Precise optical frequency references and difference frequency measurements with diode lasers[†]

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ABSTRACT

Heterodyne methods have been used in conjunction with molecular calculations to accurately determine the wavelengths of more than 35,000 infrared transitions. We have used high speed whisker contact Schottky diodes to extend this technology to the 0.8 μm spectral region. Using microwave harmonic mixing we demonstrate that it is possible to detect beat notes between diode lasers to frequencies as high as 400 GHz.

1. INTRODUCTION

Optical heterodyne techniques can play a fundamental role in precision spectroscopy and laser frequency control. Increasing demand for precise frequency measurements in the visible and near-infrared regions of the spectrum have resulted in a number of ideas for optical frequency synthesis.[1-4] These proposals often require several tunable narrow-linewidth laser sources. For purely practical reasons these sources might best be supplied by diode lasers. Achieving optical frequency synthesis and measurement will require high-accuracy optical frequency references, very narrow linewidth, well-controlled lasers, and the ability to make frequency difference measurements over extremely large frequency intervals. We have explored and continue to explore some of the promising optical frequency references that are compatible with diode lasers. Of particular interest in this area are the narrow intercombination transitions in the group-II atoms such as calcium,[5,6] barium,[7] and strontium.[8] Our effort at NIST on diode-laser compatible frequency/wavelength references has focused primarily on the calcium transition at 657 nm and on laser-cooled cesium.[9,10]

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An effort in measuring the frequencies of molecular transitions in the infrared has just been completed at NIST by J. Wells and A. Maki.[11-13] They determined the absolute frequencies of more than 35,000 molecular transitions in the wavelength range between 486 and 4352 cm^{-1}. In their measurement system tuneable lead-salt diode lasers were used to probe the molecular transitions, and heterodyne techniques were used to measure the frequency of the diode laser relative to known stabilized gas laser frequencies. These newly tabulated frequencies now provide a precise calibration atlas for wavelengths in the infrared. This work demonstrates the utility of using heterodyne methods for precision spectroscopy.

We have been exploring the potential for extending these heterodyne techniques using diode lasers to larger frequency intervals and up into the visible and near-visible spectral regions. Some time ago H. U. Daniel, J. Bergquist, and collaborators[14,15] demonstrated that very small Schottky diodes could be used to measure difference frequencies of visible lasers to hundreds of gigahertz. Their devices were similar to ours which were actually designed as millimeter-wave detectors for applications such as radio astronomy. Following their lead we have been using these high-speed, whisker-contact Schottky diodes simultaneously as photodetectors and microwave harmonic mixers. These detectors consist of small, recessed Pt-Au islands on a GaAs epilayer grown on a GaAs substrate. The area of the gold islands is about 1.5 μm^2 which gives a capacitance of about 2.6 fF and a 3 dB corner frequency for millimeter-waves of about 3.7 THz. The useful optical detection bandwidth has not yet been fully determined.

2. EXPERIMENTAL DETAILS

The experimental apparatus is diagrammed in Fig. 1. It consists of two 830 nm, AlGaAs lasers that are optically locked[16] to different modes of a single confocal Fabry-Perot cavity. The lasers' outputs are combined and focused on the Schottky diode along with the output from the microwave source. The Schottky diode generates the laser beat frequency as well as the harmonics of the microwave source. The laser beat note is detected directly or is mixed down by heterodyning with the microwave frequency or one of its harmonics. The microwaves are supplied by a klystron (at about 47 GHz) or by a synthesizer.

A picture of the beatnote between two diode lasers and the eighth harmonic of a 47 GHz klystron is shown in Fig. 2. With an optical frequency difference of 382 GHz, this beatnote demonstrates the good signal-to-noise ratio that can be achieved with this detection system even though the Schottky diode is not at all designed for optical detection. The typical experimental parameters were ≈5 mW in each of the two lasers beams, ≈200 mW of klystron power, and a spectrum analyzer resolution bandwidth of 10 kHz. The detector can be biased to enhance the mixing and/or harmonic generation efficiency. However, we have found that when the microwave power on the detector is high the bias has very little effect on the detected signal-to-noise ratio. A large experimental uncertainty in the actual microwave power that is coupled onto the detector remains, but we typically operate the detector so that

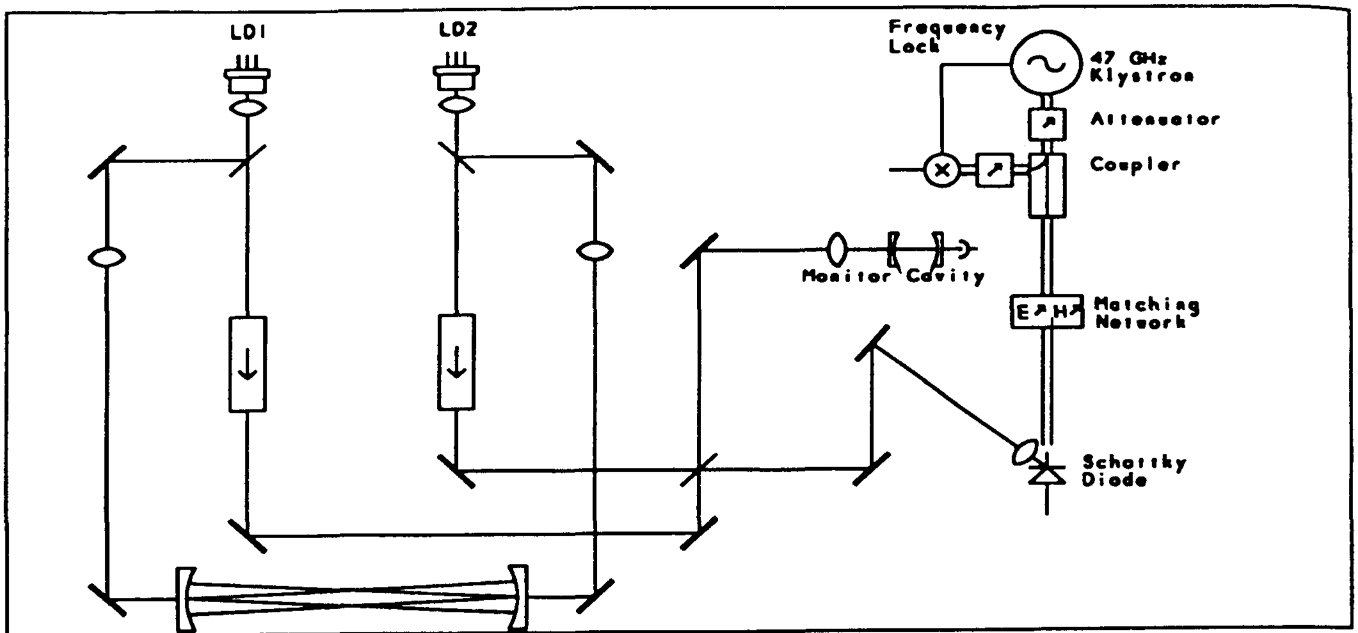

Fig. 1. Optical-microwave mixing experimental diagram.

the rectified current from the microwaves is about 1.5 mA. The direct optical detection efficiency of the laser light, as measured from the DC photocurrent, is about 20 µA/mW. Even though this value is quite low compared to silicon photodiodes (≈450 µA/mW at these wavelengths) we measure good signal-to-noise ratios on the beatnotes. With the lasers off, the dominant noise from the detector is shot noise in the rectified microwave current.

The good signal-to-noise ratio is partly the result of the narrow spectral width of the optically-locked diode lasers, which allows us to use a 10 kHz bandwidth. We measured short-term laser linewidths between 1 and 10 kHz.[10] The laser beatnote was about 70 dB above the background noise in a 10 kHz bandwidth when both lasers are optically locked. This background noise is from residual high frequency noise on the lasers. By locking both lasers to the same optical cavity we remove most of the problems of cavity vibration and drift. Even so, the lasers still have substantial low frequency jitter (approximately 100 kHz) and drift, which are mainly due to the low finesse of the optical locking cavity and mechanical instabilities in the feedback phases. The present optical locking cavity

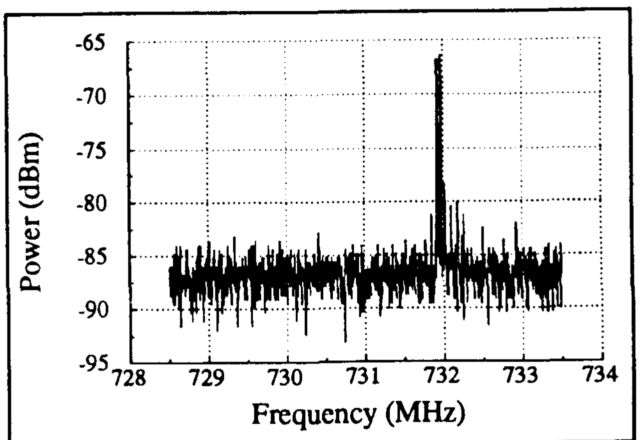

Fig. 2. Beatnote at 382 GHz between two diode lasers detected relative to the eighth harmonic of a 47 GHz klystron. Spectrum analyzer resolution bandwidth was 10 kHz.

has a free spectral range of 300 MHz and a finesse of about 30.

3. RESULTS

By mixing the laser-laser beat note with increasingly higher harmonics of the klystron, we have observed the beat note between the two diode lasers out to almost 400 GHz. A plot of the signal-to-noise ratio (SNR) as a function of the difference frequency between the lasers is shown in Fig. 3.

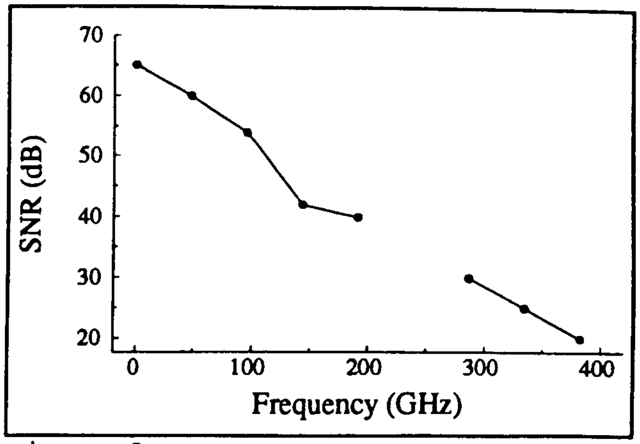

Fig. 3. Beatnote SNR as a function of frequency. Lowest frequency data point is the direct laser-laser beatnote. Other data points correspond to mixing the laser-laser beatnote with 47 GHz radiation and its harmonics.

The data points in Fig. 3 correspond to the harmonics of the 47 GHz klystron. The signal-to-noise ratio in the baseband response of the detector in direct measurements of the laser-laser beatnote is essentially flat out to about 27 GHz. The actual electrical bandwidth of the present Schottky diode mount is flat to about 8 GHz. This is presently limited by the imperfect matching of the whisker and diode mount to the 50 Ω transmission line. Better matching would be helpful, but is not necessary because the signal-to-noise ratio is limited by noise, not by signal, out to 27 GHz. This 27 GHz spans more than half of the 47 GHz local oscillator frequency. Thus we have, at least in principle, complete coverage with this detector for any laser beat note between dc and 400 Ghz. In practice, for IF frequencies above about 12 GHz an additional mixing stage with a standard microwave mixer can be helpful.

We do not know whether the roll-off we see at higher frequencies in Fig. 3 is due to some optical detection bandwidth, or whether it is due to the harmonic generation efficiency. Most probably it is the result of both. Evidence for this is seen in Fig. 4 which shows the signal-to-noise ratio as a function of harmonic number for two different LO frequencies (10 GHz and 47 GHz). Plotted in this manner, the 47 GHz data fall off faster than the 10 GHz data. In contrast, if these data are plotted as a function of the laser beat frequency, the signal-to-noise ratio of the 10 GHz data falls off very fast as the frequency approaches 100 GHz, while the 47 GHz data fall

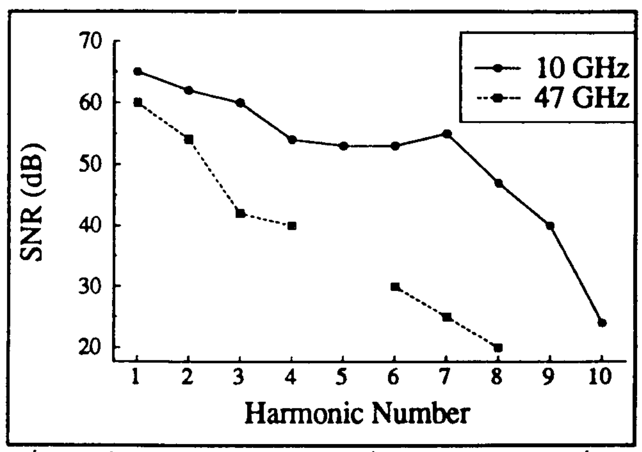

Fig. 4. Beatnote signal-to-noise ratio as a function of microwave harmonic for two different microwave frequencies, 10 and 47 GHz.

more slowly and extend out to about 400 GHz.

In order to better understand the general applicability of this technique we have looked at the wavelength dependence of the dc optical detection efficiency for our diodes. These results are shown in Fig. 5 and indicate that the optical detection efficiency is relatively flat between 600 and 850 nm.

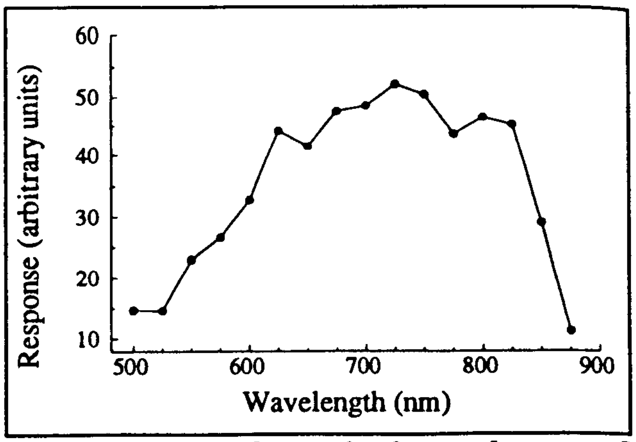

Fig. 5. Wavelength dependence of the Schottky diode optical detection efficiency.

4. CONCLUSION

Our results demonstrate that we can now directly measure the frequency difference between tunable diode lasers out to at least 400 GHz with a signal-to-noise ratio greater than 20 dB in a 10 kHz bandwidth. Although we have a long way to go in direct measurement of optical frequencies, 382 GHz corresponds to 0.1 % of the optical laser frequency and is significantly higher than has been measured with other kinds of optical detectors. We are hopeful that by using higher LO frequencies we can push the useful beatnote detection bandwidth well beyond our present 400 GHz.[14]

5. ACKNOWLEDGMENTS

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