in millimeter-wave Integrated Circuits (MMICs) that have made working with signals from 30 to 300 GHz much more widely accepted and available.

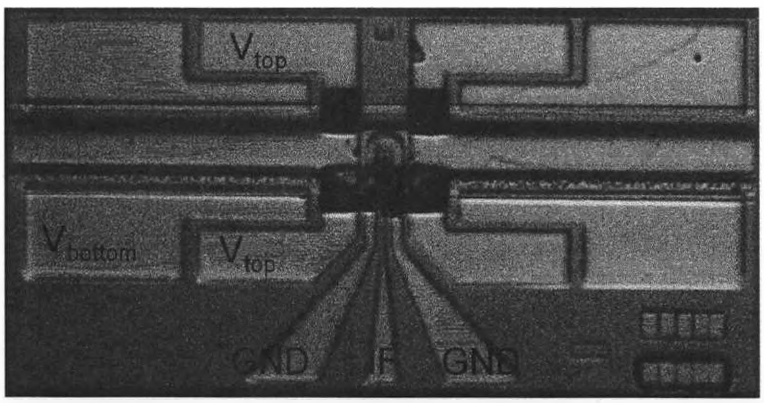
(U) A widely accepted modern convention for existing application systems using THz solid-state components is to place components such as multiplier sources, diode and superconductor detectors, antennas, *etc.* into standardized rectangular waveguide blocks that can be mated together using a standard interface. Despite waveguide dimensions of ≤ 100 μm (0.004 inch), THz rectangular waveguides are still traditionally made by conventional, though high-precision, metal machining methods. Diode mixers and direct detectors are routinely integrated into waveguide blocks. Quantum cascade lasers have proven extremely difficult to place into traditionally machined rectangular waveguide because of their small cross-sectional area, need for very precise alignment within a waveguide, and their electrical bias requirement of ~ 1 A DC current to be fed into a



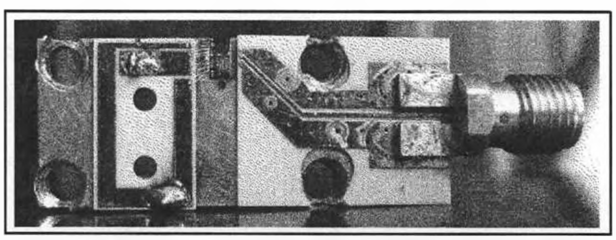
(a) (b)

(U) Figure 4.7: Images of (a) two quantum cascade laserd integrated into micromachined rectangular waveguide horn antennas, and (b) various micromachined rectangular waveguide circuit components (power splitters, couplers, and bends) that can be used with a quantum cascade laser source. (Sandia) waveguide. Very recently at Sandia, quantum cascade lasers have been successfully integrated into waveguides using modern lithographic micromachining methods. In essence, a process has been developed to adapt semiconductor lithography methods to build a rectangular waveguide around an existing quantum cascade laser's output facet. Examples are shown in Fig. 4.7. This approach solves the precision alignment issue, leaves space for the high-current bias leads to the quantum cascade laser, and is scalable to volume production.

(U) More closely analogous to MMICs would be a monolithically integrated THz integrated circuit, rather than waveguide integration, where at a minimum a THz solid-state source and detector would be built on a single semiconductor chip. Sandia recently demonstrated the first such monolithic THzIC. In this circuit, a THz semiconductor diode mixer is integrated directly into the top waveguide ridge of a quantum cascade laser. An image of the first successful prototype THzIC is shown in Fig. 4.8. Local oscillator power to the diode is supplied by having the diode sample a small portion of the strong THz field directly inside the quantum cascade laser's waveguide cavity, which



(a)



(b)

(U) Figure 4.8: (a) Optical microscope image of the first successful THzIC comprising a diode mixer detector monolithically integrated into a quantum cascade laser (the long gold bar running left-to-right in the center of all the contact pads, and (b) this THzIC chip connected to its circuit board, where the mixer's difference frequency output signal is taken from the SMA coaxial connector. This coin-sized circuit board has the same functionality as conventional table-top sized THz heterodyne receivers. (Sandia) eliminates local oscillator coupling losses. The diode itself is small enough to perturb the laser only minimally. Operation of the laser, the diode, and heterodyne down-conversion using the quantum cascade laser coupled to the diode has been shown.

(U) *Short-to-medium Term Evolution Assessment* – In the 1 to 6 year time frame, there is high confidence that THz integrated circuits will achieve:

• (U) Integration of quantum cascade lasers into rectangular waveguide so that THz radiation can be coupled out via a waveguide horn antenna

• (U) Micromachined THz waveguide components such as directional couplers, splitters, and power combiners

• (U) Monolithically integrated THz heterodyne transceiver capable of detection of a coherent THz input signal

(U) *Medium-to-long Term Evolution Assessment* – In the 6+ year time frame, there is high confidence that THz integrated circuits will achieve:

• (U) THz heterodyne transceiver consisting of a quantum cascade laser and diode mixer integrated via rectangular waveguide

• (U) Monotlithically integrated THz heterodyne transceiver capable of detecting 300 K thermal input signal

• (U) Monolithic integration of other THz functionalities such as switches and amplifiers

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of THz integrated circuits into many practical applications:

• (U) Demonstration of a room-temperature, compact integrated THz transceiver with system noise temperature of ≤ 3,000 K at 1 THz or 8,000 K at 2.5 THz

• (U) Demonstration of telecommunications or radar functionality from a waveguide or monolithically integrated THz integrated circuit using a quantum cascade laser source

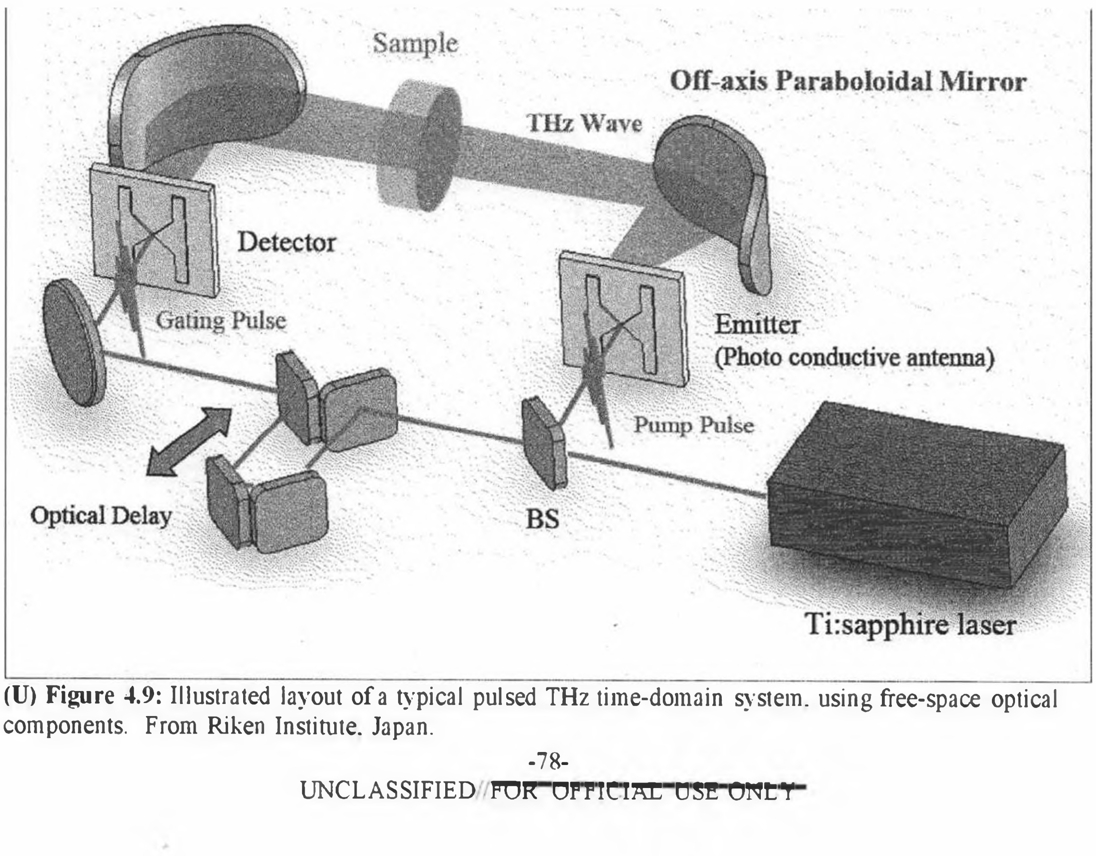
4.4. (U) THz Pulsed Time-Domain Systems

(U) Once used almost exclusively for broadband coherent THz spectroscopy, pulsed THz time-domains systems have developed over the past five years to become a technology that may be directly competitive with solid-state THz microelectronics for applications involving concealed imaging, non-destructive evaluation, and rapid assaying of chemicals.

(U) Pulsed THz time-domain systems work by using high-power femtosecond infrared pulses (typically around 800 nm wave length) to generate short-lived electrical excitations in a source material, usually a semiconductor photoconductive switch or an electro-optical crystal like ZnTe. *[42]* The rapid decay of th e optically generated electrical excitation produces a short long electrical pulse a few picoseconds long, which can propagate as an electromagnetic field into free space. Because the pulse is short, its Fourier frequency content is broad, generally covering 0.5 to 3 THz, with lower or higher frequency content possible depending on the details of how the pulse is generated. This is the THz pulse that is used for spectroscopy or imaging.

(U) At the detection end, a piece of the same infrared excitation pulse used to generate the THz pulse is split off and routed along a longer and hence time-delayed path whose delay is varied via a moving set of mirrors. This delayed detection pulse is then used to trigger or gate a THz detector similar to the THz source material. The detector responds to a THz field only when the infrared gate pulse triggers it by generating charge carriers in the detector material. The polarity of the detector's response to the THz field gives the polarity of the electric field of the THz pulse at a given instant in time. By sweeping the time delay of the infrared gate pulse and running the whole system at a high repetition rate, the electric field profile of a repetitive chain of THz pulses as a function of time can be measured. This is very different from standard electromagnetic detection methods in that the electromagnetic field itself, and not simply the power, is being measured. A schematic of a typical pulsed THz time-domain system is shown in Fig. 4.9.

(U) Because the THz pulse field is detected as a function of time rather than



(U) Figure 4.9: Illustrated layout of a typical pulsed THz time-domain system, using free-space optical components. From Riken Institute, Japan.

frequency, magnitude and phase information is collected synchronously. A complex Fourier transform of the time-domain THz field profile then yields both real and imaginary parts of the frequency spectrum of the detected pulse, giving complete information about the propagation characteristics of whatever medium the pulse propagated through or reflected from. This is the main reason for the popularity of pulsed THz time-domain spectroscopy.

(U) The complicated optics and optical alignment and high-power femtosecond infrared laser conventionally used in pulsed THz time-domain spectrometers traditionally confined this technique to specialized research laboratories. However, the last five years have seen great progress bringing pulsed THz time-domain methods out of the lab. This progress has been brought about by two significant advance in the required optics: the introduction of affordable and relatively compact semiconductor diode infrared lasers capable of generating high-power femtosecond pulses, and the ability to guide these infrared pulses through all fiber optics, including fiber optic delay lines, rather than free-space optics. The use of semiconductor diode infrared lasers dramatically cut down on cost, maintenance, size, and weight compared to standard fast-pulsed lasers. The use of fiber optics eliminated the need for careful and constant mechanical alignment of mirrors and lenses.

(U) Several small companies now sell complete pulsed THz time-domain systems. While not quite turnkey systems yet, they are rapidly approaching that status. It has been shown that these systems are not only useful in their traditional spectroscopy role, but can also be used to generate THz transmission and reflection images by rastering the object.

Such images have the advantage of containing spectral and time-delay information as well as simple magnitude information per pixel and hence have been used for things like tomography as well.

(U) Signal-to-noise and image range issues suffer from a lack of source power. Pulsed THz time-domain systems generate μW levels of average power and spread that power across a broad spectral range. Though brighter than thermal sources, they are many orders of magnitude dimmer than quantum cascade lasers. Thus the research frontier in the development of more widely acceptable pulsed THz time-domain systems is mostly in increasing the power output from THz pulse sources. Currently, using electro-optical materials such as lithium niobate, a traveling wave of coherent trains of infrared excitation pulses can build up a THz pulse to almost 1 mW of total average power spread across a 2 THz spectral band. Building the THz pulse to this power level requires use of expensive and large ultrafast lasers and laser amplifier at present. For imaging purposes, there is also active work going on in developing time-domain focal-plane array detectors.

(U) *Short-to-medium Term Evolution Assessment* – In the 1 to 6 year time frame, there is high confidence that pulsed THz time-domain systems will achieve:

• (U) COTS turnkey systems for routine THz time-domain spectroscopy applications

• (U) Commercially viable THz time-domain imaging systems that can do close-range sub-surface imaging or inspection of static objects on time scales of several minutes

• (U) Relatively compact systems, roughly one cubic meter total volume

(U) *Medium-to-long Term Evolution Assessment* – In the 6+ year time frame, there is reasonable confidence that pulsed THz time-domain systems will achieve:

• (U) New time-domain pulsed THz emitters that can output 1 to 10 mW average total power spread over a 3 to 5 THz spectral bandwidth using compact semiconductor diode lasers to generate infrared excitation pulses

• (U) Gated time-domain THz detectors integrated into an imaging focal plane array

(U) *Breakthrough Milestones* – Any of the following milestones/signposts would represent a seminal breakthrough that strongly advances acceptance of pulsed THz time-domain systems into many practical applications:

• (U) Demonstration of a THz pulse emission subsystem that uses a compact solid-state infrared excitation laser to generate THz pulses with 10 mW average power.

• (U) Demonstration of a pulsed THz time-domain imaging system using a focal-plane array "camera" capable of taking a 32 pixel x 32 pixel image at video rate.

5. (U) Analysis of Commercial Adoption/Implementation

5.1. (U) Economic Drivers

(U) Historically, the major economic drivers behind attempts to commercialize THz component technologies were primarily scientific research, mainly molecular spectroscopy and radioastronomy. Research on THz components, both tube-based and solid-state, was often initiated in a scientific research laboratory with the purpose of improving the ability to measure molecular spectra or detect THz radiation from space with high signal-to-noise. Commercial development and vending of THz components has, to date, generally been done by small companies often "spun off" by engineers and scientists trained in THz experimental methods at major research institutions. These companies historically did, and to the present day still do, the large majority of their business supplying both COTS and custom-made THz measurement components to scientific research organizations. Such research organizations are staffed by specialists who are willing to cool instruments routinely to cryogenic temperatures and to go to extraordinary trouble to achieve desired signal-to-noise and maintain finicky equipment. Because of the limited scope of this customer base, the THz solid-state component commercial has not spread beyond relatively small companies.

(U) The major new economic drivers for more practical and widely acceptable THz solid-state components that have become very relevant in the 21st century are anti-terrorist threat detection, and homeland and military security. Following 9/11/2001, there has been strong and continuing interest in new and improved methods of concealed weapon threat detection of small, common weapons such as knives and handguns.

Improvements in both overt (as with airport security screening) and covert (where the target of detection is not aware that he/she is being screened) threat detection are of interest. For covert, the threat detection has to be done at a range of minimally about 10 m. The advantages of THz radiation in its ability to penetrate common clothing material, present no ionizing radiation health hazard, yield strong contrast for metal objects, and image with sufficient (< 1 mm) resolution to clearly distinguish weapon shapes, have led to commercial interest in the research and development of fieldable THz imaging systems for this purpose.

(U) At the same time, the rise of home-made improvised explosive devices (IEDs) as the enemy's most effective weapons in the wars in Iraq and Afghanistan have given a major economic impetus to research and develop new methods for improvised explosive material detection. Such detection would preferably be at a distance of 10 m to 100 m, but highly useful application scenarios do exist for point and portal explosive material detection as well. It has been established that THz spectroscopic signatures can be used to reliably identify vapor phase and some solid phase signatures of many common explosive materials. Commercially available, professionally manufactured explosive materials have extremely small vapor pressure and hence cannot be detected directly from any vapors they emit. However, it turns out that many common home-made explosive materials as well as constituent chemicals that go into making explosives and the binding chemicals for solid-phase explosives do have rather high vapor pressures at room temperature and distinctive THz spectral fingerprints. For this reason, there has been an economic impetus to explore the ability of THz components to detect home-made explosive materials and their components.

(U) An economic driver related to explosives detection is the use of THz technology for hazardous and toxic chemical vapor and biological material sensing and identification. Both remote (100 m to 1 km) and point/portal sensing application scenarios have practical use. Again, the strong and unique THz spectroscopic signatures of many chemical vapors and biological materials is the scientific basis for these efforts. Such detection is relevant both to anti-terrorist efforts and to public safety and accident response.

(U) Non-destructive evaluation (NDE) of material and component quality and defects has recently surfaced as an economic driver for THz technology. There are several commercial application scenarios for THz NDE. For example, THz radiation has been used to image sub-surface cracks and defects in ceramics and polymeric solids. Ultrasound and X-ray methods can also be used for similar purposes, but THz radiation offers the advantages of being non-contact (unlike ultrasound) and not involving possibly hazardous ionizing radiation (unlike X-ray). Also, there has been activity exploring use of THz spectroscopy to real-time monitor the medicinal content of pills as they come off the manufacturing line in the pharmaceutical industry.

(U) A subset of NDE of materials is medical diagnostics. THz waves in the 0.5 to 1 THz frequency range are highly absorbed by water molecules but can penetrate several millimeters below skin without the ionizing radiation hazard associated with X-rays. Evidence of some near-surface cancerous tumors can be imaged using THz waves. *[43]*

(U) As a general technological forecast statement, it will require THz components and instrumentation to advance to the compactness, field-use reliability, and ease-of-use level of current radiofrequency/microwave electronics or infrared /visible photonics to achieve wide-spread commercial interest and acceptance.

5.2. (U) Major Commercial THz Component Vendors and Developers

(U) The following section includes brief descriptions of several leading commercial vendors and developers active in solid-state THz component technology. Included are companies that working in solid-state microelectronic THz technology and major players in pulsed time-domain THz systems. Companies whose main THz products are tube-based are not included. This list is not exhaustive as many small companies are trying to compete in this field, mostly via SBIR and STTR grants in the United States, but does represent what the author regards as the most widely known companies.

(U) Virginia Diode Inc. (VDI) – formed by a group of electrical engineering faculty from the University of Virginia, VDI is now widely regarded as the world's leading commercial vendor of diode and varactor based electronics for applications at frequencies from 0.1 up to 2 THz. VDI offers both COTS and custom designed components and subsystems including mixers, multipliers, amplifiers, and various passive waveguide components. VDI is currently developing harmonic multiplier sources capable of going up to 2.5 THz with a target of 1 μW average power. Their customer base is primarily radioastronomers.

(U) Picometrix – perhaps the nation's leading commercial developer and vendor of pulsed time-domain THz spectroscopy and imaging systems. Picometrix sells complete nearly turnkey THz time domain spectroscopy systems and has demonstrated the use of its systems for applications such as non-invasive inspection of luggage for weapons and non-destructive evaluation of sub-surface cracking in the space shuttle's ceramic heat shield tiles. They have sold some demonstration systems for concealed weapons detection and NDE applications.

(U) Teraview – formed by a consortium of THz researchers under the initial sponsorship of the European Space Agency (ESA). Teraview is the main international commercial competitor for Picometrix. Teraview is best known for demonstrating and advertising both continuous-wave and pulsed THz time-domain systems for explosive material identification, concealed weapons detection, and pharmaceutical screening. Teraview also is developing THz quantum cascade lasers for commercial applications.

(U) ZOmega THz Corp. – a spinoff of the academic THz research group at Rensselaer Polytechnic Institute, ZOmega is a commercial developer and vendor of pulsed time-domain THz spectrometers and imaging systems.

(U) Millitech – one of the oldest commercial presences in the THz field. Millitech supplies many basic THz solid-state components integrated into rectangular waveguide.

Millitech's products include Gunn oscillators, diode detectors and mixers, passive waveguide components, multipliers, and heterodyne mixers. The company sells mostly COTS components but does accept custom work as well. Most of Millitech's business is targeted in the frequency range 0.05 up to 0.7 THz. Millitech does not have much presence in the frequency range above 1 THz. Their customer base is composed of radioastronomers and engineers developing and testing high-speed electronics.

(U) IR Labs – the leading US supplier of COTS THz direct detection bolometer systems and traditional rival to QMC/TK (below) in this area. The THz portion of their business has has historically been as OEM vendors to spectrometer system manufacturers such as Bruker, though they do sell stand-alone THz bolometer systems.

(U) QMC/Thomas Keating – formed by several THz engineers and scientists from Queen Mary College, England, QMC is considered by many the world's leading commercial vendor and developer of direct detection bolometers for THz applications. It's sibling company Thomas Keating is considered the world's leading designer and manufacturer of optical components made specifically for THz applications. These companies sell individual components as well as custom design and build large scale THz systems. Their customer base has historically been radioastronomers and spectroscopists.

(U) ThruVision – a spin-off composed mostly from researchers at the Rutherford-Appleton Laboratory and founded as a technology transfer from the ESA's Star Tiger program, ThruVision markets passive (*i.e.* thermal emission or emissivity contrast sensing) THz imaging systems sensitive to frequencies around 0.5 THz. Details of their sensing technology are proprietary but are likely either bolometer or pyroelectric based.

(U) Emcore – are selling a turnkey continuous wave THz photomixer system aimed at spectroscopy and point/portal hazardous chemical vapor sensing.

(U) Goodrich ISR – are marketing a portable (large suitcase sized) 0.1 to 1.1 continuous wave THz photomixer spectrometer aimed at hazardous gas identification.

(U) Coherent – the US commercial leader in building and selling all kinds of lasers, Coherent acquired DEOS, the world leader in THz molecular gas lasers. Coherent acts in large part as OEM supplier of the infrared lasers needed for photomixers, pulsed THz time-domain systems, and optical parametric THz generation.

6. (U) Worldwide Research Activities

(U) THz technology is being researched and developed worldwide by academic, government, and industrial organizations. Research groups range from very small and specialized to large broadly oriented ones. This section contains brief descriptions of the most well known and leading research efforts.

6.1. (U) United States

(U) Jet Propulsion Laboratory (JPL) – NASA/CalTech's JPL is the traditional US leader in solid-state components for THz detection, historically for radioastronomy and earth atmospheric monitoring purposes. The group headed by [redacted] has designed and built heterodyne and direct detection systems that have been airborne and satellite qualified. The group headed by [redacted] is a leader in the use of superconducting detection of THz signals.

(b) (6)
OGA

(U) Sandia National Laboratory (SNL) – The molecular-beam epitaxy semiconductor growth project headed by [redacted] is the leading place in the US for high precision growth of THz quantum cascade laser semiconductor heterostructures and integration of quantum cascade lasers with THz heterodyne and direct detectors.

(U) The THz Microelectronics effort headed by [redacted] and [redacted] is at the forefront of integration of THz quantum cascade lasers and heterodyne mixers into waveguided and integrated circuits. SNL also maintains capabilities in THz quantum cascade laser design and simulation. THz chemical and material spectroscopy and imaging, and THz time-domain spectroscopy.

(U) Massachusetts Institute of Technology (MIT) – the research group of Prof. Qing Hu at MIT is widely considered the US leader, and one of the world's two leading groups (the other being Jerome Faist's group at ETH Zurich), in design and fabrication of cutting-edge THz quantum cascade lasers. Over the past seven years this group came up with several breakthroughs in the understanding of quantum cascade lasers and in laser performance at higher power, longer wavelength, and higher operating temperature.

(U) The research group of Prof. Keith Nelson is the leader in using sophisticated non-linear optical methods to generate high-power picosecond THz pulses. This group developed an optical pulse train excitation technique that can generate picosecond THz pulse with repetition rates from kHz to MHz and average power of ~ 1 mW, compared to few μW by conventional pulsed THz methods.

(U) University of Massachusetts Lowell (UML) – the research group headed by Prof. Jerry Waldman has historically been a leader in the design and application of Schottky diodes and low-noise bolometers for sensitive THz detection, particularly in radioastronomy applications. UML has in the past two years demonstrated the capability to grow THz quantum cascade laser structures and apply them in conjunction with UML's THz detectors.

(U) Harvard University – the group of Prof. Federico Capasso is historically considered a world leader in mid-infrared rather than THz quantum cascade lasers. In the last year this group has moved strongly into THz quantum cascade lasers. Together with a group at ETH Zurich, they made the first demonstration of coherent THz emission at room temperature by generating a difference frequency between two monolithically integrated mid-infrared quantum cascade lasers. This group also recently took the record for highest operating temperature in a fundamental THz quantum cascade laser, showing THz lasing at 178 K.

(U) Renssalaer Polytechnic Institute (RPI) – the group of Prof. X.-C. Zhang is the US and possibly world leader in pulsed THz time-domain methods and applications, including spectroscopy and imaging. Although THz time-domain is outside the strict purview of this article, RPI is actively pursuing integrated packaging of THz time-domain systems using fiber-optics to couple solid-state components. RPI's strategy may prove to be competitive with more traditional THz solid-state integration approaches.

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(U) Los Alamos National Laboratory (LANL) – the research group headed by [redacted] is widely regarded as a leading group in pulsed THz time-domain spectroscopy, particularly of solids and novel materials.

(U) Stanford University – the research group of Prof. Marty Fejer has been doing extensive research on improving optical parametric THz generation using multi-pass idler cavities and periodically poled lithium niobate non-linear crystals.

(U) University of California Santa Barbara – the research groups of Profs. Jim Allen and Mark Sherwin at the THz Free Electron Laser facility at Santa Barbara have historically done much research on innovative semiconductor THz detectors using quantum mechanical effects.

(U) The research group of Prof. Eliot Brown is widely known for its expertise in building high-efficiency, high-power photomixer elements using erbium-doped GaAs and low-temperature grown GaAs semiconductors. This group often sells or licenses its photomixer components to commercial vendors.

(U) Oklahoma State University – the research group of Prof. Dan Grischkowsky is one of the original developers of the pulsed THz time-domain technique and continues to be a leading innovator in the field.

(U) Boston University – the research group of Prof. Richard Averitt has brought Prof. Averitt's many years of expertise in pulsed THz time-domain measurements from Los Alamos to BU.

(U) Rice University – the research group of Prof. Dan Mittleman does highly innovative work in applications of pulsed THz time-domain methods, especially in THz waveguiding and advanced THz imaging techniques.

(U) National Radio Astronomy Observatory (NRAO) – the NRAO engineering group in Charlottesville, VA headed by Dr. Anthony Kerr is the traditional leader in development of extremely high sensitivity millimeter-wave and THz detector systems, including associated waveguides, amplifiers, and signal processing. This group probably knows more about superconducting THz heterodyne receivers than anyone else in the world.

(U) National Institute of Standards & Technology (NIST) Boulder – the group led by Dr. Erich Grossman is a leader in active and passive THz imaging using bolometer focal-plane arrays. Their main application is concealed weapons detection.

(U) University of Virginia (UVA) – the group led by Profs. Robert Weikle, Art Lichtenberger, and Bascom Deaver do THz waveguide design and fabrication for diode and superconductor source and detector components. Virginia Diode Inc. is a spin-off of this group. This group also has significant expertise in the use of THz components for scale model radar applications.

6.2. (U) Canada

(U) National Research Council (NRC) – NRC has been traditionally strong in the design and fabrication of semiconductor quantum well infrared photodetectors. Over the past three years, the group led by Dr. Zbig Wasilewski and Dr. H. C. Liu have extended this strength into the growth by molecular beam epitaxy and fabrication of THz quantum cascade laser structures and THz semiconductor detectors.

6.3. (U) European Union

(U) SRON – the Netherlands Institute for Space Research is now probably the world's leading research institution in developing and applying THz remote sensing systems. SRON has been developing direct and heterodyne THz detection systems qualified for airborne and space applications in support of various ESA-sponsored radioastronomy missions such as HIFI and Herschel. SRON has significant expertise and resources in all aspects of solid-state THz component and system technologies. SRON researchers have a close working relationship with TU Delft.

(U) TU Delft – the Technical University at Delft in the Netherlands works closely with SRON to research and develop many different types of THz solid-state components, including quantum cascade lasers, multipliers, and superconducting detectors and mixers. Most of the THz microelectronics work is led by Dr. Jian-Rong Gao and Dr. Teun Klapwijk. Another TU Delft group led by Prof. Paul Planken is highly regarded for their creative work using pulsed THz time-domain systems.

(U) DLR – the German Aerospace Center has a major project developing airborne-qualified THz detector and receiver systems primarily for radioastronomy. DLR has world-class expertise in superconducting THz detectors and heterodyne receivers and in building flyable systems. Most of the THz work is led by Dr. Heinz-Wilhelm Huebers.

(U) University of Cambridge (Cavendish Laboratory)– the semiconductor physics research group led by Prof. David Ritchie and the molecular beam epitaxy facility run by Dr. Edmund Linfield were the first to successfully grow a THz quantum cascade laser structure and they remain regarded as the world's leading grower of THz quantum cascade laser material.

(U) University of Pisa (Scuola Normale Superiore) – the group led by Prof. Alessandro Tredicucci was the first to design, fabricate, and demonstrate a THz quantum cascade laser, using material grown at Cambridge. They also established the basic physical principles of THz quantum cascade laser operation. This group continues to be a respected innovator of THz quantum cascade lasers

(U) ETH Zurich – the group of Prof. Jerome Faist (formerly at Univ. of Neuchatel) is considered one of the world's top two research groups in state-of-the-art THz quantum cascade laser research and development (the other being the MIT group of Qing Hu) for longer wavelengths, higher operating temperature, and higher output power. This group collaborates extensively with the Harvard group of Federico Capasso.

(U) TU Vienna – the Technical University of Vienna group led by Prof. Karl Unterrainer has a long history of forefront research work in quantum semiconductor THz detectors. They have recently begun doing research on THz quantum cascade lasers as well.

(U) University of Paris – the group led by Prof. Stefano Barbieri and Prof. Carlo Sirtori have made highly recognized contributions to the design and understanding of advanced THz quantum cascade lasers that push limits on higher operating temperature and lower frequency.

(U) Rutherford-Appleton Laboratory (RAL) – has a long tradition of developing high-frequency (microwave to THz) continuous wave sources and detectors for radioastronomy. In recent years researchers at RAL have begun demonstrating use of their THz technology for security and defense purposes as well. RAL has been a "gateway" for several small company spin-offs in THz technology, primarily through EU seed funding programs such as Star Tiger, which developed the basics of the millimeter-wave passive imaging camera technology that launched ThruVision.

(U) United Kingdom National Physical Laboratory (NPL) – has a similar history as RAL in microwave to THz detectors and THz frequency spectroscopy and metrology, historically in support of radioastronomy. NPL has also directed its THz efforts in recent years towards security screening and bio-medical applications.

6.4. (U) Russia

(U) Moscow State Pedagogical University – the group led by Prof. Gregory Gol'tsman is perhaps the world leader in superconducting hot-electron bolometric mixers for THz heterodyne detection.

6.5. (U) Japan

(U) RIKEN Institute – the group led by Prof. Kodo Kawase (also at Nagoya University) is considered a world leader in optical parametric generation of THz radiation and in applications of this method to non-destructive evaluation and pharmaceutical/drug screening. This group has made several important advances in tunability, power output, and compactness of THz optical parametric generators.

(U) National Institute of Information and Communications Technology (NICT) – the lead research & development agency for Japan's Ministry of Internal Affairs coordinates a broad program involving many academic research groups and industries to develop THz technology applications. NICT supported research includes extending millimeter wave integrated circuits up to low THz frequencies, THz quantum cascade laser research, superconducting THz devices, pulsed THz time-domain systems, and high-sensitivity THz detectors. NICT focuses on applications such as real-time hazardous chemical sensing, detection of contraband drugs in luggage or in the mail, and security imaging.

(U) Semiconductor Research Institute – the group of Dr. Jun-Ichi Nishizawa leads an effort to apply pulsed THz time-domain spectroscopic and imaging techniques to non-invasive medical diagnostics.

(U) Osaka University – the group of Prof. Masayoshi Tonouchi is a leader in the study of the interaction of THz radiation with various exotic materials. In particular, this group has demonstrated coherent THz emission by optically or electrically pumping a surprisingly wide variety of material sysems, including high-T_c oxide superconductors, iron-implanted semiconductors., and ferroic oxides.

7. (U) Conclusions

(U) It is widely recognized worldwide that the THz electromagnetic spectrum offers significantly new or extended capabilities of direct importance to national defense, security, and intelligence missions. These capabilities include new modalities in hazardous or toxic chemical and biological agent detection, highly secure high-speed telecommunications, and imaging and identification of concealed threats and weapons. Use of THz technology can both enhance the United States' interests, and can be deployed against the United States by foreign adversaries.

(U) To date the THz spectrum does not have the same solid-state technological infrastructure that makes the rf/microwave and infrared/visible spectral ranges so broadly useful and acceptable in technological applications outside of the laboratory, a situation which is commonly termed the "THz technology gap." It is generally believed that in order for the THz spectrum to become more widely useful and accepted by end users, an all-solid-state technology base amenable to modern microfabrication production methods must be developed. This has proven to be more challenging than might be anticipated because frequencies near 1 THz turn out to be unsuitable for either conventional electronics or photonics. 1 THz is too fast for electron transit time limitations in transistor electronics, but is too small for the narrowest bandgaps that occur in natural semiconductors usable in photonics.

(U) An additional challenge toward using the THz spectrum in ground or near-ground level applications, especially applications requiring transmission of THz waves across distances more than roughly 10 m, is the fact that the atmosphere is nearly opaque to

THz radiation. Across a distance of approximately 1 km at sea level in clear weather, one can expect an absolute minimal atmospheric attenuation of 100 dB at frequencies of 1 to 5 THz. This poses very daunting signal-to-noise problems in a frequency range where neither electronics nor photonics work well to begin with.

(U) In terms of THz microelectronic components, the most challenging research area is in solid-state THz sources. Because solid-state THz detectors are approaching physical limits on sensitivity, it is generally regarded that significant improvements must be made in THz coherent sources. The overriding issue in THz solid-state sources is generating high enough average power to overcome attenuation by atmosphere or by intervening materials such as clothing or packaging. At a bare minimum, an estimated 10 mW of coherent power is required to do anything useful, and power levels of 100 mW to 1 W are far more desirable for most applications. Other THz source related issues are frequency range coverage and agility, DC-to-THz power conversion efficiency, and ability to operate without sophisticated or delicate cryogenic cooling.

(U) Currently, worldwide leadership in THz microelectronic component research is probably in the European Union (EU). Through a variety of EU government-university-industrial collaborative R&D programs, several EU research institutions and start-up companies are recognized leaders in many aspects of THz solid-state technology, especially technologies related to security and defense applications. THz R&D funding in the US is not coherent. As a result, US research institutions and companies have largely ceded leadership in many areas of THz microelectronic technology to EU counterparts. THz R&D in Asia is primarily in Japan, where the application drivers are more oriented towards quality control, non-destructive evaluation, and pharmaceutical sensing rather than defense or security.

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