Photomixer Systems as Submillimeter Oscillators and Coherent Test Sources

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ABSTRACT

The development of widely tunable coherent frequency sources for application as local oscillators or simply as test equipment above 1 THz remains an impediment in receiver development and characterization. Photomixer sources have demonstrated sufficient power to pump SIS mixers to over 600 GHz and have demonstrated over 2.5 THz of bandwidth in a single device. First generation photomixer system solved the problem of frequency calibration, but failed to fully address the needed spectral purity required for heterodyne applications. A number of improved laser technologies are greatly simplifying the implementation and improving the spectral purity of photomixer systems, however a full system demonstration in the THz frequency range remains elusive. The current state of the art for photomixer based sources is explored in light of heterodyne local oscillator and coherent tests sources for antenna and component characterization at THz frequencies.

Keywords: Heterodyne, Receiver, Local Oscillator, Submillimeter, Frequency Synthesis, THz, Photomixer, difference frequency

1. INTRODUCTION

The frequency region above 1 THz and below 10 THz remains an enormous technical challenge to conventional electronics and quantum electronics. Resistance due to ohmic losses in skin effect resistance and radiation, inductance due to distributions of the current paths and parasitic capacitance from the physical size of the device combine to limit the high frequency performance of conventional electronics, while quantum electronics are limited by the maximum size and uniformity of the quantum structure that can be produced. As a result, both approaches have been tried with minimal success in the THz regime. Photomixing or difference frequency generation facilitates the use of traditional higher frequency quantum electronics as the sources and limits the "conventional" electronics to a single photomixer device, which produces and radiates the difference or beat frequency of the two signals. The photomixing approach has several very beneficial aspects for systems design. First, the bandwidth is determined by the quantum electronics at higher frequency and is directly down converted into the THz regime. As a result a 1% bandwidth in a semiconductor laser can translate to several octaves in the THz. Second, the overall system does not necessarily require any cryogenics although cold operation can alleviate some potential thermal problems in the photomixers.

The THz region of the electromagnetic spectrum provides a window into a number of important chemical processes and allows for much higher resolution imaging than at microwave or millimeter wave frequencies. The rotational transitions of light molecules like water dominate the THz region of the spectrum. However, the THz region of the spectrum also contains most of the fundamental vibrational modes of larger molecules and is the time scale of most chemical processes. For astrophysics the THz region of the spectrum offers the best window into the Universe of any wavelength, because the peak of the power spectrum is in the THz and the minimum in our local background is also in the THz. Unfortunately for THz technology, the water in our atmosphere makes almost the entire THz region opaque from the surface of the earth. Current applications of THz systems include atmospheric chemistry[1], astrophysics[2,3] and spectroscopy[4,5]. Experiments have shown that THz systems could be useful in medical imaging, defending against chemical or biological attack and secure short-range communications. Ultimately our push to achieve large bandwidth communication systems and faster electronics will result in an enormous amount of THz electronics. A major challenge

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is to develop the source components necessary to perform the spectroscopy required to understand fundamental device physics and test system response in the THz frequency range. THz technology available in the form of optics, mixers, detectors, but fundamental coherent sources remain the biggest problem and without a source it is very difficult to perform any kind of coherent spectroscopic investigation.

2. SOURCE REQUIREMENTS

Coherent spectroscopic systems can either be heterodyne systems where a source is used to drive a mixer, which down converts an emitted signal to a frequency where conventional spectrum analysis is possible or direct systems where a source is transmitted through and absorber and detected. More complicated network analysis is ultimately one of the two previous categories with more sources and/or detection elements. In heterodyne systems the power required from the local oscillator is highly dependent on the type of mixer used. Schottky mixers have good proven THz performance[6], however they typically require a few milliwatts of local oscillator power at room temperature and around a milliwatt when operated cryogenically. SIS mixers have proven performance to 1.27 THz[7] and require a local oscillator powers on the order of microwatts. Unfortunately the local oscillator power required in SIS mixers increases with frequency and junction size. It appears the cryogenic mixer of choice for the THz region is the hot electron bolometer mixer, which can either be cooled by electron diffusion of phonon coupling to the electrons. Diffusion cooled hot electron bolometer mixers require a local oscillator power[8] that scales as:

$$P_{LO} = 4L(T_c^2 - T^2)/R. \qquad (1)$$

Where L is the Lorentz constant and R the device resistance. Phonon cooled mixers require a local oscillator power proportional to the volume of the bolometer element. Less than 100nW absorbed in a phonon cooled device has been demonstrated[9]. If a THz heterodyne detection system is to be constructed the source must be able to drive the mixer, which translates to a power of 0.5-5 microwatts depending on the coupling details. If the source is going to be used as a signal to characterize a heterodyne system, the requirement is only to exceed the noise power of the mixer and background in the detection bandwidth. At 300K the background power per MHz of bandwidth is between 3.6×10^{-15}W and 1.56×10^{-13} W at 1 THz and 10THz, respectively and the noise is the square root of the power. The quantum limit is between 48 and 480 Kelvin, but the best HEB mixers are currently 5-10 times worse than the quantum limit. Assuming a 2000 K receiver temperature, the internal noise dominates the background in the 300K background in the THz and the effective power detection limits are raised by a factor of 10 in 1 second. Even so the detection limit is less than 10^{-12} watts anywhere in the THz, which means 1 nW of signal in a 1 MHz bandwidth provides greater than 1000 to 1 signal-to-noise in one second and is sufficient for evaluation of the receiver, its beam and a host of other test applications.

Direct systems offer a slightly different problem, because the detector bandwidth is generally quite large and must accept several THz of 300K radiation bandwidth. This noise power is converted into output noise, which is integrated over the output bandwidth.

$$P_n = \frac{2(kT)^{5/2}}{ch^{3/2}}(AB\Omega\cos\theta)^{1/2}\left[J_4(x_1) - J_4(x_2)\right]^{1/2}$$
$$J_4(x) = \int_0^x \frac{x^4 e^x}{(e^x - 1)^2}dx \qquad (2)$$
$$x = \frac{h\nu}{kT}$$

Here, k is Boltzmann's constant, T is the temperature, h is Plank's constant, c is the speed of light, ν is the frequency, A is the area of the detector, B is the output bandwidth, x_1 and x_2 represent the low and high frequency cut-off frequencies, θ is the angle of incidence on the detector and Ω is the observed solid angle. The effective aperture is given by:

$$A\Omega\cos\theta \approx \frac{\lambda^2}{2\pi}. \qquad (3)$$

Typical sensitivities of commercially available THz cryogenic detector systems result in 10pW being in a 1 to 1 signal to noise in 1 second and engineering a better detector and filter can reduce this to comparable or lower levels than needed in heterodyne systems. As a result, a source with a 10nW can easily generate >1000 to 1 signal-to-noise.

These power levels assume that our source is spectrally pure. Unfortunately this is easy to say, but never the case with a real source and there will be some spectral energy distribution and the signal will have both amplitude and phase modulated sidebands or wings. In the case of a balanced double sideband mixer, phase noise cancels to the level of the match between upper and lower sidebands. In an image rejection or single sideband mixer amplitude noise cancels to the level of the image rejection. Direct detection systems typically modulate the source in amplitude, phase or both and modulation schemes can be designed to minimize the effect of self-generated noise, but it is always lower noise to avoid producing excess internal noise. In heterodyne systems a general rule is for the local oscillator injected noise to be about 10% of the mixer noise in the IF band. This can be calculated from the mixer pump power relative to the detectable power, which is approximately –150dBc for and SIS mixer and –140dBc for an HEB mixer depending on the sensitivity. Additionally, it is necessary that the spectral power density of the local oscillator in each detection bandwidth from the carrier fall fast enough to not make ghosts of strong detected signals. For a 20dB dynamic range in adjacent channels in a 1 MHz detection bandwidth, the average spectral power density in the sideband would be –80dBc in the channel given by 0.5-1.5 MHz offsets. 20 dB dynamic range for adjacent channels is good for most available spectrometers and about 40 dB dynamic range is all that is needed for most sources at large offsets from the local oscillator carrier. The result is the average spectral power density would be –80dBc to –100dBc at offsets from the carrier to the bandwidth of the spectrometer. This is true for both double and single side band detection, but applies to AM and FM respectively.

The last consideration is frequency accuracy. For heterodyne detection the frequency knowledge and stability must be on the order of 10% of the detection channel spacing, which is typically on the order of 0.1 to a few MHz in THz receivers. Assuming 10% of a 1 MHz bandwidth in a 2 THz receiver the needed accuracy is 5 parts in 10^8. In direct detection systems the frequency accuracy is a function of the width of the absorption feature. For conventional molecular absorptions, the full width at half maximum is approximately 3 MHz at 2 THz. The line center can easily be determined to 5% or 150kHz, 1-2% or 30-60kHz if the baseline and line shape are fitted. This corresponds to an accuracy of a 1.5 to 3 parts in 10^8. If sub-Doppler techniques are used the line is 50kHz wide and the center can be determined to 5% or about 2 kHz, which translates to 1 part in 10^9. The stability of the source should once again be about 10% of the measurement accuracy. For a system used in THz component characterization, the frequency accuracy must be better than the detection channel width unless phase information is desired. If phase information is required, the signal must be somehow locked to the reference signal so phase does not accumulate.

Any practical system is required to meet the applicable specifications for its use. In the case of photomixer systems, these specifications pose several major technical challenges. First, a power level of a few microwatts at a few THz has not been achieved. Second, obtaining the required frequency accuracy is big challenge, because there is no direct lock to a known fundamental standard. Lastly, the spectral purity is a measurement challenge without a mixer characterized by another means and its achievability has only been partially demonstrated in one case[9]. In the subsequent sections, the status and lessons learned in trying to achieve these requirements are presented.

3. LASER SYSTEMS

The laser system is ultimately responsible for all of the specifications except achieving the THz power level, but even there the laser power is big consideration. The lasers are required to produce a difference frequency with the necessary spectral qualities. A simplifying aspect is two lasers don't have to be stable or known in frequency, they just have to track each other with the required accuracy and stability. The challenge is to know the difference frequency to the desired accuracy and for practical purposes a direct comparison with a known THz signal is impossible without a pumped cryogenic mixer. Such a system was implemented and potentially could prove useful in controlling phase if necessary[9]. In spite of the engineering challenges, very few attempts have been made to solve all the control problems associated with difference frequency generation. For CW applications most investigators have tried a two-laser scheme. The first attempt was in regard to SO2 spectra using two free-running dye lasers[10]. The instantaneous line width of the dye lasers was clearly less than the SO2 transitions, but about two MHz of jitter was observed. A later attempt used two external confocal cavities with a finesse of 110 and narrowed two free running DBR to approximately 50 kHz[11]. The other "two-laser" system is uses two modes of the same laser to generate the THz difference frequency[12]. Unfortunately none of these two laser schemes could determine the radiation frequency with anything close to the accuracy needed. A three-laser system was developed to facilitate calibration of the frequency through the use of an ultra low expansion etalon and a microwave offset lock. Figure 1a shows a three-laser system and figure 1b shows the coupling optics, amplification and photomixer when used for absorption spectroscopy[13].

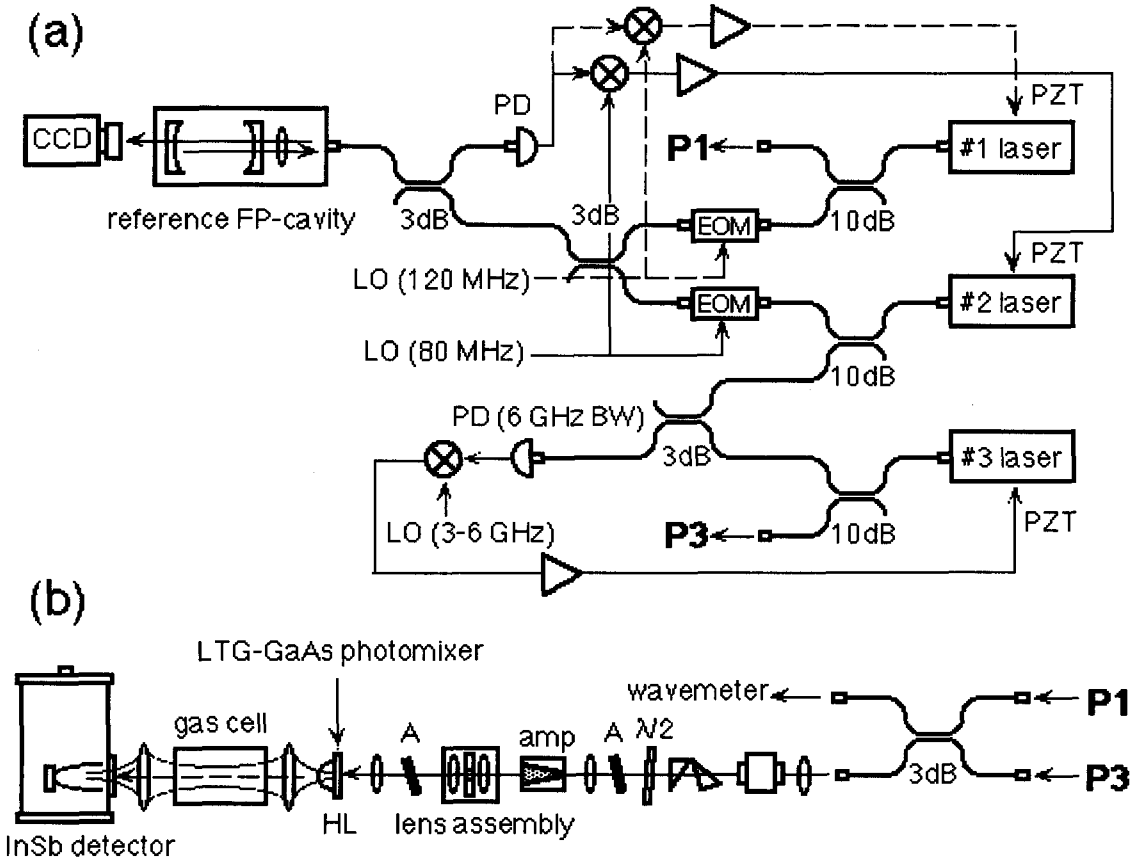

Figure 1a and 1b. A three-laser source for precise frequency control of the difference frequency used in THz generation by photomixing.

The three-laser system solves the frequency calibration problem by counting the order number of an accurately known free spectral range of the cavity and counting the microwave offset frequency. The lasers used were 850nm distributed-Bragg-Reflector (DBR) Lasers, which had a free running line width of 3 to 30 MHz depending on how well the current and temperature were optimized to a 27 GHz longitudinal mode. Electrical feed back was initially attempted, but it was discovered that the two modulation mechanism, bulk thermal 27 GHz/C and electron induced index changes 580 MHz/mA, had opposite phases with the former being 10 times a large in gain but with a 3dB point at about 100 kHz. As a result, there is no null in the modulation index, but there is a 180-degree phase shift at about 1 MHz, which is substantially less than the laser line width. The conclusion was to use optical feedback and an external cavity was constructed. Figure 2 shows the optical feedback configuration of the DBR. The full-width at half-maximum of the beat note obtained with the system was on the order of 1 MHz. The best frequency calibration was 3.5 parts in 10^8 from calibrating the cavity and typical calibration accuracy was 1 part in 10^7. During operation other beat signals would appear from time to time. It is believed that the lasers would emit on two or more of the external cavity modes and possible on two of their internal modes as well. While this is good enough for some laboratory spectroscopy studies of light molecules, the performance falls well short of what is ultimately needed for a workhorse system.

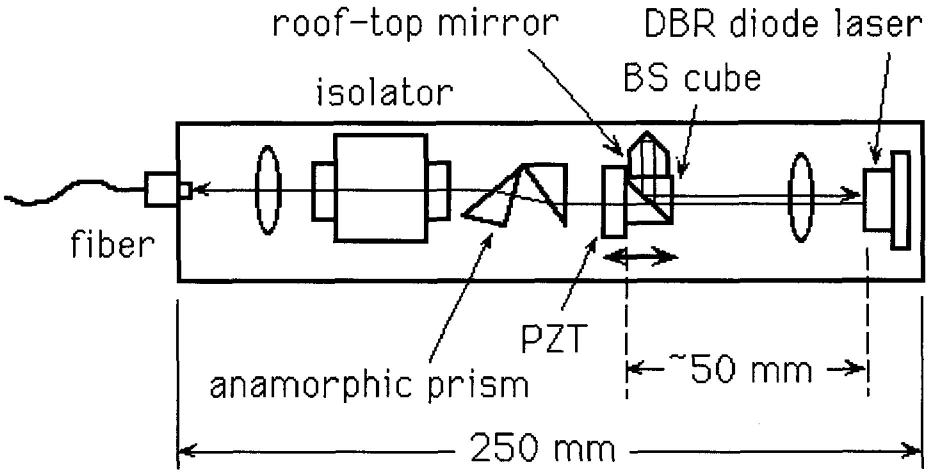

Figure 2. Feedback for the DBR laser in the three-laser system.

Ultimately the three-laser system or any two-laser system will need to perform substantially better in terms of spectral purity and frequency accuracy. There are several potential improvements that can be made. The most important is the phase shift associated with the optical feedback. A completely cavity external cavity has a 90-degree phase shift at the half maximum intensity point, the cavity used for the DBR's also has a 90-degree phase shift at the half maximum point, which is approximately half the free spectral range. A comparison of the line widths between the two systems leads directly to the conclusion that the laser needs to have a external optical feedback mechanism, which has a very large phase shift associated with a small change in frequency. If this is the case, electrical feedback can be used to further narrow the line width. In general the lasers and optics at 1.5 or 1.3 microns are better behaved and less expensive than the 0.85-micron lasers and optics. As a result it is highly desirable to use these wavelengths if possible.

Another area for improvement or potential simplification of the three-laser system is the frequency determination scheme. Any calibrated system will require some form of etalon with a known free spectral range. The precision with which the free spectral range is known times the number of modes to the other laser is away gives the frequency accuracy. The approach taken in the first attempt at a three-laser system was to fix the free spectral range and try to protect against change. A more accurate fix would be to count the frequency offset from a known atomic or molecular line to the nearest cavity mode. For an 850nm laser this could work by measuring the frequency difference between the ULE etalon mode and the Cs D-line at 351 THz. The difference in the observed Cs line frequency from the previous calibration of the free spectral range divided by the number of free spectral ranges (more than 10^5 for a 3 GHz free spectral range) gives the calibration shift. This coupled with an approximately 10^8 initial knowledge of the FSR will allow for statistics to improve the accuracy and for small changes to be "re-calibrate" on the fly. A better approach, which could be used with a two-laser system and a tunable etalon, employs a double modulation including an adjustable frequency tuned and measured to the free spectral range of the etalon. Observations are made at the sum or difference of the two modulations. Once the free spectral range frequency is applied a null signal is observed regardless of any DC offsets in the lock loops[14]. This technique has been used to observe frequency dependent dispersion in optical coatings and is accurate to the level of a part in 10^{10} or better than any projected local oscillator need[15]. This could work with a two or three laser system, but the two-laser system would require the cavity to be tuned during the measurements. For heterodyne applications the two laser system could be discrete frequencies and not tunable as well.

4. PHOTOMIXERS

The performance of the photomixer itself is the other major technical challenge. The promise of photomixing comes from optical heterodyne theory where the output power can be shown to be[16]:

$$P_{out} = \frac{R}{2}\eta_1\lambda_1\eta_2\lambda_2\left(\frac{e}{hc}\right)^2 \frac{P_1P_2}{\left[1+(\omega_3\tau)^2\right]\cdot\left[1+(\omega_3 RC)^2\right]}, \qquad (4)$$

where λ_1 and λ_2 are the wavelengths of the two pump lasers, P_1 and P_2 are the pump powers η_1 and η_2 are the external quantum efficiencies, ω_3 is the difference frequency , τ is the photo carrier lifetime, R is the differential resistance of the THz load and C is the photomixer capacitance. Unfortunately, equation 4 is only valid if the photomixer has much higher source impedance than R and is in the small signal limit. In low-temperature-grown (LTG) GaAs several effects are known to occur first τ increases with high bias voltage[17] or high excitation fields[18]. This is now known to be due to saturation of available traps. Studies of the large field effects in LTG GaAs gave an output power that scaled as the input power to the 1.7 or 1.8[19] rather than the expected 2. The photocurrent was observed to be linear at a fixed laser power for bias voltages below 10 V and quadratic above 10 V with the power being proportional to the square of the bias voltage and saturation with bias was seen in all devices[19]. This effect is presumably due to velocity saturation similar to Schottky diodes. Additionally it was noted that the thermal conductivity of LTG GaAs was substantially worse than regular GaAs, with the shortest lifetime material being the worst thermal conductors[20] and that devices were subject to thermal failure and performed substantially better cold[21].

The approach to improving the existing LTG GaAs photomixers is two fold, first the thermal performance and quantum efficiency of the device could be improve and second a device could be designed to reduce the laser power density or better match the source impedance. To increase power handling photomixers were fabricated on Si[22], with ErAs islands[23] and with AlAs reflective layers[19]. Unfortunately all these only resulted in a maximum laser power of ~120mW and sub microwatt output powers at 1 THz. The first piece of the second approach was the design of a traveling wave photomixer where the power could be distributed over a large area[24]. Figure 2 shows an angle tuned traveling wave photomixer. In the traveling wave device a significant loss was discovered due to the propagation of the THz signal over the relatively thick substrate. Two other studies explored de-imbedding the photomixer impedance from the microwave circuit[25,26].

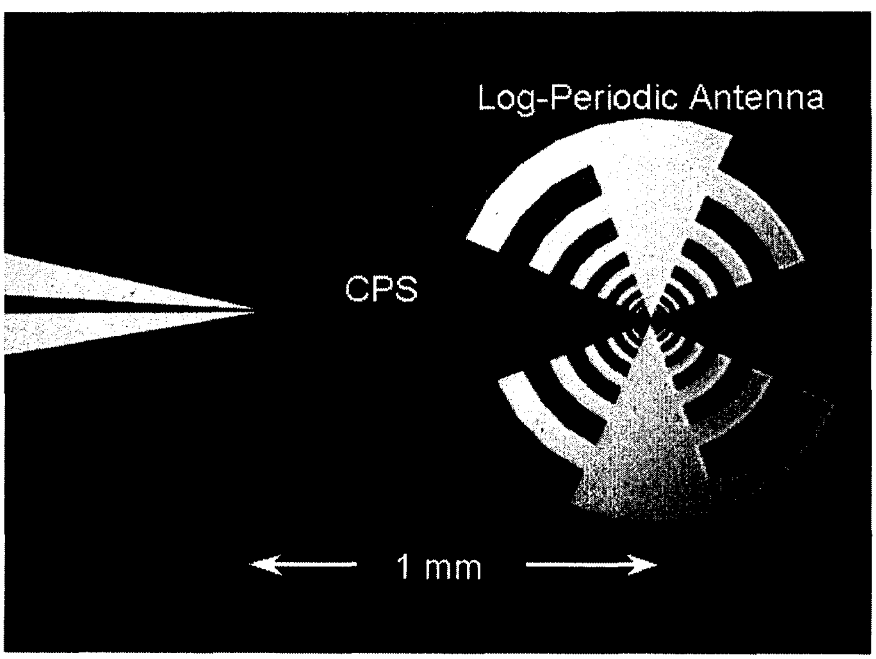

Figure 2 Angle tuned traveling wave photomixer with log-periodic antenna.

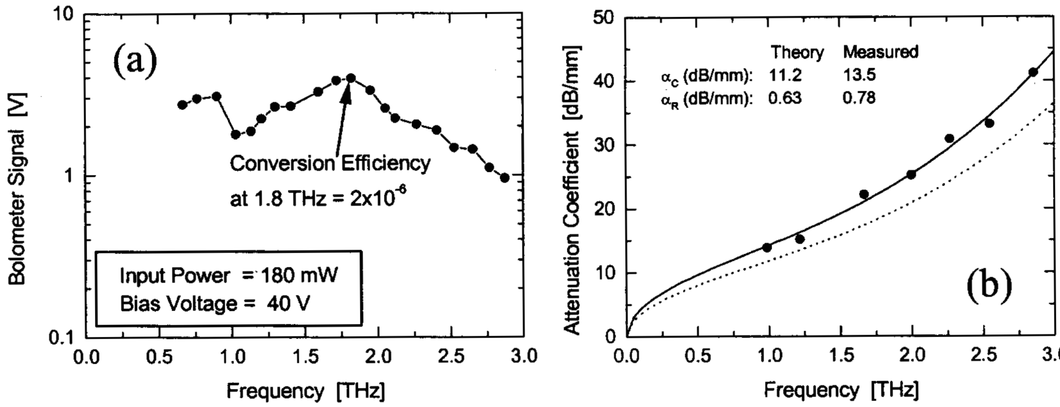

Figure 3. Output power in Volts on a Bolometer (1V is approximately 100nW) and loss as a function of position of the illumination in the stripline: loss is proportional to $\alpha_c\sqrt{f} + \alpha_r f^3$. This power is clearly enough for direct detection systems and test sources and is marginal at best for heterodyne local oscillators, but is clearly within a factor of a few of what is needed.

At high frequencies, equation 4 reduces to:

$$P \propto \frac{P_1 P_2}{\omega^4 R C^2} \qquad (5)$$

Which means that larger devices and proportionately larger capacitance and have no net performance gain. The important engineering steps are to design the device to minimize loss and maximize optical coupling. The design shown in figure 4 has a traveling wave photomixer in a self-compensating angle-matching mount. The drawing in the center is for an array of dipole antennas without a substrate. Removal of substrates reduces stripline losses and eliminates the possibility of launching modes into the substrate.

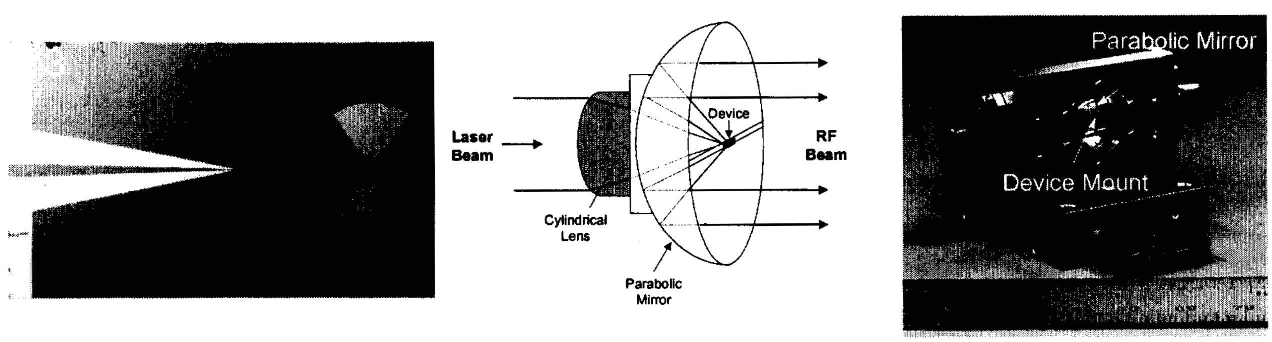

Figure 4 showing RF designs for high performance THz photomixers and self-phase matching mount for the two laser frequencies.

Another photomixer development is the use of InP based materials. The best of these devices the Uni-Traveling-Carrier Photodiode has managed to generate 0.5mW in W-band[27]. Efficiency as high as 1.8% in W-band has been generated[28]. Performance at low levels has been observed to 625 GHz[29]. The InP material system will have the same problems and limitations as GaAs, InP has a higher electron mobility and will probably ultimately yield better THz devices, however all the device engineering applied to LTG GaAs will need to be applied to InP as well. The advantage is that there is much better laser and optics technology at 1.5 microns where InP based materials absorb, which will make system design much easier.

5. CONCLUSIONS

Photomixing is still a promising approach to cover the THz frequency band, but a number of engineering tasks must be completed. First a very short recombination lifetime InP material must be developed. It will need to be engineered to have enough traps and high avalanche breakdown voltage. Second, a laser system with the necessary spectral purity and frequency accuracy must be constructed at 1.5 microns. Third, the InP material must be engineered into a device that maximizes thermal management and minimizes THz losses. Of these tasks only the InP material is a big step, but given the photodiode results it is very promising. Regardless the LTG GaAs material is good enough for many applications in test and measurement equipment if a few minor steps are taken to improve the existing laser concepts.

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