for the *Proceedings of the IEEE Ultrasonics and Frequency Control Conference*, Kansas City, June 2000

FREQUENCY-CONTROLLED SOURCES OF FAR-INFRARED RADIATION FOR SPACEBORNE APPLICATIONS

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INTRODUCTION

Among the difficulties in developing far-infrared (FIR)[2] technology, a perennial lack of frequency-controlled sources has kept this spectral region's technology far behind that of the surrounding spectral regions. Technologists working at microwave frequencies effectively utilize a "wave" and "electron" approach, while those working in the infrared effectively utilize a "particle" and "photon" approach. Unfortunately, given the state of technology today, neither approach is optimal for use in the FIR. With only marginal success, researchers toil diligently to stretch the boundaries of both wave and particle technologies to the FIR. The pessimist may complain about the state of FIR technology, but the optimist will note that this field is ripe for development, and possesses great potential for breakthrough discoveries.

As is the case in other spectral regions, astronomers and atmospheric scientists drive much of the cutting-edge technology development in the FIR. The dramatic attenuation of FIR radiation by water and other constituents of Earth's atmosphere forces many of the scientists' measurement platforms above the atmosphere, into space. Therefore, there is a strong correlation between the development of new FIR technology and spaceborne instrumentation. In this paper, we address the needs of the FIR space-flight community, providing an introductory-level treatment of the common heterodyne receiver configurations and the state of technology for various front-end components. We make frequent reference to the added challenges of producing such receivers for space environments. Meeting science needs with a robust instrument that can withstand a rocket launch and several years in space can be extremely difficult – but can be equally rewarding.

FIR RADIATION SOURCE APPLICATIONS

With the sluggish advancement of FIR technology, there has been only one spacecraft to date which has successfully utilized FIR heterodyne radiometers: the Submillimeter-Wave Astronomy Satellite (SWAS) [1]. Launched in 1998, this spacecraft has generated impressive astrophysical measurements at frequencies near 490 and 550 GHz (where atmospheric attenuation is particularly strong). Several other spacecraft are due to launch in the near future with FIR heterodyne radiometers for astrophysical, atmospheric, and cometary studies. Here we outline the applications, the expected scientific understanding to be generated, and a sampling of spacecraft that will perform the measurements. Because there has been only minimal application of FIR technology in spacecraft to date, even the simplest FIR measurements offer great potential for breakthrough discoveries.

Astronomy

Characteristic temperatures, molecular bond strengths, and dust grain sizes are responsible for filling the heavens (and Earth!) with FIR radiation. COBE spacecraft measurements showed approximately *98% of ALL the post-Big Bang photons* in a typical galaxy lie in the FIR spectral region [2]! Add to this the evidence that the 1.9 THz carbon line, a *single* spectral line, is responsible for 0.25% of the energy radiated by a galaxy [3]! As an added benefit, the wavelength of FIR photons is such that one can probe deeply inside regions of gas and dust that surround stars, without the dramatic attenuation typically seen by near-infrared photons. This gas and dust, in many places responsible for the birth of new stars and galaxies, is at temperatures that exhibit a peak in the Planck blackbody radiation spectrum in the FIR [4].

Using Doppler information collected by high-spectral-resolution heterodyne radiometers, the dynamics of galaxies new and old may be understood. Spectral linewidths, line shapes, and relative line strengths can reveal the temperatures, pressures, and ionization states of these star-forming regions. Typical frequency resolution better than a part in a million is necessary for many of these studies. Ideal local oscillator sources for heterodyne radiometers in the FIR regime would therefore have linewidths and frequency stability of order 100 kHz.

As discussed previously, the SWAS mission has been extremely successful, and leads the way for future spaceborne heterodyne FIR instruments. Most notable is the Far-Infrared Space Telescope (FIRST), a collaboration between the European Space Agency (ESA) and NASA. Set to launch in 2007, it will utilize

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[2] Here, the term "FIR" refers to frequencies from approximately 300 GHz to 6 THz (wavelengths of 50 μm to 1 mm), and is synonymous with "submillimeter" or "terahertz."

cold optics and state-of-the-art superconducting mixers to make extremely sensitive measurements of near and distant objects at frequencies exceeding 1 THz [5]. As is now quite common, the local oscillator (LO) technology is perhaps the most limiting aspect of the mission. The somewhat archaic semiconductor-harmonic-multiplier source scheme (discussed below) is planned for use here. Realistically it is the only scheme with a chance of meeting mission requirements before launch, and yet only with heroic efforts will it even be able to source useful power and bandwidth of the highly-desired THz radiation.

Several small space missions are being proposed for the latter part of this decade, but the full value of heterodyne radiometry may not be realized until the next decade. Then, we may have the technology to build kilometer-baseline interferometers for the ultimate in spatial resolution of astrophysical sources. While direct detection holds a sensitivity advantage over heterodyne radiometry for some applications in the FIR, the longest-baseline interferometers will require the phase-coherent techniques of heterodyne measurements to allow realistic combination of the numerous telescope signals. Very-large-aperture telescopes (perhaps tens of meters in diameter, from inflatable structures) will be required to make the sensitivity of such an interferometer of practical use for many astrophysical studies [3].

Atmospheric Chemistry

We all have been touched to some extent by regulations imposed to maintain a healthy atmosphere. We may notice the effects of reduced smog levels, trends in global warming, a potentially life-saving ozone layer, or the expense of a CFC-free refrigerator, but, behind the scenes, governments make extremely difficult choices in balancing economic and environmental priorities. Atmospheric scientists strive to provide governments with unequivocal data that makes these choices obvious. As fate would have it, important molecules in the Earth's atmosphere exhibit vibration and rotation spectra in the FIR. By monitoring such molecules, one can gain a better understanding of atmospheric dynamics, obtain more realistic data for atmospheric models, and provide real-time feedback on atmospheric conditions [6].

Precise observation of molecular spectral line shapes, widths, and amplitudes are critical to extracting the relevant information from measurements. Doppler-broadening and pressure-broadening of the spectral lines typically results in linewidths of order 1 to 10 MHz [7]. For sufficient accuracy in data collection, one desires spectral resolution of better than a part in a million, and LO linewidths of order 100 kHz for LO frequencies up to 2.5 THz.

The Upper Atmosphere Research Satellite, Microwave Limb Sounder (UARS-MLS) instrument began operation in 1991, and has been consistently returning useful data of this nature to the present day [8]. Although the highest frequencies observed with UARS-MLS were only in the neighborhood of 200 GHz, it has laid the groundwork for the next generation Earth Observing System, Microwave Limb Sounder (EOS-MLS). Set for launch in 2003 in NASA's AURA spacecraft, EOS-MLS is presently the largest American FIR space mission, and will observe the atmosphere in five radiometer frequency bands from 100 GHz to 2.5 THz with semiconductor-based heterodyne receivers [9]. An additional follow-on mission to launch near the end of the decade is being proposed.

FIR heterodyne receivers also find application in cloud ice crystal observations, an important part of accurate global-warming models [10]. A DC-8 airplane-based instrument is presently being built at JPL to demonstrate the usefulness of this technique, and will hopefully lead to a space-based global application. Lastly, the effects of aerosols and dust spewed into the atmosphere by volcanoes are readily observed in the FIR, and are occasionally detected by the MLS radiometers.

Planetary Science

Earth's atmosphere is but one of many interesting atmospheres in our solar system. Remote or *in-situ* FIR measurements are particularly well-suited to intriguing atmospheres like those of Venus, Mars, and Saturn's moon Titan. By learning about the atmospheric composition and dynamics on remote planetary bodies, scientists can develop models of planetary evolution and suitability for future exploration. The sensitivity of FIR radiometry to emission from water molecules may lead to missions to Mars and Jupiter's moon Europa. In fact, missions to Mars have been proposed, and a potential FIR study of Venus' atmosphere is presently receiving much attention. The reduced size of FIR antennas with respect to their millimeter-wave counterparts also makes them attractive for *in-situ* "weather stations" and sensor webs.

Other solar system bodies are realistic candidates for FIR study -- comets and other Kuiper Belt objects (KBOs) offer clues to understanding the creation of our solar system, and possibly life on Earth as well. The molecular gas and dust outflows from heated comets offer much information in the FIR, from identification of molecular species to the size, quantity, and albedo of the ejected debris. Rosetta, another ESA-NASA collaboration, will contain the MIRO instrument for 236 and 562 GHz remote studies of the comet 46 P/Wirtanen as it orbits the comet. The instrument will remotely measure gas volatile composition, coma temperature, gas velocity, and subsurface temperatures of the cometary nucleus to a depth of 2 cm or more. Key measurements include CO and water in the head and tail of the comet, temperatures, and isotope ratios. Launch is in 2003, and rendezvous is expected in 2011, with observations lasting at least 2 years thereafter. Future FIR studies of the albedo, size, and position of KBOs will be useful for understanding the conditions that regulated the formation and evolution of the debris that coalesced into our solar system [4].

As many signatures of life (as we know it) can be found in the molecules detectable with FIR radiometers, one would hope that space missions in the distant future would include large-aperture, large-baseline interferometers for examining the chemistry of extra-solar planets. The ratio of planet to stellar flux increases significantly as one moves from the near-IR to the FIR. Although extremely large telescopes (at this time unfeasible) would be required for the necessary sensitivity, the predicted molecular species and planetary atmosphere temperatures associated with life make FIR radiometers particularly well-suited to the task of detecting extraterrestrial life.

Non-Scientific Spaceborne Applications

The information-carrying capacity of signals with terahertz bandwidths is obviously immense. Due to atmospheric absorption, one finds few applications of free-space FIR transmission at the Earth's surface. However, satellite-to-satellite communication can be achieved with the immense bandwidths offered by the FIR. Defense applications exist here as well because of the difficulty in eavesdropping through the atmosphere. Compact, low-power FIR radiation sources, detectors, and filters must be developed before such applications become economically feasible.

HETERODYNE RADIOMETERS

People in the frequency control community will be most concerned with those FIR instruments containing heterodyne mixers, rather than direct detection elements. Mixers are utilized because of the lack of suitable amplifiers in this frequency range, necessitating the frequency downconversion to the convenient microwave region for further signal processing.

Why Heterodyne?

Heterodyne technology offers highest sensitivity in the longer-wavelength region of the FIR. As wavelengths decrease, the attractiveness of direct detection instruments increases. Nonetheless, for most applications in the FIR that require high frequency resolution (a part in 10,000 or more), heterodyne receivers are most practical. Figure 1 shows the detector niches in the FIR, both in terms of sensitivity and as a function of frequency resolution. Most often, the specific targeted application will make the choice of heterodyne vs. direct for you.

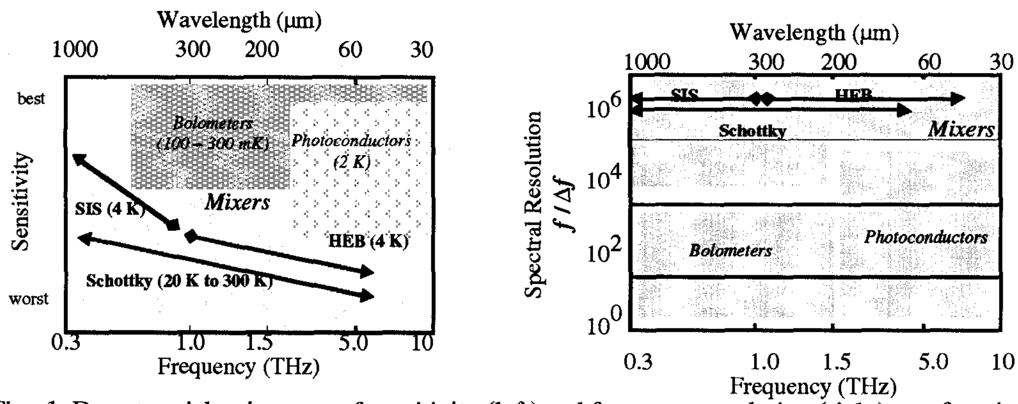

Fig. 1. Detector niches in terms of sensitivity (left) and frequency resolution (right) as a function of frequency. SIS refers to superconductor-insulator-superconductor tunnel junctions, HEB refers to hot-electron bolometers, and Schottky to metal-semiconductor diodes. Typical operation temperatures are noted.

Typical Configuration

Referring to Figure 2, the typical heterodyne radiometer is composed of

- an antenna (mirror), with size proportional to wavelength for a given angular resolution, that focuses the signal radiation onto the mixer(s)
- a switchable mirror in the optical path to adjust the beam direction for calibration purposes; the mixers may look at cold space or some local temperature-controlled absorber
- optics for spatially separating the individual frequency bands of interest, so mixers optimized for each frequency band will receive the appropriate signals
- a local oscillator (LO) with diplexer to couple the LO to the mixer without loss of signal in the process
- the mixer, which generates an output signal with frequency equal to the difference of signal and LO frequencies

- the low-noise intermediate frequency (IF) amplifier (typically HEMT amplifiers are used), with bandwidth large enough to capture the entire frequency range of the signal of interest (typically at least 1 GHz, and often as high as 20 GHz), and gain high enough to make the noise contribution of following components negligible
- "back-end" processing which may consist of further mixer downconversion and spectrometers; filter banks, correlators, and acousto-optic spectrometers (AOS) are used to measure the power contained in frequency bins with significant frequency resolution to resolve important features of the observed signal (typically of order 1 to 10 MHz).

Arguably, the most primitive technology in these instruments is the local oscillator.

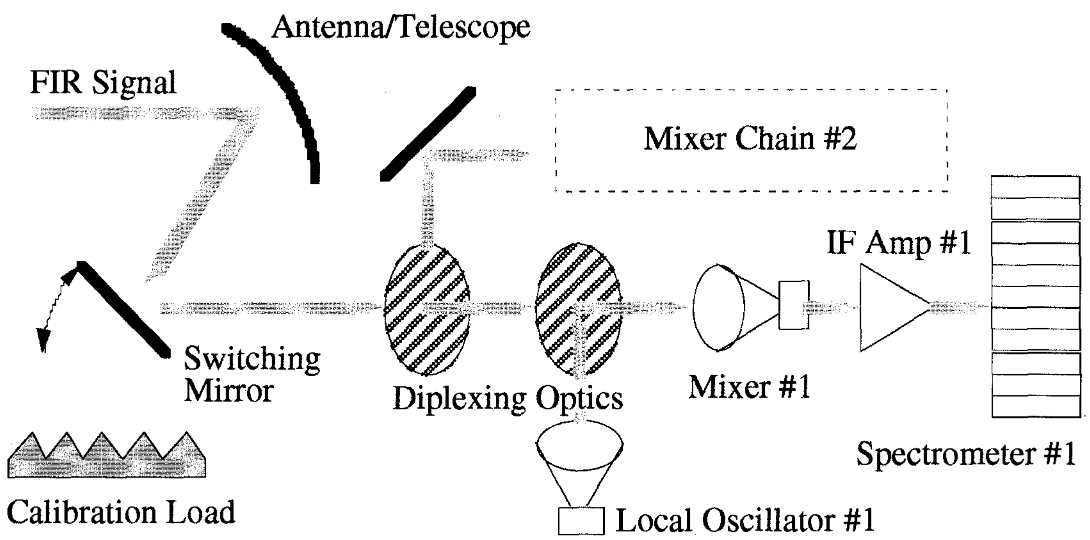

Fig. 2. Schematic of a typical heterodyne radiometer.

Mixers

As indicated in Figure 1, the highest-sensitivity applications requiring high frequency resolution utilize superconductor-insulator-superconductor (SIS) tunnel junction mixers operating at temperatures of 4 K or below. For frequencies above about 1 THz, one resorts to hot-electron bolometer (HEB) mixers if high sensitivity is needed. Again, these operate at temperatures near 4 K. For room-temperature operation, or simplicity in low-sensitivity applications, Schottky diodes are used. The convenience of operating at room temperature typically carries a penalty of a factor of 5 or so in sensitivity. For the frequency control community, the important factors associated with these mixers are the amount of LO power required, and the LO amplitude stability. Typical LO power requirements range from 100 nW (HEBs) to 1 μW (SIS) to 1 mW (Schottky), and has enormous consequences on the applications in which these mixers are used. Inefficiencies in diplexing and optical coupling can raise the actual LO source powers needed by a factor of 5. Note that arrays of such mixers are envisioned for the future, and the aforementioned LO power must be multiplied by the size of the array (assuming a very efficient LO power distribution scheme). SIS and Schottky mixers enjoy an advantage over HEB mixers in the power stability requirements of the LO. The SIS and Schottky mixers operate in a region where fluctuations in LO power are compressed somewhat: fractional changes in LO power correspond to perhaps ten times lower fractional changes in IF output power. HEB mixers, however, operate in a regime where such compression is much less significant, and LO fluctuations are nearly indistinguishable from signal fluctuations. Requirements on power stability are typically 1% for the SIS and Schottky, but 0.1% for the HEB mixers.

Local Oscillators for Spaceborne Use

There is a division of approaches used for LO technology, with electronic techniques generally used at frequencies below 1 THz, and photonic techniques above 1 THz. While reasonable success has been achieved in the former regime, the latter frequency regime has only rarely been able to meet the demands of use in spacecraft. The limitations of greatest influence that are placed on local oscillators by space flight include

- input power; ideally less than 10 W

- output power; ideally more than 1 mW, but useful even at 1 μW
- frequency linewidth, stability; ideally better than 100 kHz
- mass; ideally less than a few kg
- volume; ideally less than 100 cm^3
- thermal stability for operation in environments with drift at rates close to 1° C/min
- ability to withstand launch vibration of magnitudes typically between 5 g, rms and 50 g, rms
- radiation hardness; from ≈ 10 krad (Si) (in low Earth orbit) to > 1 Mrad (Si) (near Jupiter)
- minimal susceptibility to (and responsibility for) electromagnetic interference.

Fundamental Sources

A number of schemes presently exist for fundamental sources below 150 GHz, but useful power at higher frequencies is not ordinary. For flight applications, such fundamental sources include, but are not limited to the following:

1. Monolithic millimeter-wave integrated circuit (MMIC) power amplifiers in the 100 GHz range driven by YIG (Yttrium Iron Garnet) oscillators are capable of high output power levels over large fractional bandwidths. Phase lock/frequency stabilization is relatively straightforward with these oscillators. Output power of the final power amplifier stages has been measured to be 200-400 mW over 18% bandwidth, using GaAs PHEMT (pseudomorphic high electron mobility transistor) technology [11]. At higher frequencies, InP HEMTs are the best choice for high power. InP power amplifiers with output power levels between 25-40 mW have been demonstrated as high as 140 GHz [12]. See Figure 3 for picture and data from an InP HEMT MMIC
2. Gunn diode oscillators are available below ≈ 300 GHz, and are mechanically tunable over a large fractional bandwidth. Electronic tuning is possible over a much narrower bandwidth and allows for phase-locking to provide phase/frequency stability. Available output power is usually much less than that of a W-band power amplifier. The highest power reported for a single diode, fundamental mode Gunn at 100 GHz is 200 mW [13]. When operated in a second harmonic mode, power levels of 3.5 mW at over 200 GHz, and 1 mW at 300 GHz have been achieved [14]. Junction temperature of these devices is a reliability concern which potentially complicates thermal designs for space applications. Recent developments at U. Michigan fabricate InP Gunn devices on diamond heat sinks for thermal management [15].
3. Tunnel-injection transit time (TUNNETT) diodes offer power comparable to Gunn devices below 300 GHz, but are relatively new, and are not obviously better than Gunns for space use [15].

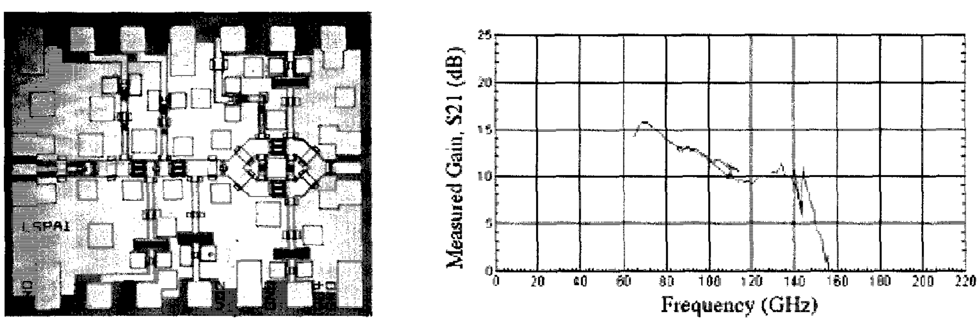

Figure 3. A JPL/HRL collaboration has produced a 65-145 GHz bandwidth InP HEMT MMIC amplifier with over 10 dB gain. This three stage transistor amplifier with coplanar waveguide interconnections exhibits at least 9 dB of gain over 80 GHz of bandwidth and spans three waveguide bands.

Other types of oscillators are available, such as backward wave oscillators (BWOs) and silicon IMPATT diodes. IMPATTs have sourced 7.5 mW at 285 GHz with efficiency in the 0.35% range, and until recently, were the highest power fundamental solid-state source above 300 GHz (superceded by InP Gunns [15]) [16]. Although they have been the only fundamental solid-state device so far to produce CW power at these levels, the IMPATT diode operates at relatively high junction temperatures (300° C), presenting reliability and lifetime concerns. In addition, the avalanche process makes them relatively noisy and therefore not well suited for use in sensitive receivers. BWOs are very useful laboratory sources of high frequency tunable power, but require bulky, heavy, and power-hungry high-voltage power supplies, and often require water-cooling. Most often Russian-made, they are excellent laboratory sources but unsuitable for space flight. Other tube and travelling-wave oscillators offer performance inferior to the best BWOs [17].

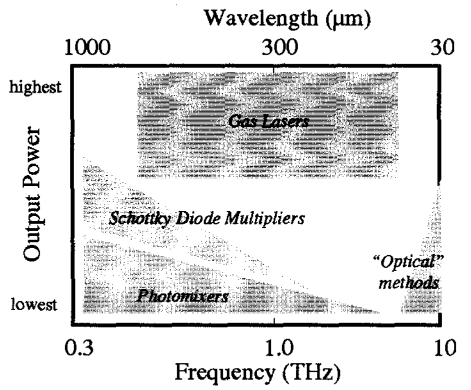

Figure 4. FIR source niches as related to output power and frequency.

Varactor Multipliers

For space flight use in sensitive receiver applications, the aforementioned fundamental sources commonly drive passive Schottky diode harmonic varactor multipliers. Figure 4 above shows how these varactor multipliers compare with other generators of FIR power. All will be discussed below. Doublers and triplers are combined to give on the order of x2x2x3 multiplication to provide 1 THz signals. This technique allows for space qualifiable components with low mass and low power consumption. They are not easily tunable on a spacecraft, as load impedance variations require complex backshort, E-plane, and/or H-plane tuning configurations. This limits their operation generally to only one frequency (or a narrow band).

The key advantages of multipliers are low input power and proven reliability. The drawbacks are the low output power levels, narrow fractional bandwidth, and the complexity of a complete LO system, due to the tuning and large number of components required for generating radiation above 1 THz. At present, it is difficult to envision that this approach is easily adaptable for pumping arrays of heterodyne mixers since a full multiplier chain must be matched to each array element.

The highest frequency demonstrated to date with Schottky multipliers was 1.5 THz with a BWO-pumped tripler, generating approximately 15 μW [18]. The highest frequency with an *all-solid-state* source was 1 THz, generating approximately 100 μW using a cascade of whisker-contacted varactor triplers [19]. This chain approach is the baseline technology for the local oscillators for FIRST. Hence, this approach is being intensively pursued at JPL and other institutions.

Phase Lock Circuitry

As seen in Figure 5, the phase lock circuitry for simple Gunn oscillators is not trivial, and can consume a great deal of effort as one attempts to make it temperature-stable and reliable. In this application, a 10 GHz dielectric resonator oscillator (DRO) is locked to a 5 MHz reference signal sent from the spacecraft. This 107 GHz Gunn oscillator is then locked to the DRO. For FIR operation, the Gunn output would be multiplied in frequency to a higher harmonic by a passive Schottky diode device.

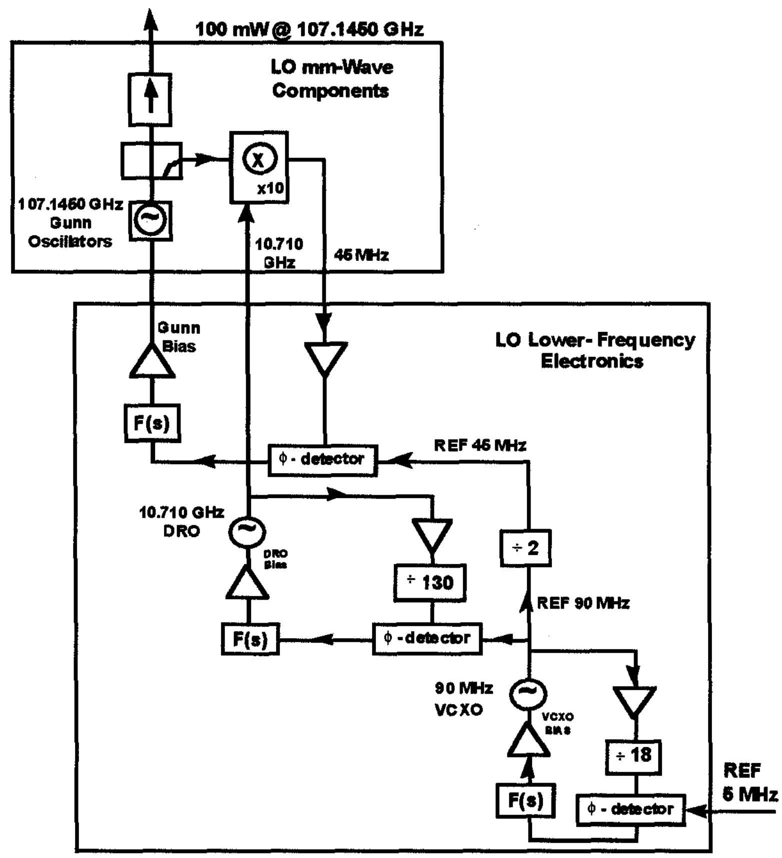

Figure 5. Block diagram of the 107 GHz phase-locked oscillator for EOS-MLS.

<u>Photonic Approaches for LO Sources above 1 THz</u>

Generation of radiation in the 1 to 3 THz region with an all solid-state source has proven difficult and remains a challenge. One finds that transit time limits the frequency response of most electronic sources, and only with deep submicron technology can one realistically bring such devices into the terahertz regime. Therefore, one finds the most promising approaches involve photonics. Several approaches have been tried, with mixed success.

The first approach consists of optically pumping a photoconductor having a very short carrier lifetime. Most common is to take advantage of the unique material properties of low-temperature-grown (LTG) GaAs: high breakdown field (greater than 10^5 V cm^{-1}), semi-insulating behavior (_as high as 10^7 Ω cm), short lifetime (approaching 100 femtoseconds), relatively high "transient" mobility (μ near 150 cm^2/V sec), and ease of integration with other III-V devices [20]. One generally places such material in an interdigitated-finger configuration, with connections to a FIR antenna [21], although travelling-wave structures are being used for more efficient power distribution [22]. By illuminating the photoconductor with two interfering, frequency offset, near-IR lasers, one modulates the device resistance at the beat frequency, and generates an RF current to drive the antenna. This approach to generation of THz wave has been coined optical-heterodyne mixing, or, more commonly, photomixing, and is particularly attractive for its very large tuning range. The reported power levels from such photomixer range from approximately 1 μW at 1 THz to of order 100 nW near 3 THz. Terahertz linewidths of less than 1 MHz have been demonstrated with the use of tunable cavity-locked diode laser sources using Pound-Drever-Hall techniques [23]. Potential exists for sub-100 kHz linewidth if optimized lasers are used. Other frequency-stabilization schemes are also of interest, such as the coupled optoelectric oscillator (COEO) and dual-mode lasers, which offer the potential of a simpler source and much narrower linewidths [24].

Above 3 THz, completely optical approaches presently become more attractive than the photomixer approach. Considering *solid-state* sources, nonlinear optical approaches have received the most attention [25]. Typically, a crystal with large second order nonlinear coefficient, _$^{(2)}$, is used to mix two frequency-offset near-IR lasers or to parametrically scatter incident laser photons. There has been some generation of

FIR power, but output powers achieved have been very low (~nW), predominantly due to the small of the crystal at the very long wavelength. Some interesting new crystals are being explored, with orders of magnitude increase in _(2) [26]. To complicate matters further, difficulties in phase-matching over a sufficiently long distance in the crystal exist because optical pump beams and THz waves travel at different velocities. This severely limits the size of the active volume and, consequently, the power-handling capability. More recently, quasi-phase matching (QPM) techniques have been pioneered where _(2) periodically reverses spatially in order to avoid spatial separation of the two waves. This has shown success at the expense of reducing the tunability of the setup. Finally, quantum limits (e.g., the Manley-Rowe relation) also place disheartening limits on the maximum efficiency of such devices at typically less than 0.1%, limiting their practical use as low-power spaceborne sources.

As seen in the discussion above, the most advanced solid-state photonic sources presently offer little more than Schottky-based multiplier chains. The one alternative most successful laboratories (and one at least one future spacecraft) are forced to use is the optically-pumped FIR molecular gas laser. Here, vibrational transitions of molecules are excited by a pump laser, and the resulting population inversion leads to lasing at specific frequencies throughout the entire FIR spectral region [27]. Through proper choice of FIR lasing gas, one can usually find a laser line within a typical IF frequency of the signal frequency, and with sufficient FIR output power (>10 mW is often achievable with simple laser systems). Although the lasers are typically the heaviest and largest component of any radiometer, new developments such as sealed-off, RF-excited CO_2 pump lasers have greatly increased the usability of such systems. Through DeMaria Electro-Optic Systems (DEOS), NASA is presently developing a CO_2 - pumped methanol laser for use in the EOS-MLS spacecraft instrument at 2.5 THz [28]. An engineering-model version of this laser demonstrated output power of more than 20 mW at 2.5 THz, with approximately 140 W of plug power, a mass of 20 kg, and volume of 30 cm x 10 cm x 75 cm. Lifetime requirements of the spacecraft will force the developers to seal the methanol cavity (allowing yet for piezo-electric tuning of mirrors to set proper cavity length) adequately for 5 year operation.

The gas laser technology can be extended somewhat, by integrating sideband generators for some tunability [29]. Most success has been through using a Schottky diode (suitable for mixing) to combine the gas laser carrier signal with a microwave input. Such systems have found practical use in FIR radar system [30], but are not expected to source more than 100 μW in the THz frequency region. Note that the microwave signals can be of frequency greater than 100 GHz, giving significant frequency agility to these gas laser-based sources.

Future Technologies for Local Oscillators

In order to evaluate the relative merits of the above listed technologies it is important to make a distinction between short-term opportunities and long-term possibilities. Schottky-based multipliers and FIR gas lasers are practical for frequencies well into the THz range, but their drawbacks severely limit the number and types of space missions that can be proposed which target the FIR region. The drawbacks of undesirable complexity, size, mass, reliability, frequency tunability and bandwidth, input power, and FIR output power all need to be addressed in future work developing FIR oscillators. Here, we discuss some of the interesting technologies being investigated for the future.

In the lower-frequency regime, we see the advent of submillimeter semiconductor amplifier technology. Several companies in collaboration with JPL have been fabricating FET amplifiers in the range of 200 GHz and above [31]. As commercial and scientific interests pursue higher frequency applications, the drive will exist to push existing technology from 0.1 micron gate-length InP HEMT technology (on 50 μm-thick InP substrates) to even smaller gate lengths and thinner substrates – making 300 GHz technology possible. In addition, heterojunction bipolar transistor technology has moved to a higher level with the advancement of flip-chip backside processing technology, whereby both emitters *and* collectors can be fabricated to submicron dimensions, enabling transistors with a maximum frequency of oscillation in excess of 1 THz [32]. Although the techniques are experimental, current projections place submillimeter amplifier technology with these devices on a 2-3 year time scale.

Improving the output power, bandwidth, and reliability while reducing the complexity of multiplier chains is key to most of the present work on such devices. One of the most difficult aspects in the design of harmonic multipliers is properly terminating the unwanted harmonics, so one obtains the maximum power at the desired frequency. Using varactors with antisymmetric capacitance vs. voltage characteristic, such as heterostructure barrier varactors (HBVs), will ensure that only odd-order harmonics are produced [33]. This relatively uncomplicated method of eliminating even harmonics in the production of a x3 multiplier may lead to higher efficiency devices.

Operation at the high frequencies of the FIR requires great care in minimizing parasitic resistance and capacitance in the Schottky diode elements. While proven useful for spaceborne use, the whisker-contacting method is frowned upon for its sensitivity to thermal and vibrational stress, and complexity in assembly. The advent of submicron photolithographic techniques has enabled the planar Schottky element to capture the community's attention. Figure 6 compares the technique of whisker contacting with modern planar lithographic technology. Shown in Figure 7, advances in planar GaAs diode fabrication technology at JPL include "substrateless" GaAs diodes and matching circuits and "MOMEDs" (MOnolithic MEmbrane Devices) [34]. These new technologies allow for higher levels of integration including matching circuits and arrays of devices on a single chip, which enable higher frequencies of operation and higher input power handling. Currently, a 400 GHz, substrateless, balanced doubler exhibits 15% efficiency and 5 mW output power.

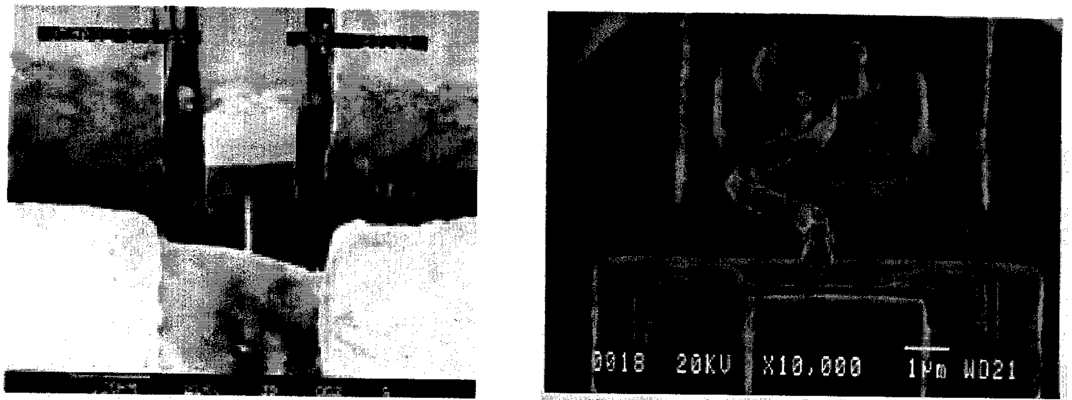

Figure 6. Left: UVa point-contact GaAs Schottky diode for 200 GHz mounted in metallic waveguide mixer block for the UARS MLS instrument (1986). Right: SEM of JPL submicron T-gate style Schottky anode for the EOS MLS 2.5 THz receiver (1998).

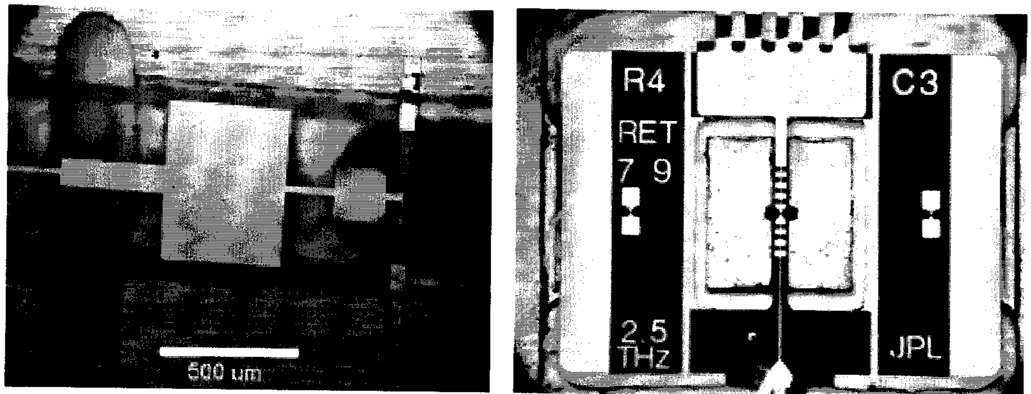

Figure 7. Left: Substrateless multiplier, with input and output waveguides visible. The metal regions are supported only by a thin GaAs frame around the edges. Right: A MOMED mixer mounted in the mixer block. The mixer diode is positioned in the middle of the 50 µm x 100 µm waveguide (the dark rectangle in the center of the picture).

In the higher-frequency regime (above 1 THz), the greatest drawback of solid-state sources is insufficient FIR power output. However, the future prospects of photomixers appear promising for several reasons. To date, the RF design of these devices has either been neglected or treated only superficially. Large improvements in performance are expected with more attention to the device layout. This is convincingly demonstrated by the recent success of the traveling-wave photomixer, which resulted in an increase of output power, by an order of magnitude at 2.5 THz [23]. Better antenna designs may further improve this power by another factor of ten. The difficulty in realizing such improvements is the requirement for expertise in both the optical as well as in the microwave field, and innovations are required in both domains. It is therefore commonly concluded that the resulting system complexity is too great. Rapid advances in the laser field, such as accurate tuning of semiconductor lasers using microwave sources and fiber optic-based optical amplifiers, make a compact driving source possible [24]. Further, significant work on improving photoconductive materials has taken place in the last few years and alternatives to the conventionally available low-temperature GaAs are now available [35]. The surge in activity and interest is largely due to a realization of the potential benefits of a photomixer-based frequency source: Assuming performance predictions come to fruition, the significant advantages of this technology are tunability, room-temperature operation and integration into arrays.

Electronically or optically pumped quantum-well structures are attracting much attention, after the great success of the quantum-cascade laser in the mid-IR [36]. Transitions induced between subbands in the same well or between adjacent wells result in the emission of photons having an energy equivalent to the energy difference between the states. Extension of the same principle to shorter wavelengths is, however, nontrivial. The internal quantum efficiency of the lasers becomes smaller for longer wavelengths since the spontaneous emission rate increases. In addition, the smaller energy level spacing would require cryogenic cooling for operation and narrow linewidth emission.

Numerous other solid-state sources based on more exotic physical mechanisms are in early stages of development. At present, such sources offer THz power only with very significant restrictions in operating conditions or, very low power levels, and/or inadequate linewidth. For further information, refer to the noted references for the following devices:

1) p-Ge lasers, which utilize transitions induced between the heavy-hole and light-hole branches in the valence band [37]
2) negative-effective-mass in very small semiconductor structures [38]
3) Bloch oscillations, coherent tunneling through superlattice structures [39]
4) resonant tunnel diodes [40]
5) the Smith-Purcell effect, which utilizes the radiation from relativistic electron beams moving across, and just above, the surface of a diffraction grating [41].

Space Flight Qualification

Lifting a radiometer into space is no easy task. The complexity and cost of such systems can easily be an order of magnitude larger than similar systems built for ground use. There must be a strong science driver and a friendly political climate to enable such missions. When given the necessary endorsement and funding, one must then take into account the need for

- instrument immunity to launch vibration
- survival in the harsh radiation/space environment
- adequate testing, given the improbability of repairs in space (including vacuum testing)
- adequate thermal simulation and testing to ensure success in the widely variable conditions of space
- lightweight, low-power, and compact/deployable components
- precise, careful engineering to ensure the best instrument performance (justifying the cost of launch)
- reliability and lifetime analyses and tests
- cleanliness
- immunity to electromagnetic interference
- careful prevention of electrostatic discharge damage to sensitive components
- materials choices (low outgassing, minimal mechanical stress in optics,...)
- quality assurance, configuration control, documentation.

Although it is possible to create a low noise terahertz receiver in the laboratory, a serious challenge exists in making it robust enough for practical use. Most of the FIR sources mentioned above are relatively immune to launch vibration, as their small mass places resonant frequencies high above the few-hundred Hertz typical of launch vehicles. Schottky diodes are known to be relatively immune to total-dose effects resulting from the deposition of ionizing energy, but other devices now being introduced may suffer more from their use of minority carriers or nano-scale features [42]. To ensure radiometer lifetimes in excess of common 2-to-10 year mission durations, accelerated lifetests with fit to Arrhenius-lognormal or electromigration models are necessary. This is of particular importance with novel device designs and their high current densities.

Summary

While very few space missions have applied heterodyne FIR technology, it is quite clear that its utilization is of utmost importance in many fields of science. In perhaps the most relevant application to human day-to-day life, FIR radiometers can effectively monitor the atmospheric chemistry that results in the ozone hole. With such knowledge, one hopes to prevent widespread cases of skin cancer without bankrupting nations. FIR technology is of similar importance to astronomers, who hope to understand the evolution of the universe by making use of the vast number of FIR photons in space. The molecular excitation energies prevalent in the FIR make this spectral region important in the detection of life – in our solar system, or on planets orbiting distant stars. Many breakthrough discoveries in these fields can reasonably be expected, but are being hindered by a lack of FIR technology. Arguably, the most deficient link in the technology needed to create useful instruments is the generation of FIR radiation.

The development of far-infrared technology to be on a level similar to microwave or infrared technology is critical. With numerous commercial and biomedical ("T-Ray") applications becoming apparent, this field is already expanding at a very rapid pace.

Acknowledgements

We would like to acknowledge the many valuable contributions of the following people: W.R. McGrath, P.H. Siegel, J.W. Waters, and the continuing contributions of the Submillimeter Wave Advanced

Technology team at JPL. This work is performed at the California Institute of Technology, Jet Propulsion Laboratory, under contract with the NASA's Office of Advanced Concepts and Technology.

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