A TERAHERTZ GRID FREQUENCY DOUBLER

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Abstract—**We present a 144-element terahertz quasi-optical grid frequency doubler. The grid is a planar structure with bow-tie antennas as a unit cell each loaded with a planar Schottky diode. The maximum output power measured for this grid is 24 mW at 1 THz for 3.1-μs, 500-GHz input pulses with a peak input power of 47 W. An efficiency of 0.17% for an input power of 6.3 W and output power of 10.8 mW is measured. To date this is the largest recorded output power for a multiplier at terahertz frequencies. Input and output tuning curves are presented and an output pattern is measured and compared to theory.**

I. Introduction

There is increasing demand for THz components such as tunable oscillators, mixers and multipliers for use in submillimeter-wave sources. These sources are used in radio astronomy and remote sensing [1,2]. Conventional sources such as lasers and vacuum-tubes are large and heavy. They need high voltage power supplies and have limited tuning range. However, solid-state diode multipliers like Schottky diode multipliers can be used to generate higher harmonics from low-frequency tunable signal sources such as Gunn-diode oscillators. Currently most of these diode multipliers are a single diode, or a cascade of two or more diodes mounted in waveguide with a whisker contact. Rydberg *et al.* have demonstrated a Schottky varactor-diode frequency tripler with an output power more than 120 μW at 803 GHz [3]. Erickson and Tuovinen have presented a waveguide tripler with an output power of 110 μW at 800 GHz [4]. Zimmermann *et al* . have demonstrated a cascade of two whisker-contacted Schottky-varactor frequency tripler with an output power of 60 μW at 1 THz [5].

Another approach is to combine the output powers of many solid-state devices in free space thereby eliminating the losses associated with waveguide structures. The first THz grid frequency doubler was presented by J-C. Chiao *et al.*. This 6 × 6 doubler grid had a peak output power of 330 μW at 1 THz [6]. This grid had a null in the output beam because of the diode orientations used. Later a second THz grid doubler was presented that corrected the diode orientation problem. The output power reported for this 12 × 12 grid was 5.5 mW at 1 THz for 3.1-μs, 500-GHz input pulses with a peak power of 36 W [7]. In the grid presented in this paper input and output tuners are used to increase the output power of the grid in [7]. A diode-grid frequency doubler is an array of closely spaced planar Schottky diodes placed in a setup as shown in Fig. 1. The fundamental beam excites RF currents on the leads of the bow-tie. The diodes act as a nonlinear surface and generate harmonics. The low-pass filter in the input insures that only the fundamental frequency of the laser will hit the grid. The high-pass output filter allows the higher harmonics generated by the grid to pass through, but blocks the fundamental. The input and output tuning slabs are for impedance matching of the input and the output.

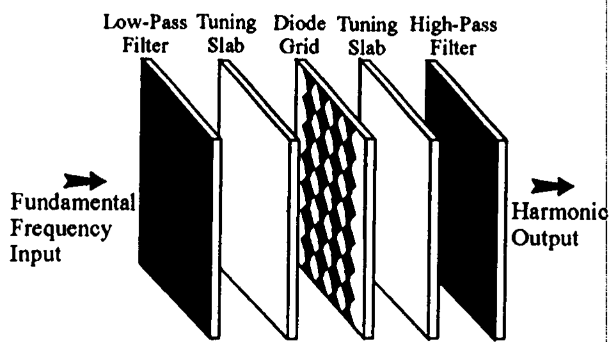

Fig. 1. A grid frequency multiplier [8]. The fundamental frequency enters the grid through a low-pass filter. The grid acts as a nonlinear surface and generates harmonics which pass through a high-pass filter.

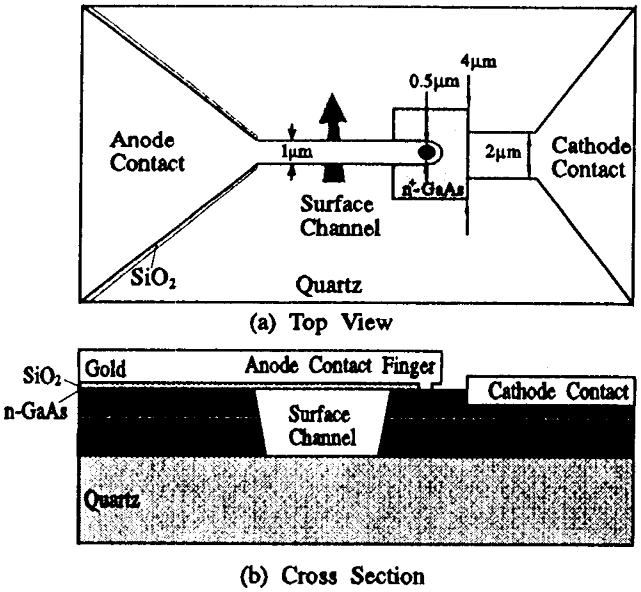

Fig. 2. Schottky-diode layout. (a) The top view. (b) The cross section. The n-GaAs layer is 0.1 μm thick and has a doping concentration of $4 \times 10^{17} cm^{-3}$. The n^+-GaAs layer has a thickness of 3 μm and a doping of $5 \times 10^{18} cm^{-3}$. The AlGaAs layer has a thickness of 1.5 μm.

II. Construction

The grid multipliers were fabricated at the University of Virginia using monolithic technology [9]. To make diodes for terahertz frequencies, series resistance and shunt junction capacitance should be greatly reduced by reducing anode diameter and choosing optimum active layer doping and thickness. Fig. 2 shows the top view and the cross section of the Schottky diode. The anode has a diameter of 0.5 μm. A surface channel is etched under the anode contact finger to reduce the shunt capacitance. The diodes have an estimated junction capacitance of 0.6 fF at zero bias, and a dc-series resistance of 14 Ω.

The grid consists of an array of 12×12 bow-tie antennas on a 30 μm thick fused-quartz substrate. Fig. 3 shows the grid and the unit cell. Each unit cell is 70 μm on a side. The Schottky-diode junction is located at the center of the cell. The diode grid is first fabricated on a GaAs substrate. After the fabrication, the GaAs substrate is etched away and the diode structure is glued on a 30-μm thick quartz substrate.

III. Measurements

The measurement setup is shown in Fig. 4. The input source for these measurements is the free-electron laser (FEL) at the University of California, Santa Barbara [10]. The free-electron laser is capable of generating kilowatts of pulsed power tunable from 120 GHz to 4.8 THz. The pulse width in the measurements is 3.1 μs. The input power passes through a low-pass multi-mesh filter with a cutoff frequency of 660 GHz and is varied by rotating a polarizer. The second non-rotating polarizer placed after the first one is to maintain the polarization of the beam. A beam splitter directs part of the input power into a pyroelectric reference detector. The rest of the input is focused onto the grid. A metallic-mesh Fabry-Perot interferometer is used to measure the frequency content of the output. The output beam is focused onto a liquid-helium-cooled InSb bolometer through a high-pass filter with a cutoff frequency of 870 GHz.

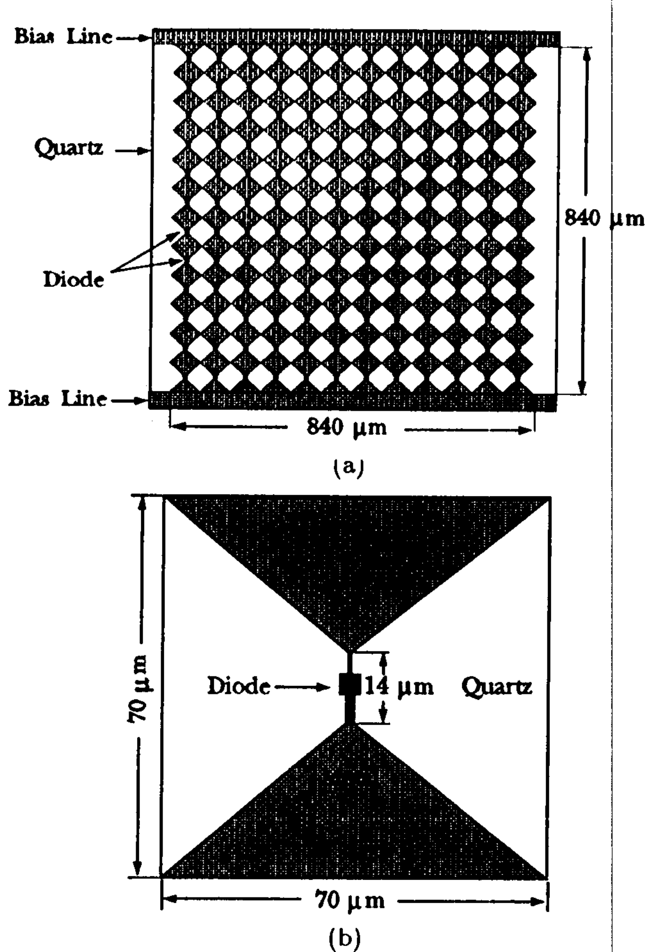

Fig. 3. The multiplier grid. (a) The entire 12×12 array. The diodes are in series from top to bottom. The grid can be biased through the bias lines at the top and bottom of the grid. The metal contacts in a row are all electrically connected. (b) The unit cell. The diode is located at the center of the cell.

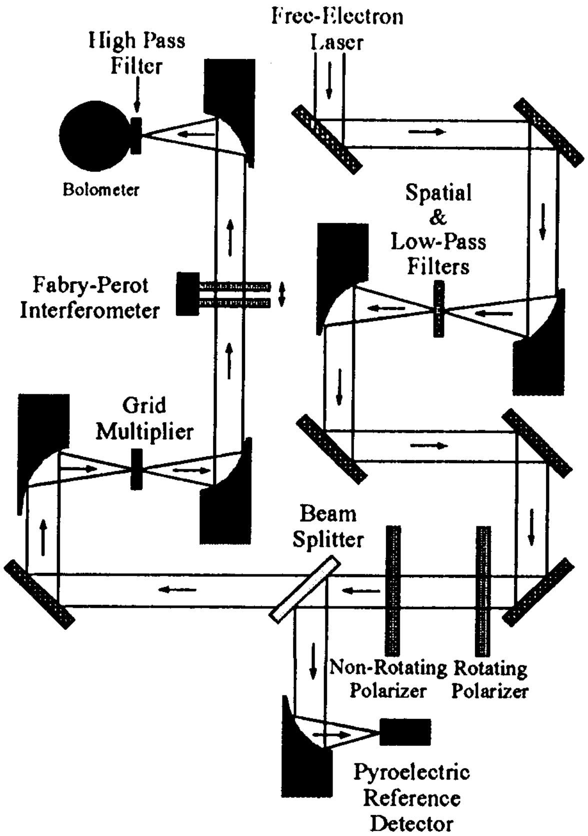

Fig. 4. Measurement setup. All the mirrors in the setup are f/1.2 parabolic, with focal length of 13 cm and diameter of 10 cm. Arrows indicate the direction of the beam.

The diode grid is suspended in air by gluing it over a hole in a microscope cover slip. The grid is placed in the setup shown in Fig. 4 and excited by a 500-GHz input beam. There are no water absorption lines in 500 GHz and 1 THz [11], therefore measurements can be done in free space without the aid of a dry-box. The reference and the output signals are synchronized with the FEL trigger signal that has a frequency of 0.75 Hz. To measure the peak input and output power each pulse is integrated over certain time interval. To account for the noise in our measurements the pulses are also integrated over the same time period before the arrival of the FEL trigger signal. This offset is subtracted from the measured peak power. This method is used for all the measurements.

To investigate whether the grid generates terahertz second harmonics a Fabry-Perot interferometer as shown in Fig. 4 is used to verify the output frequency of the grid. Measuring the output power versus the metal-mesh spacing of the interferometer indicates that for an input frequency of 500 GHz a 1 THz output signal is present. No other harmonics were detected.

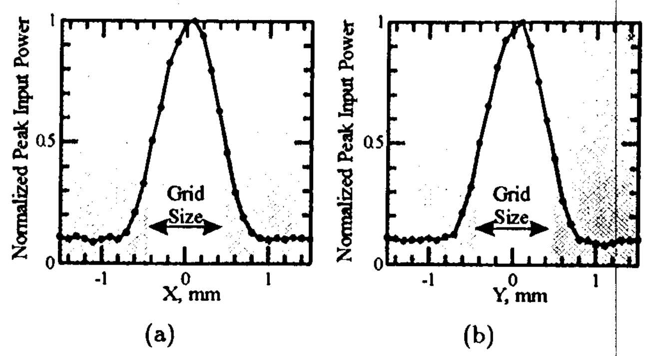

Fig. 5. Input spot-size measurement at the focal plane using a pyroelectric detector. (a) E-plane pattern. (b) H-plane pattern.

In order to make sure that the output radiation is actually from the grid, we removed the grid. The output pulse disappeared. Also, rotating the grid by 90° had the same effect. This shows that the output signal is not a harmonic of the laser or generated by the GaAs epitaxial layer [7].

IV. Input Power Measurement

To determine the amount of the input power incident on the grid a pyroelectric detector mounted on a two-dimensional positioner is used to measure the spot size of the incident beam at the focal point, where the grid is placed. The measured E and H-plane patterns of the incident beam are shown in Figs. 5(a) and 5(b) respectively. Comparing the spot size of the incident beam to the grid size which is 840 μm on the side indicates that almost all of the input power is incident on the grid.

V. Tuning Measurement

Dielectric slab tuners as shown in Fig. 1 can be used to achieve higher output power and efficiency. We used z-cut crystal-quartz discs with a dielectric constant of ? as tuners. The input tuner has a thickness of 60 μm and the output tuner is 30-μm thick. To investigate whether the tuners improve the power performance of the grid we first measured the output versus the input power of the grid with no tuners, Fig. 6.

To measure the input tuning curve shown in Fig. 7(a) the output tuner in Fig. 1 is removed and the output power is measured versus the input tuner relative distance from the grid. At its closest point to the grid (0 in Fig. 7(a)) the tuner is less than 500 μm away from the grid. The average spacing between the peaks in this figure is 300 μm, which is half the wavelength of the fundamental frequency. After the first two periods there is

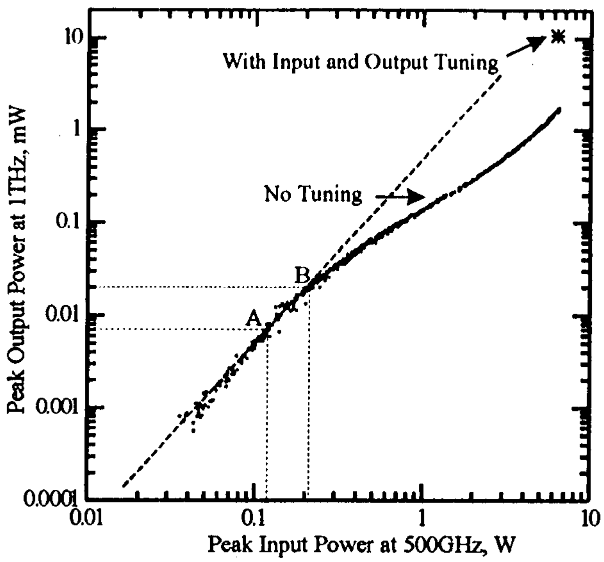

Fig. 6. Measured peak output power at 1 THz versus the input power at 500 GHz with and without tuners. A and B show the points where the input and output tuning measurements are done. The dashed line shows the square-law relationship.

a significant drop in the output power which is probably due to diffraction. Point A in Fig. 6 shows the input and the output power of the grid for the input tuning measurement before the tuning slab is added. This corresponds to an output power of 7 μW shown with a dashed line in Fig. 7(a). By adding the input tuner the 7-μW output power increases to 37 μW (Fig. 7(a)).

The output tuning curve is shown in Fig. 7(b). For this measurement the input tuning slab shown in Fig. 1 is removed and the output is measured versus the relative position of the output tuning slab from the grid. Here also, the closest distance from the grid (0 in Fig. 7(b)) is less than 500 μm. The average spacing between the peaks is 150 μm which is half the second harmonic wavelength. Point B in Fig. 6 shows the input and the output powers before adding the output tuning slab. For this measurement the output power of the grid with no tuners is 20 μW shown with a dashed line in Fig. 7(b). The output tuner increases the output power from 20 μW to 32.5 μW. It appears that this tuning slab also tunes the input as is evident from the alternating high-low peaks in Fig. 7(b).

Next, with both the input and the output tuners in place (Fig. 1) we optimized the position of these tuners for maximum output power. For an input power of 6.3 W an output power of 10.8 mW was measured indicating an efficiency of 0.17% (Fig. 6).

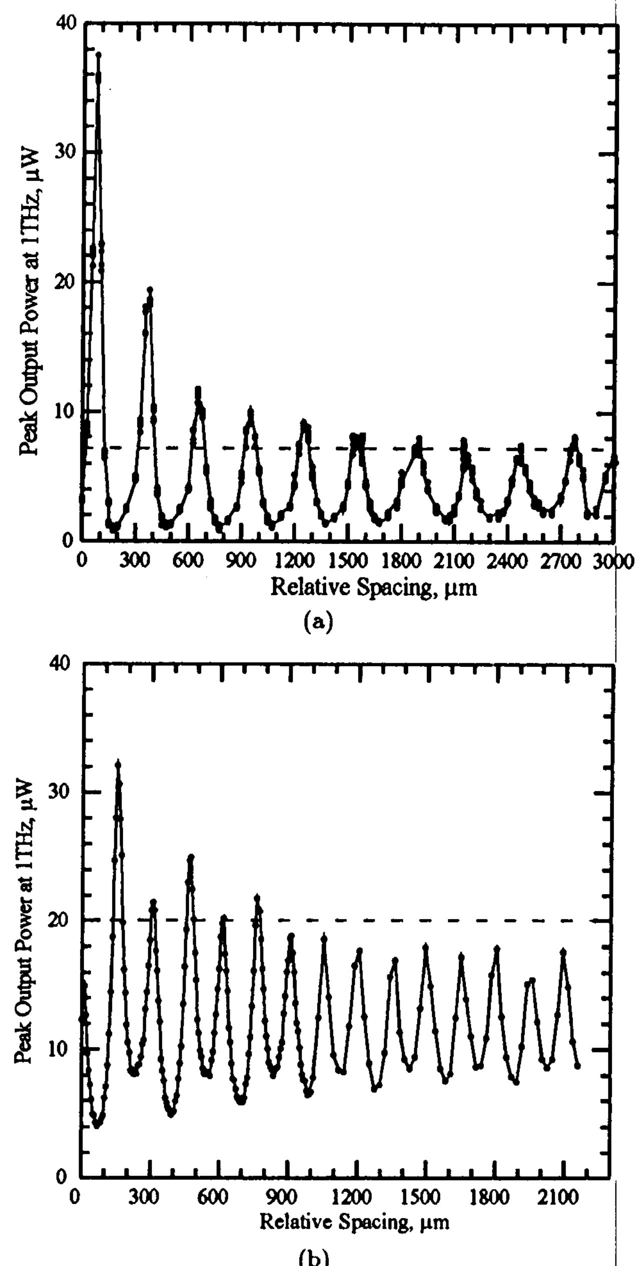

Fig. 7 Measured output power versus the relative position of (a) the input tuner, (b) the output tuner. The dashed line is the output power with no tuner for each measurement.

VI. Maximum Output Power

To measure the maximum output power of the grid at 1 THz we placed both the input and the output tuners in the setup of Fig. 1, optimized their position for maximum output, and increased the input power until the grid was damaged. Fig. 8 shows the output versus the input power measurement before the input and the output tuners are added, and compares it to

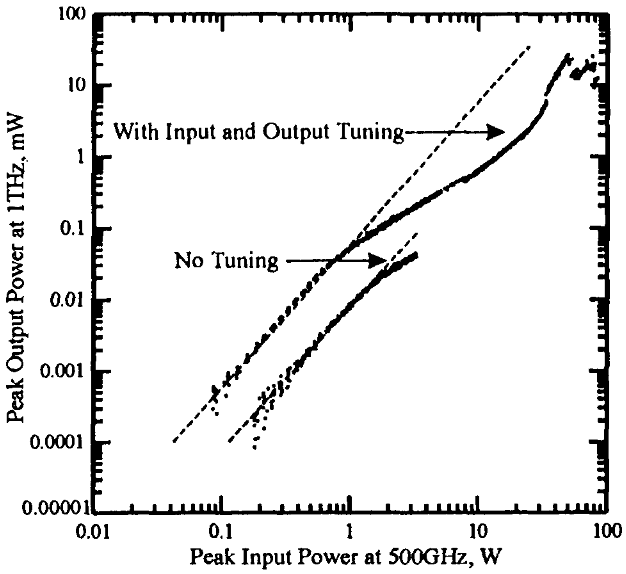

Fig. 8. Measured peak output power at 1 THz versus input power at 500 GHz with and without tuning. The dashed lines show the square-law relationship.

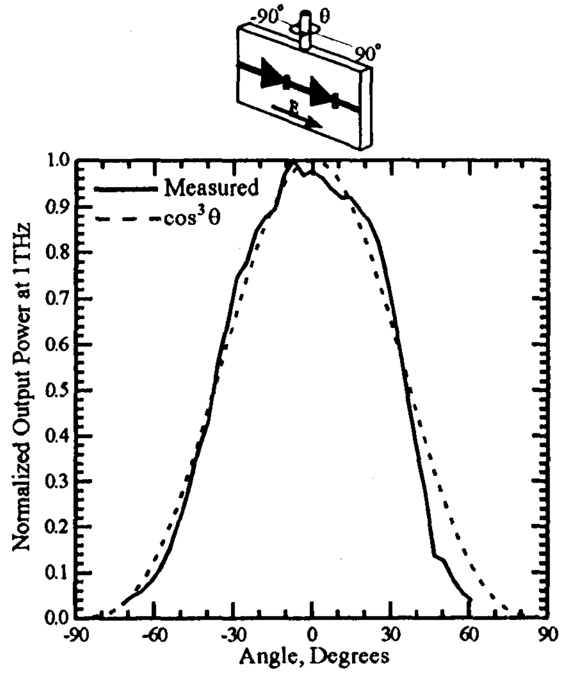

Fig. 9. Output pattern. The measurement was done by rotating the grid from −90° to 90° with the electric field parallel to the diodes.

the same measurement with the tuners optimized for maximum output. The tuners are at a distance less than 500 μm from the grid. A maximum output power of 24 mW is measured at 1 THz with an input power of 47 W for 3.1-μs input pulses.

At an input power of 47 W the output starts rolling over indicating damage to some devices. As the input power increases further, the output power starts increasing again until some more devices are damaged. Fig. 8 shows a second decrease in the output power. We stopped the measurement at this point.

The discrepancy between the power dependance of the grid in Fig. 6 and Fig. 8 is possibly due to alignment of the grid with the input beam. With low input power, the data in both Fig. 6 and Fig. 8 follow a square-law relationship. At higher input power there is a kink in the data for both measurements. It is possible that this kink is a self-biasing effect, where the RF power changes with the diode impedance.

VII. Pattern Measurement

Fig. 9 shows the effect of rotating the grid about its axis from −90° to +90°. Unlike the pattern for the previous doubler grid, reported by Jung-Chih Chiao [6], this pattern has no nulls. In the case of the previous grid the diodes were oriented with opposite polarity about the centerline of the grid, causing a null in the output. Here, the diode orientation is corrected eliminating the null in the pattern. The output power stays within 30% of the maximum for angles up to 30°. A theoretical $\cos^3\theta$ obliquity factor is also plotted in this figure. Because the incident beam to the grid is approximately the same size as the grid, rotating the grid about its axis causes the input power density to reduce by a factor of $\cos\theta$. The second factor of $\cos\theta$ in this obliquity factor is because the grid is a square law device, and the third factor is because the output beam becomes wider as the grid rotates, missing the output detector.

VIII. Conclusion

In this paper we have presented a planar grid of 144 Schottky diodes suitable for use as a quasi-optical frequency doubler. This grid has a maximum efficiency of 0.17% for an output power of 10.8 mW, and a peak output power of 24 mW at 1 THz for 3.1-μs 500-GHz input pulses with a peak power of 47 W.

IX. Acknowledgements

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X. References

[1] T.G. Phillips, "Development in Submillimeter Astronomy," *The 19th International Conference on Infrared and Millimeter Waves,* Sendai, Japan, Oct. 1994.

[2] J.W. Waters and P.H. Siegel, "Applications of Millimeter and Submillimeter Technology to Earth's Upper Atmosphere: Results To Date and Potential for the Future," *The 4th International Symposium on Space Terahertz Technology,* Los Angeles, CA, March 1993.

[3] A. Rydberg, B.N. Lyons and S.U. Lidholm, "On the Development of a High Efficiency 750 GHz Frequency Tripler for THz Heterodyne Systems," *IEEE Trans. on Microwave Theory and Tech.,* vol. 40, No. 5, pp. 827-830, May 1992.

[4] N. Erickson and J. Tuovinen, "A Waveguide Tripler for 800-900 GHz," *The 6th International Symposium on Space Terahertz Technology,* Pasadena, CA, March 1995.

[5] R. Zimmermann, T. Rose and T. Crowe, "An All Solid-State 1 THz Radiometer for Space Applications," *The 6th International Symposium on Space Terahertz Technology,* Pasadena, CA, March 1995.

[6] J.-C. Chiao, A. Markelz, Y. Li, J. Hacker, T. Crowe, J. Allen, D. Rutledge, "Terahertz Grid Frequency Doublers," *The 6th International Symposium on Space Terahertz Technology,* Pasadena, CA, March 1995.

[7] A. Moussessian, M.C. Wanke, Y. Li, J.-C. Chiao, F.A. Hegmann, S.A. Allen, T.W. Crowe, D.B. Rutledge, "A Terahertz Grid Frequency Doubler," to be presented at *The IEEE MTT-S Int. Microwave Symp.*, June 1997.

[8] C.F. Jou, W.W. Lam, H.Z Chen, K.S. Stolt, N.C. Luhmann, Jr. and D.B. Rutledge, "Millimeter Wave Diode Grid Frequency Doubler," *IEEE Trans. on Microwave Theory and Tech.*, vol. 36, No. 11, pp. 1507-1514, Nov. 1988.

[9] T.W. Crowe, R.J. Mattauch, H.P. Röser, W.L. Bishop, W.C.B. Peatman and X. Liu, "GaAs Schottky Diodes for THz Mixing Applications," *Proceedings of the IEEE,* vol. 80, No. 11, pp. 1827-1841, Nov. 1992.

[10] S.J. Allen, K. Craig, B. Galdrikian, J.N. Heyman, J.P. Kaminski, K. Campman, P.F. Hopkins, A.C. Gossard, D.H. Chow, M. Lui and T.K. Liu, "Materials Science in the FAR-IR with Electrostatic Based FELs," presented at *FEL 94,* Stanford, CA, August 1994.

[11] H.M. Pickett, R.L. Poynter, E.A. Cohen, M.L. Delitsky, J.C. Pearson, H.S.P. Müller, "Submillimeter, Millimeter, and Microwave Spectral Line Catalogue," JPL Publication 80-23, Rev.4, NASA, Jet Propulsion Laboratory, Caltech, March 10, 1990.