**FORTY-FOURTH ANNUAL SYMPOSIUM ON FREQUENCY CONTROL**

# HIGH-ORDER HARMONIC MIXING WITH GaAs SCHOTTKY DIODES*

MARCO PREVEDELLI
Universita 'di Firenze
Pisa, Italy

and

F.L. WALLS AND STUART P. BEATON
Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO 80303

## ABSTRACT

In many areas of precision frequency metrology, it is useful to use a single nonlinear element to both multiply a source frequency and mix this harmonic with a higher frequency source. This process is commonly called harmonic mixing. When the frequency span is great, it is advantageous to use large harmonic numbers to reduce the complexity, the number of local oscillators, and ultimately the cost. Planar GaAs Schottky diodes are good candidates for high-order harmonic mixing because of their high cut-off frequency. Their robust construction should lead to excellent lifetime, reliability, and reproducibility. We have investigated the performance of one type of fast planar Schottky diode for harmonic mixing with harmonic numbers from 8 to 201. Our measurements indicate that, with optimum biasing and power, harmonic mixing with harmonic numbers up to approximately 80 can be achieved with good signal-to-noise ratios. Detectable signals have been observed for harmonic numbers of 201. In a test of both the nonlinear and the high-frequency performance, we were able to obtain a beat signal between the 34th harmonic of a 74.17 GHz klystron and a laser operating at 2522 GHz. The resulting signal-to-noise ratio was 48 dB (bandwidth of 3 kHz). This is more than sufficient to phase lock the laser to the multiplied reference signal. From the nonlinear characteristics of the diode and the signal-to-noise ratio obtained at lower frequencies, it looks as though we can multiply from 70 GHz to about 4.5 THz in one step.

## INTRODUCTION

The absolute measurement of frequency and precision frequency synthesis up to approximately 10 THz often requires the use of harmonic mixers. Many types of diodes have been successfully used in this frequency range with the metal-insulator-metal (MIM) the most common [1-7]. Josephson junctions based on niobium have been used up to approximately 3.5 THz [8-10]. With the advent of the new high temperature superconductors it may eventually be possible to extend this upper limit by a factor of 10 or more. We report here the results for harmonic mixing with harmonic numbers from 8 to 201 using GaAs schottky diode constructed with planar geometry [11]. As many as 1000 separate diodes are fabricated on one die and attached to a 5 mm diameter post. A 25 μm diameter tungsten whisker of approximately 9 mm length and sharpened to point of approximately 100-1000 Å radius of curvature is used to select the particular diode, to couple in both the high frequency and the low frequency radiation into the diode and to couple the IF signal into a 50 Ω coaxial line. Alternately we have used coaxial tees and directional couplers at lower frequencies to inject the subharmonic into the diode, and to extract the IF frequency. Both schemes lead to a high signal-to-noise ratio (SNR) for harmonic mixing with harmonic numbers up to 80 with detectable signals up to harmonic numbers of 201. There is no evidence of significant roll-off with this approach up to 2.5 THz, which is consistent with the reported cut-off frequency of 11 Thz for this diode structure[11]. These diodes appear to have a long lifetime and excellent diode-to-diode reproducibility. Failures were traced to input power in excess of about 15 mW or severe shock. Their use has the potential for substantial simplification in the hardware and reduction in the number of local oscillators required for frequency synthesis in the 30 Ghz to 10 THz region.

*Contribution of the U.S. Government, not subject to copyright.

## EXPERIMENTAL TESTS

Figure 1 shows the block diagram of the setup used to compare the SNR for high-order harmonic mixing. The phase shifter is a simple line stretcher. The low-pass filter is used to separate the high frequency and the subharmonic from the IF frequency. For these measurements the high-frequency signal was fixed at 74.17 Ghz and the subharmonic signal derived from a frequency synthesizer. Fixing the high frequency eliminated uncertainties in the SNR with harmonic number associated with frequency roll-off. The low-phase noise 74.17 GHz signal was coupled into the diode by placing the WR 15 waveguide about 5 mm from the tungsten whisker. The subharmonic signal is coupled into the diode using a coaxial tee or directional coupler. The induced bias current is maximized for low subharmonic power by adjusting the phase shifter. The subharmonic power is then adjusted to create a bias current of 0.5 mA through a 1 kΩ resister. The beat frequency is coupled out

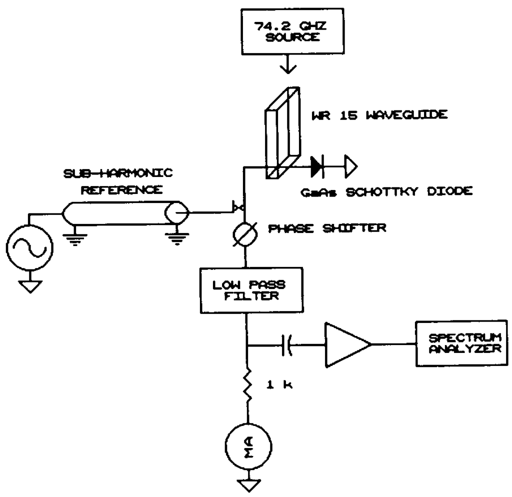


Figure 1. Schematic diagram of the test setup used to measure the high-order multiplication and mixing properties of planar GaAs Schottky diodes. The phase shifter was of the line stretcher type.

through the low pass filter and amplified in an amplifier with a noise figure of approximately 9 dB. The SNR of the beat frequency observed on a spectrum analyzer for harmonic numbers from 8 to 80 is shown in figure 2. The noise bandwidth is 3 kHz. These results were highly reproducible from day to day and from diode to diode. Figure 3 shows the spectrum analyzer trace on a linear scale at harmonic mixing of 201 with a noise bandwidth of 3 kHz.

It is notable that the difference between odd and even harmonic mixing is very small for harmonic numbers above 11. This is in considerable contrast to results with many other diodes [12]. The decrease in SNR with increasing harmonic number is also remarkably small compared to many other systems [12].

A diode from the same die as above has also been used to harmonically mix the 74.17

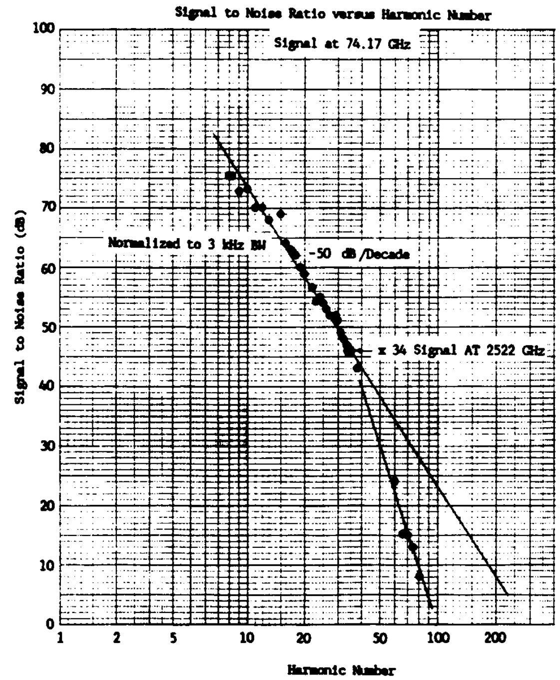


Figure 2. Measured SNR versus harmonic number for planar GaAs Schottky diodes. The upper reference frequency was held at 74.17 GHz for all except the point labeled "x 34 signal at 2522 GHz" where the upper reference frequency was 2522 GHz. Repeatability of the SNR measurements was typically +/-3 dB.

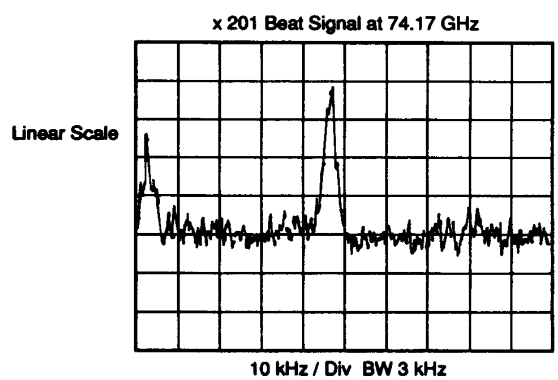


Figure 3. Spectrum analyzer plot for the beat frequency between the 74.17 GHz reference and the 201 st harmonic of the frequency synthesizer. The drive level was about 6 dB higher than for the data of figure 2.

GHz signal with the 118.8 μm (2522.7816 GHz) laser line of $CH_3OH$ (methyl alcohol). The block diagram is shown in Figure 4. The 74.17 GHz klystron source was phase locked 30 MHz below the 7th harmonic of a very stable 10.6 GHz source[13]. The width of the phase-locked 74.17 GHz source was approximately 5 Hz. The 118.8 aim line was oscillating with approximately 1 mW of power. Figure 5 shows the spectrum analyzer trace for the beat frequency with a noise bandwidth of 10 kHz.

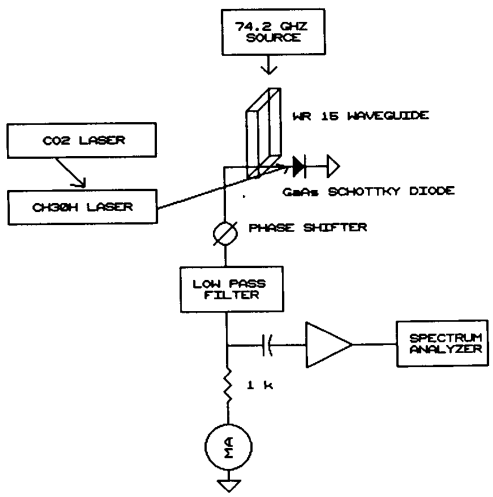


Figure 4. Schematic diagram of the test setup used to measure the SNR for the beat frequency between the 34 th harmonic of 74.17 and the 2.522 THz methyl alcohol line.

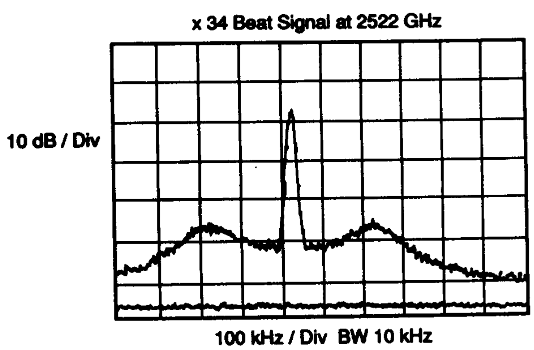


Figure 5. Spectrum analyzer plot for a 1 MHz sweep over the beat frequency between the 34th harmonic of the 74.17 GHz reference and the 2.522 THz line of methyl alcohol line. The noise bandwidth was 10 kHz.

Figure 6 shows the spectral analyzer for a noise bandwidth of 3 kHz. The increase in the apparent noise floor at about 200 kHz is due to the residual phase noise in the klystron source that was not removed by the phase-locked-loop. This increase can in principle be significantly reduced by increasing the bandwidth of the phase-locked-loop. The SNR for this signal is about 46 dB if one considers the noise in the wings which are not effected by the noise bump. This result is in close agreement with that measured at low frequencies and shown in figure 2. Evidently the roll-off effects in the diode are still small at 2.5 THz.

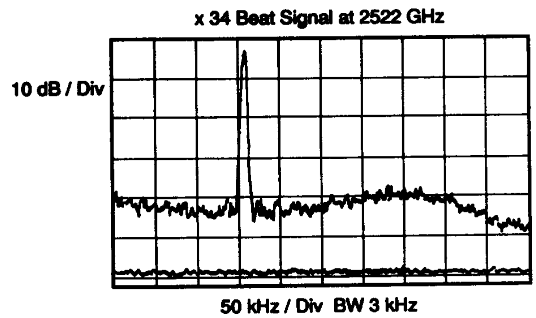


Figure 6. Spectrum analyzer Plot for a 500 kHz sweep over the beat frequency between the 34th harmonic of the 74.17 GHz reference and the 2.522 THz line of methyl alcohol. The noise bandwidth was 3 kHz.

## CONCLUSION

We have shown that sample GaAs Schottky diode of the planar type are sufficiently nonlinear to yield very high SNR for harmonic mixing up to order 80. Detectable signals can even be obtained for harmonic number of 201 for stable sources where the noise bandwidth can be reduced to 100 Hz. Frequency roll-off effects in the diode were not detectible at 2.5 THz, which is consistent with the calculated value of 11 THz based on the mask geometries. The SNR is nearly identical for either odd of even order harmonic mixing for harmonic numbers above 11. The sample diodes tested were very stable in time and reproducible diode to diode on the same die.

## ACKNOWLEDGEMENTS

The authors are very grateful to K.M. Evenson and D.A. Jennings for many fruitful discussions and help in aligning the $CH_3OH$ laser.

## REFERENCES


[1] T.Y. Chang and T.J. Bridges, "Laser Action at 452, 496, and 541 μm in Optically Pumped $CH_3F$," Opt. Commun. 1, 423 (1970).

[2] H.R. Fetterman, B.J. Clifton, P.E. Tannenwald, and C.D. Parker, "Submillimeter Detection and Mixing Using Schottky Diodes," Appl. Phys. Lett. 24, 70 (1974).

[3] C.O. Weiss and A. Godone, "Harmonic Mixing and Detection with Schottky diodes up to the 5 THz Range," IEEE J. Quantum Electron. QE-20, 97 (1984).

[4] K.M. Evenson, D.A. Jennings, and D.J.E. Knight, "Optical Frequency Measurements," IEEE J. Quantum Electron., 74, 168-179 (1986).

[5] D.J.E. Knight, G.J. Edwards, P.R. Pearce, and N.R. Cross, "Measurement of the Frequency of the 3.39 μm Methane-Stabilized Laser to ± 3 Parts in $10^{11}$," IEEE Trans. Instrum. Meas. IM-29, 257 (1980).

[6] T.G. Blaney, D.J.E. Knight, and E.K.M. Lloyd, "Frequency Measurements of Some Optically-Pumped Laser Lines in $CH_3OD$," Opt. Commun. 25, 176 (1978).

[7] F.R. Petersen, K.M. Evenson, D.A. Jennings, J.S. Wells, K. Goto, and J. Jiménez, Correction to "Far Infrared Frequency Synthesis with Stabilized $CO_2$ Lasers, Accurate Measurements of the Water Vapor and Methyl Alcohol Laser Frequencies," IEEE J. Quantum Electron. QE-12, 86 (1976).

[8] D.G. McDonald, A.S. Risley, J.D. Cupp, and K.M. Evenson, "Harmonic Mixing of Microwave and Far-Infrared Laser Radiation Using a Josephson Junction," Appl. Phys. Lett. 18, 162-164 (1971).

[9] T.G. Blaney and D.J.E. Knight, "Direct 825th Harmonic Mixing of a 1 GHz Source with an HCN Laser in a Josephson Junction," J. Phys. D: Appl. Phys. 7, 1882-1887 (1974).

[10] T.G. Blaney, N.R. Cross, and D.J.E. Knight, "Harmonic Mixing and Frequency Measurement at 2.5 THz Using Josephson Junctions," J. Phys. D: Appl. Phys., 9, 2175-2181 (1976).

[11] W. C. B. Peatman and T. W. Crowe, "Design and Fabrication of 0.5 Micron Gallium Arsenide Schottky Barrier Diodes for Low-Noise Terhertz Receiver Applications", Int. Journ. Infared and MM Waves; 11, #3, 355-365, (1990).

[12] K.M. Evenson, F.R. Petersen, and J.S. Wells, "Laser Frequency Measurements: A Review, Limitations, Extension to 197 THz (1.5 μm) in Laser Spectroscopy III, (Ed. J.L. Hall and J.L. Carlsten, Springer Verlag 1977) pp. 56-68.

[13] F.L. Walls, C.M. Felton, and T. Martin, "High Spectral Purity X-Band Source," these proceedings.