POWER AND SPATIAL MODE MEASUREMENTS OF A SIDEBAND GENERATOR SUBMILLIMETER-WAVE SOURCE

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Abstract

Coherent, black-body-referenced measurements of submillimeter-wave sideband generator (SBG) output power are reported here. This SBG utilizes a submillimeter-wave laser, microwave synthesizer, and high frequency Schottky diode to produce tunable radiation. An output power 10.5 μW at a drive frequency of 1.6 THz has been obtained, and SBG radiation was efficiently separated from the laser driver with Si etalons. The power measurements were made using a dual CO_2-Submillimeter-wave laser system and two Schottky diodes, one as the sideband generator and one as the coherent receiver. The SBG efficiency of four different models of University of Virginia (UVa) diodes were studied and the output mode of the sideband (without the unshifted laser present) was also easured. Finally, the design of a single-sideband submillimeter-wave receiver is presented.

I - Introduction

Tunable sources of submillimeter-wave radiation are rare. The most common source uses a high-temperature blackbody coupled with a Fourier Transform Spectrometer to effectively simulate a tunable source.[1] While such a system can have wide bandwidth, the output power is very small in the submillimeter (on the order of 1 nW per wavenumber of bandwidth[2]) and the practical resolution is limited by the instrument size and maximum allowable time for a scan.

The desire for a narrow-band, tunable source, has prompted the development of a number of other techniques. One approach is the free electron laser (FEL). In a FEL, electrons are first sent through an accelerator and then through a series of magnets to cause the electrons to undulate. The resulting emitted radiation is coherently reinforced thus producing a coherent beam whose frequency can be tuned. While FEL's have very impressive tuning bandwidths, they also suffer from great complexity, emission at higher harmonics, and rms frequency instability of at least 0.05%.[3] Another technique involves the mixing of two CO_2 lasers in a MIM diode.[4] This method has been shown to produce roughly 200 nW of power and some tuning flexibility, $\sim\pm120$ MHz about each selected CO_2 line. Further tuning range has been achieved, at the expense of roughly a factor of three in output power, by adding a microwave source to the mixing scheme.[5] Recently a method involving the mixing of two near IR lasers in a device fabricated from LT GaAs, photomixing, has demonstrated promising results.[6]

In the technique utilized in the present work, the SBG, a submillimeter laser is mixed with a microwave source in a Schottky diode. This was first demonstrated in 1978 by D. D. Bicanic et. al.[7] and H. R. Fetterman et. al.[8, 9] and has subsequently been achieved by a number of other groups.[10, 11] Several review articles have been published on SBG's in recent years.[11 - 14]

The sidebands produced in this manner are radiated from the coupling antenna and typically separated from the unshifted laser using a diplexer. The achieved separation efficiency usually results in a beam with the sideband power roughly 20 dB below the unshifted laser.[15] In the current work we have employed two silicon reflection etalons to improve separation. In the resulting beam the sideband is 20 dB above the unshifted laser, a 40 dB improvement.[34] This allowed examination of the spatial beam profile through conventional mode scans with an apertured incoherent detector. Spatial aperture techniques combined with careful optical adjustment yielded a reasonably pure spatial mode.

The remainder of this paper will describe results in separate sections: II - Coupling the Laser to the Diode; III - Coherent Measurement of the Sideband Power; IV - Sideband Separation and Spatial Mode Performance; V - Single-Sideband Submillimeter-Wave Receiver; VI - Summary and Conclusions.

II - Coupling the Laser to the Diode

In order to make the most efficient use of available laser power one must optimize the coupling of the laser mode to the antenna pattern of the corner-reflector-mounted diode. Several papers have been published on this topic[16 - 18] and scaled model experiments have been performed.[8, 19] Based on these results we decided, as have other groups,[20] to have the bottom face tilted away thus resulting in a 4 λ antenna mounted in a dihedral, instead of a "cats eye" corner-cube. Tilting of the bottom face of the mount by 19° resulted in a 9 dB decrease in backreflected laser radiation and no observed degradation in receiver noise temperature. The above results were measured with a bolometer and a beamsplitter in the former case, and by performing noise temperature measurements, with identical corner-reflectors with and without tilted bottom faces, in the latter case.

In the present study, coupling experiments were performed in order to confirm the optimal coupling parameters predicted by Grossman,[18] namely that the beam waist w_0 be 1.82 λ at the diode. In our experiments the size of a collimated Gaussian laser beam was varied and subsequently measured using a computer-controlled translation stage and an apertured LHe-cooled bolometer. The collimated beam then propagated to a 59.7 mm focal length off-axis parabolic reflector as the final optic before the diode. To determine which beam size was optimal, the Schottky's non-linear video responsivity was measured over a range of incident power levels between 1 and 10 mW for each tested configuration. This was necessary since these Schottky diodes are known to be non-linear video detectors above ~ 100 μW.[21] Assuming the paraxial wave equation to be correct for systems employing optics this fast,[22] and using the predicted waist size and location for an off-axis parabolic reflector focusing a Gaussian beam[23] (we cannot scan at the focus of the parabolic reflector due to spatial constraints), we have confirmed the optimal waist size at the diode

$$w_0 = 1.82\,\lambda, \tag{1}$$

for a 4 λ antenna mounted 1.2 λ from each face of a dihedral.[18] Further we have observed that this coupling is quite sensitive; a waist size of 2λ produces noticeably weaker diode response and waists smaller than that of condition (1) also result in significantly less response. As the predicted[23] waist size approaches λ, the correction terms to the paraxial equation become important, and thus our "assumed" waist at the diode is slightly too small.

III - Coherent Measurement of the Sideband Power

The apparatus for the sideband power measurement is shown in Figure 1. The submillimeter lasers are independent systems each pumped by a nominal 100 W, CW CO_2 laser. The LO and Drive lasers were running the 191.61960 μm laser line[24] in CH_3OH (1564.5187 GHz) and were tuned to operate roughly 3 MHz apart.

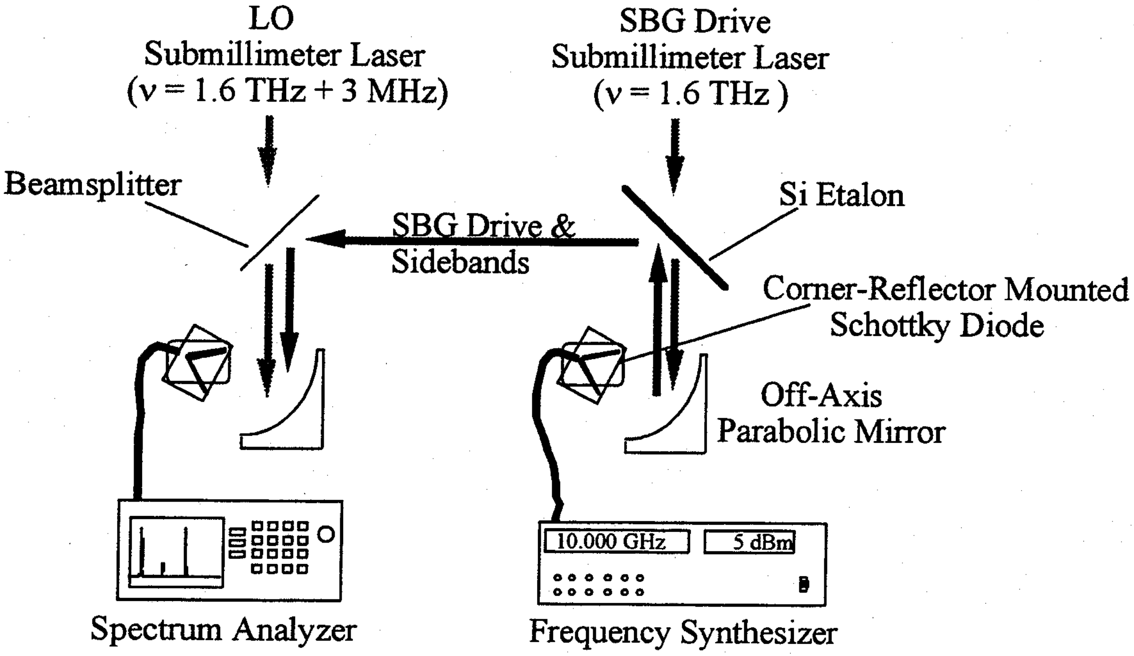

Figure 1: Apparatus used for sideband power measurements. Not included in the figure, is an amplifier placed between the receiver diode and the spectrum analyzer.

This separated the upper and lower sideband by 6 MHz and also served to separate the sidebands from any pick-up signal present at the microwave synthesizer frequency. Without this separation, signal at the synthesizer frequency picked-up by the receiver could be mistaken for sideband radiation. The synthesizer was operated at 10 GHz and provided ~ 5 dBm of microwave power at the diode. The Si etalon will be described in detail in the next section. Essentially, it transmits nearly 100% of the laser radiation while reflecting 80% of the sideband radiation. The 1 mil Mylar® beamsplitter has a reflectivity of 50% for s-polarized radiation at this wavelength.[25] The power of the LO was measured to be 5.5 mW and the Drive laser power was measured for each diode tested. The laser power data was obtained with a Keating Absolute Power Meter.[26] The receiver diode was a University of Virginia (UVa) model 1T17 and the SBG diode was one of the following: 1T7, 1T12, 1T17, 1T15.

In order to accurately measure the sideband power, it was necessary to measure the conversion loss of the receiver diode. This was done *in-situ* by placing a cold load and chopper in the beam path between the two Schottkys and performing measurements of the system noise temperature for different values of IF temperature. This procedure was performed 5 times in order to assure accuracy. With this data the conversion loss and mixer temperature can be determined from[27]

$$T_{sys} = T_M + L_c T_{IF} \qquad (2)$$

where T_{sys} is the system noise temperature, T_M is the mixer temperature, L_c is the conversion loss, and T_{IF} is the noise temperature of the IF electronics. Since the measurement was performed *in-situ* the conversion loss included the 3 dB contribution of the beamsplitter. The measured conversion loss was 17.3 dB which corresponds to a diode conversion loss of 14.3 dB. This fairly poor value of L_c is mostly due to the ~2.5 dB measured impedance mismatch at 10 GHz,[28] and to a lessor extent, the fact that 2.8 mW of LO power is not quite enough to optimize this receiver at 1.6 THz.

With the above information, the gain of the IF chain, and the fact that the etalon reflects 80% of the sideband, the power in the sideband can be determined by measuring the power at the IF. Namely,

$$P_{sideband} = P_{IF} - G_{IF} + L_c + 1\ dB_{(etalon\ loss)} \qquad (3)$$

where $P_{sideband}$ is the single sideband power in dBm, P_{IF} is the IF power in dBm, G_{IF} is the gain of the IF chain, and L_c is the conversion loss of the receiver. The IF power was measured with the spectrum analyzer set to a resolution bandwidth of 100 kHz and the amplitude accuracy of the spectrum analyzer was checked against two calibrated power meters. The accuracy of the P_{IF} readings is dominated by spectrum analyzer calibration error which is less than 0.5 dB.

A typical IF spectrum is presented in Figure 2. The resolution bandwidth was set to 30 kHz for this data to clearly resolve the mechanical-vibration-induced integrated-laser-linewidth. It is important to note that the noise floor shown in Figure 2 is the noise floor of the spectrum analyzer and not that of the receiver. The fairly weak pick-up signal from the microwave synthesizer is clearly seen in the figure and smaller peaks from other laser modes are also observed.

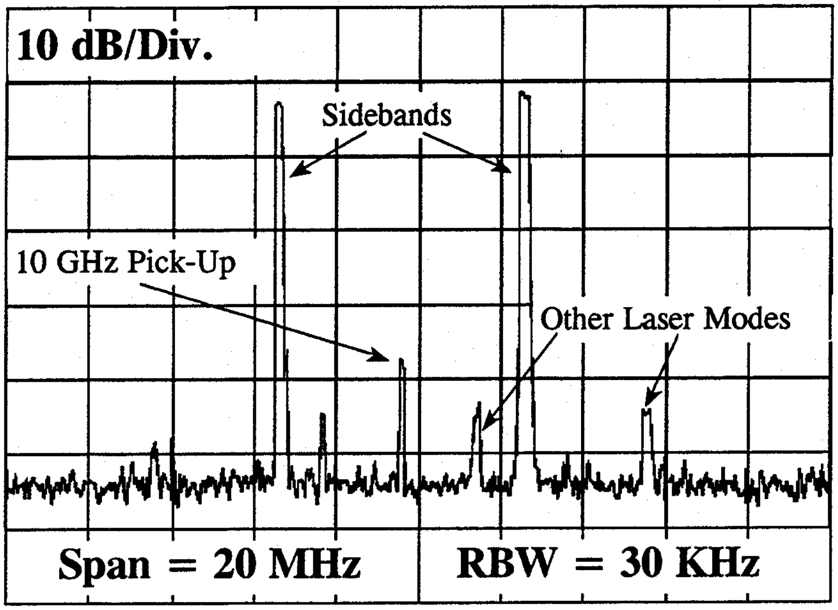

Figure 2: Typical IF spectrum. The pick-up signal is at the synthesizer frequency, and the upper and lower sidebands are separated by two times the difference frequency of the submillimeter lasers.

A summary of SBG diode performance is presented in Table 1. The Drive power was measured for each diode and then the SBG efficiency was calculated by dividing the single-sideband (SSB) power by the Drive laser power. Any error in the above measurement will only serve to underestimate the sideband power either through not coupling all of the sideband power into the receiver, or due to the fact that the IF exhibits ~100-150 kHz of jitter due to laser mirror vibrations. However, we believe that we are coupling the sideband into the receiver well and the IF jitter should be almost completely accounted for by the resolution bandwidth used in the power measurements.

Table 1

Respective sideband generator performance of four different models of Schottky diodes. The SBG efficiency is defined as the single-sideband power divided by the Drive laser power.

UVa Diode Model	SBG Efficiency	SSB Output Power
1T7	6×10^{-5}	0.6 μW
1T12	5×10^{-4}	6.6 μW
1T17	4×10^{-4}	4.2 μW
1T15	8×10^{-4}	10.5 μW

In examining Table 1 it is important to note that several contactings of the same diode can each lead to somewhat different performance. The results presented in Table 1 represent experiments performed with: 1 - 1T7 diode; 3 - 1T12 diodes, 2 - 1T17 diodes, and 1 - 1T15 diode.[29] The best results of these experiments are shown in Table 1 but the diode-to-diode variation was less than 1.5 dB, for a given model. Thus the 1T12 and 1T17 appear to be about on par, the 1T7 is clearly lower in efficiency, and the 1T15 is clearly the best tested. The results compare well with noise temperature and required LO power for these diodes at 184.3 μm.[21] Namely, the 1T15 achieves better noise temperature and requires roughly 3 dB less LO power to be optimized. Our conclusion is that the Drive power couples better into the 1T15 probably owing to its low junction capacitance (0.41 fF) and series resistance (14.4 Ω). The 1T15 has a nominal anode diameter of 0.25 μm making it very sensitive to static and other damage. Nevertheless this diode was operated in the SBG system for a week and no degradation in performance was observed. It should also be noted that the 3 - 1T17 diodes are slightly better receivers than the 1T12 diodes. The 1T17's tend to exhibit lower conversion loss.

IV - Sideband Separation and Spatial Mode Performance

Almost any experiment will benefit from pure, predictable, spatial mode performance of the source and some measurements may even require it. Examination of the mode of the sideband radiation requires either removing the unshifted laser from the beam, or scanning a coherent receiver through the beam. The latter approach is expected to be fraught with technological difficulties and thus the former technique was employed. Reflection etalons were designed using available ultra-high-precision complex index of refraction data on high-purity Si.[30] Using the Fresnel equations for a multilayered system,[31] a program was written to find a practical etalon thickness where, at an angle of incidence of 45°, the unshifted laser would be almost completely transmitted but the sideband radiation would be highly reflected. The calculated performance is presented in Figure 3. As demonstrated there, the 3 dB reflection bandwidth of the etalon is ~20 GHz and the reflection behavior will cyclically repeat with higher offset frequency.

While the calculation indicates that the laser radiation reflection should be 43 dB down, it was observed to be 23 dB down. In an effort to understand this discrepancy a more complete calculation was performed[32] including the effects of Gaussian beam walkoff.[33] This calculation predicts the reflection to be - 25 dB, in reasonable agreement with experiment, considering that the absorption loss is neglected in reference 33.

With roughly 10% of the laser radiation being reradiated from the antenna,[34] ~10 mW of laser Drive power, and 5 - 10 μW of sideband power, approximately 40 dB of unshifted laser radiation had to be removed from the beam so that conventional mode scans of the SBG radiation could be conveniently performed. The use of two etalons provided this rejection. After careful alignment of the etalons, the unshifted laser was 20 dB below the sideband. This was measured by placing a bolometer with a 2 mm diameter aperture in center of the beam and turning off the frequency synthesizer to see only the unshifted laser. While this measurement was performed, the DC bias point of the diode was varied over the entire safe range to confirm that the diode bias point change caused by the presence of the microwave source did not effect the amount of reradiated laser.

Further, the 20 dB ratio of sideband power to laser power was confirmed at several other points in the beam.

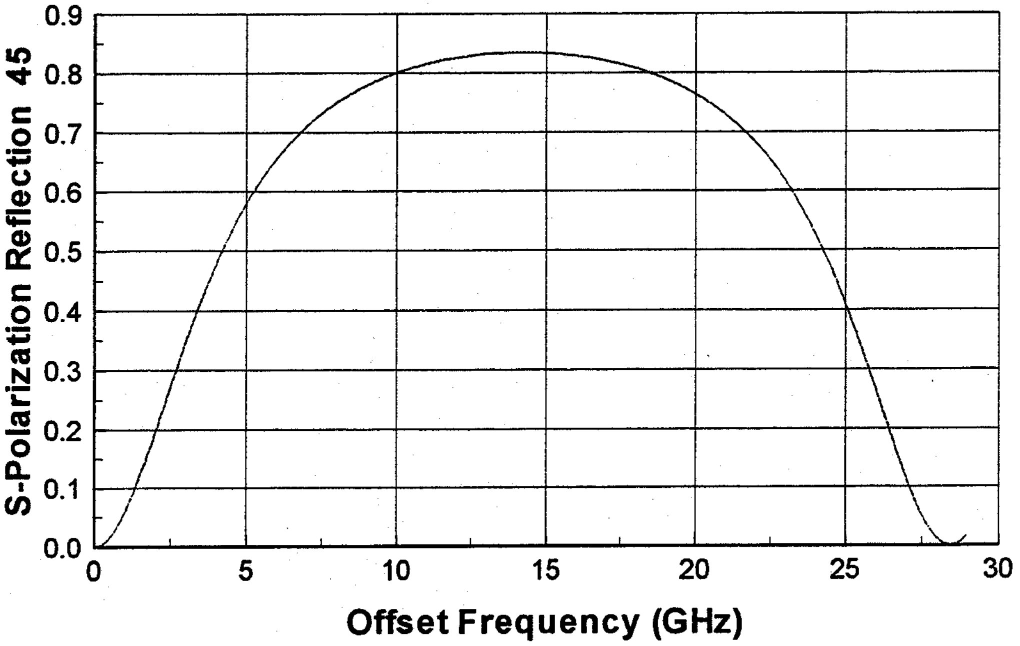

Figure 3: S-Polarization reflection versus offset frequency for the 1576.75 μm thick Si etalon used in the measurements. Zero offset corresponds to the laser center frequency, 1564.5187 GHz.

A typical antenna pattern of one of the mounted diodes is presented in Figure 4. This pattern was measured by UVa.[28] With the diode located at the focal point of the off-axis mirror, the expected output mode would be the collimated antenna pattern. Examination of Figure 4 leads one to believe that the output mode will not be a good Gaussian. Initial SBG mode scans confirmed this and revealed some structure due to cross-polarized radiation. This is to be expected since the antenna cannot be perfectly aligned in the dihedral. The cross-pol structure was eliminated with a polarizer placed in front of the SBG diode.

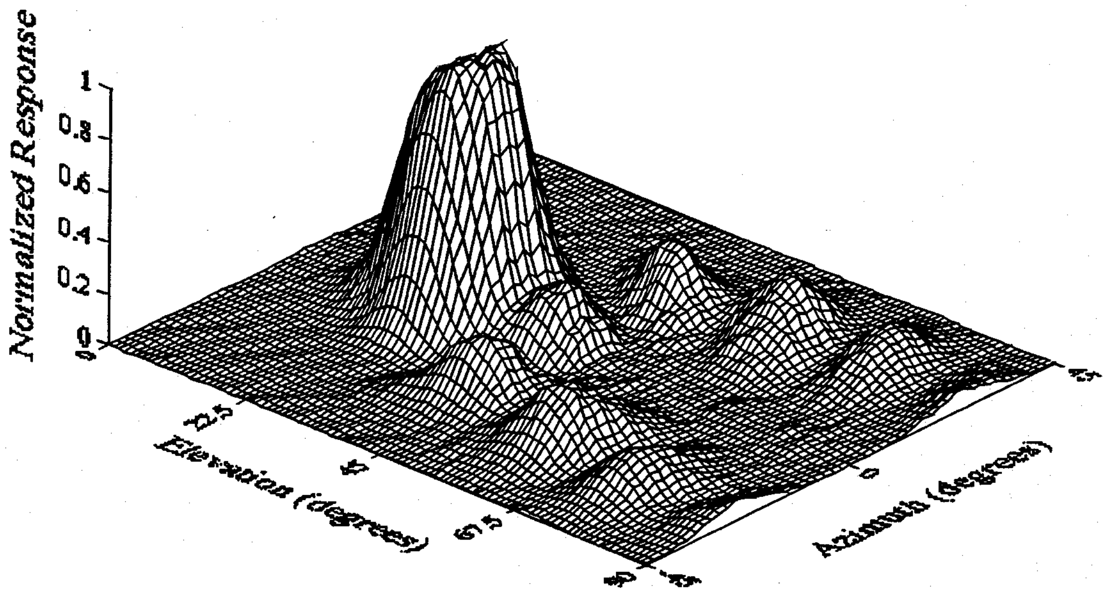

Figure 4: Antenna map of a diode mounted in a dihedral. Zero degrees elevation corresponds to the antenna parallel to the laser propagation direction. At zero degrees azimuth the dihedral is symmetric with the incident beam.

The first attempts to improve the mode involved careful adjustment of the diode orientation. This was accomplished with a five degree of freedom stage. While these efforts were somewhat successful, the resulting mode was so sensitive to corner-reflector alignment and individual diode antenna alignment that exchanging SBG diodes resulted in very different output modes. The final approach used to improve the mode employed two spatial filter apertures (SF's) to redefine the beam and effectively select only the central portion of the main beam. The first SF was somewhat oversized and located ~ 2" from the second etalon while the second SF was undersized and 19" from the first SF. The first SF removed rapidly diffracting structure on the skirts of the beam while the second selected the main lobe of the remaining beam. The resulting mode is presented in Figure 5. The sidelobes are ~18 dB down from the peak. The mode scan in Figure 5 is the result of subtracting a scan made with the synthesizer off from a scan made with the synthesizer on. This was done to insure that the unshifted laser present in the beam did not affect the low-level data on the skirts of the beam. As expected, this subtraction caused no significant shift in the data.

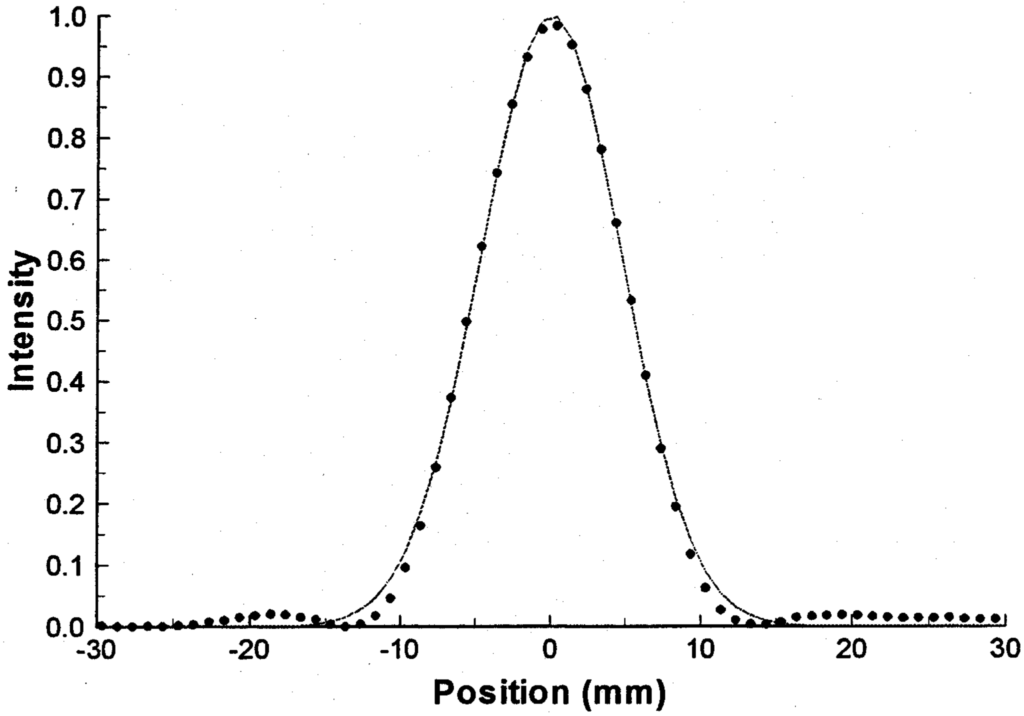

Figure 5: Mode scan of the sidebands. The data was taken using a bolometer with a 2 mm aperture and a computer-controlled translation stage. The solid line is the best fit Gaussian to the data, neglecting data that is more than 7 dB below the peak.

The second SF in the system was small enough that fairly noticeable diffraction was observed near it. However, the propagation of the mode further in space was well predicted by the paraxial equations[35] once the beam was 20 - 25" from the second SF. Four different SBG diodes were tested in the system once adequate mode performance was obtained. All of these produced virtually the same mode pattern beyond the two SF's. The SF's did unfortunately cause a loss of about 3 - 5 dB in sideband power in the beam.

While this method of sideband separation keeps both sidebands in the beam we have developed a receiver which will be respond to only one of the sidebands.[36] This receiver design is presented in section V, below.

V - Single-Sideband Submillimeter-Wave Receiver

A single sideband (SSB) receiver has been developed and implemented for use with a submillimeter SBG. While the sideband generator emits both an upper and lower sideband, and even some unshifted laser radiation, the receiver responds to only one sideband. The operator of the system can choose which sideband to receive. Rejection of the undesired signal is accomplished through selective frequency shifting coupled with the use of a commercially available single-sideband microwave mixer. This receiver is fully coherent, preserving phase and amplitude information.

The advantages of coherent reception include: greatly improved sensitivity (NEP's in the range of 10^{-19} W/Hz are typical)[37], phase and amplitude measurement, predetection bandwidth narrowing through IF bandwidth narrowing, and discrimination between upper and lower sidebands (as will be shown here). This section will describe the operation of the coherent SSB receiver by tracing the mixing products through the system.

A block diagram of the receiver is shown in Figure 6. The lasers are operated with one laser on line center and the other tuned 2 MHz above line center.[14] The first laser is the drive for the sideband generator and the second laser is the LO for the reference and receiver Schottkys. In the example presented in Figure 6 the microwave synthesizer is operated at 12 GHz and the frequency-shifting synthesizer is operated at 16 MHz.
The lower-case letters **a** - **e** denote locations where frequency content will be illustrated. Before describing frequency content it is important to note that since the laser frequency ν is in the THz range mixing products of frequency ν or greater will be rapidly attenuated in the coax or waveguide connecting the remaining portions of the circuit, and can be ignored. With this in mind, the first-order frequency content at position **a** is

$$\text{2 MHz,} \qquad \text{(a)}$$

and at position **b** is

$$\begin{matrix} \text{14 MHz} \\ \text{18 MHz} \end{matrix} \qquad \text{(b)}$$

16 MHz (LO mixer leakage)

2 MHz (RF mixer leakage).

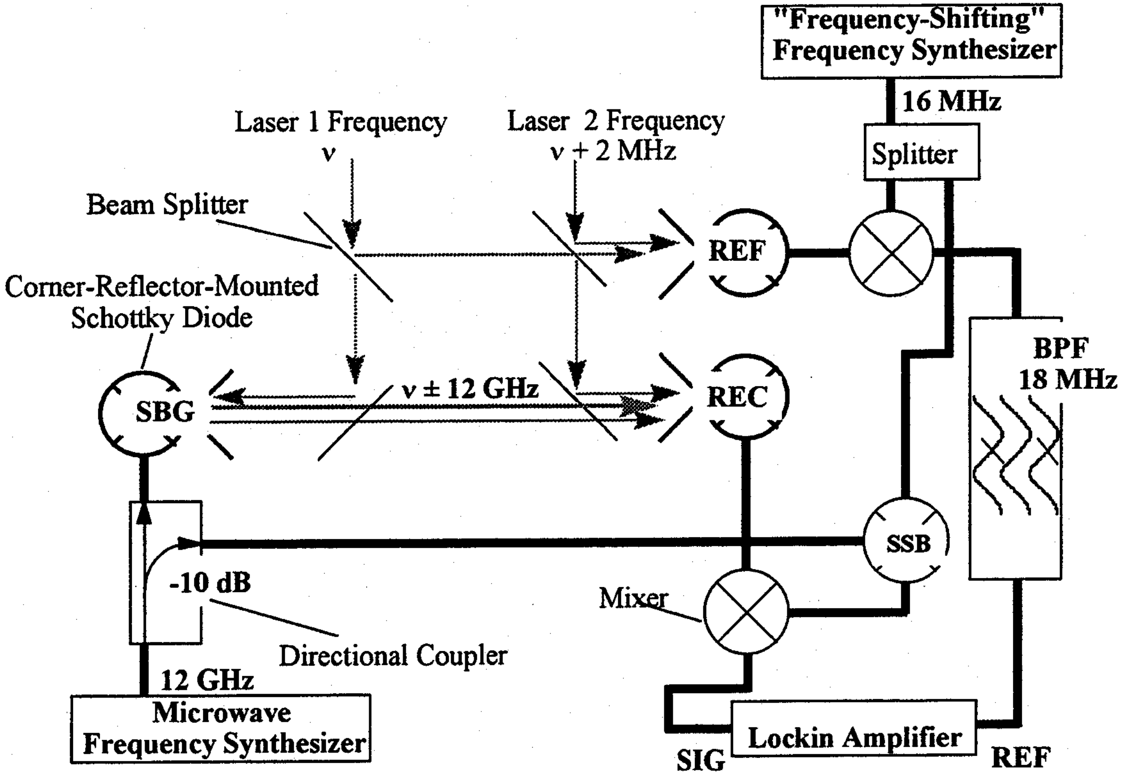

Figure 6: Block Diagram of the SSB receiver. The bandpass filter (BPF) is centered at 18 MHz and has a 3 dB width of 400 kHz.

Before examining position **c** one must remember that a number of frequencies enter the receiver Schottky. Considering only first-order sideband generation, in the interest of brevity, the following spectrum enters the receiver: ν + 2 MHz (Laser 2, LO), ν + 12 GHz (Upper Sideband), ν - 12 GHz (Lower Sideband), and ν (Laser 1, Unshifted Drive).

Therefore the first-order frequency content at **c** is

2 MHz

12 GHz (u, l)

12 GHz - 2 MHz (u) (c)
12 GHz + 2 MHz (l)
24 GHz (u, l)

where (u) and (l) denote upper and lower submillimeter sidebands, respectively. If at this point one simply mixed (3) with the microwave synthesizer signal, the upper and lower sideband would both be at 2 MHz, and DC. Next, examining location **d**, the frequency content is

12 GHz + 16 MHz, (d)

neglecting the other component which is at least 28 dB down, as a result of the image rejection of the SSB mixer.[38] Using this as the LO for the mixer prior to **e**, noting that the electronics between position **c** and the mixer prior to **e** will not pass 2 MHz, at position **e** the first order frequency content is,

16 MHz (u, l)
18 MHz (u)
24 GHz + 14 MHz (u)
14 MHz (l) (e)
24 GHz + 18 MHz (l)
12 GHz ± 16 MHz (u, l)
36 GHz + 16 MHz (u, l).

One can now see that the upper submillimeter sideband has been mixed down to 18 MHz, while the lower submillimeter sideband has been mixed down to 14 MHz.

If a bandpass filter centered at 18 MHz is placed after **b**, the two-phase lockin (I - Q demodulator) will be locked to the upper sideband. Further, as the sideband frequency is tuned, the upper sideband will always be at 18 MHz. The lockin will track any laser jitter since it is coincidentally measured with the reference Schottky. The lower submillimeter sideband can be chosen instead of the upper by simply tuning laser 2 to be 2 MHz below laser 1.

A further advantage of this circuit stems from the fact that the reference Schottky never "sees" the sideband radiation. Therefore the problem of cross-talk through sideband radiation in the LO laser path is eliminated.

V - Summary and Conclusions

An accurate measurement of the power of a submillimeter sideband generator has been performed and output power at ~ 1.6 THz of 10.5 μW has been obtained. Optimal coupling parameters at one frequency have been confirmed, $w_0 = 1.82\lambda$, and good spatial mode performance has been achieved. A technique has been presented for removal of unshifted laser radiation and this technique has been demonstrated to provide a beam with the sideband 20 dB above the unshifted laser. If the above etalon technique were used in a very wideband system the periodic "holes" in the etalon reflection could be compensated for by designing etalons with different null spacing, ie. different thickness, and performing one frequency scan for each etalon set.

A single-sideband receiver for use with a submillimeter sideband generator has been developed. The rejection of the unwanted sideband is achieved through selective frequency shifting in the IF electronics. This receiver permits the user to select which submillimeter sideband to demodulate, eliminates the cross-talk problem, and allows for correction of laser drift through adjustment of the "frequency-shifting" synthesizer.

Acknowledgments

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