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Frequency stabilization of an optically pumped far-infrared laser to the harmonic of a microwave synthesizer

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Measurements of the frequency stability of a far-infrared molecular laser have been made by mixing the harmonic of an ultrastable microwave source with a portion of the laser output signal in a terahertz (THz) Schottky diode balanced mixer. A 3 GHz difference-frequency signal was used in a frequency discriminator circuit to lock the laser to the microwave source. Comparisons of the short- and long-term laser frequency stability under free-running and locked conditions show a significant improvement with locking. Short-term frequency jitter was reduced by an order of magnitude, from approximately 40 to 4 kHz, and long-term drift was reduced by more than three orders of magnitude, from approximately 250 kHz to 80 Hz. The results, enabled by the efficient Schottky diode balanced mixer downconverter, demonstrate that ultrastable microwave-based frequency stabilization of THz optically pumped lasers (OPLs) will now be possible at frequencies extending well above 4.0 THz.

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1. INTRODUCTION

Many applications of CO_2 optically pumped, far-infrared molecular lasers (OPFIRLs), like spectroscopy [1], plasma fusion diagnostics [2], and radar imagery (particularly SAR) [3] require frequency-stable terahertz (THz) radiation. For example, for a 2 m long OPFIRL operating at 1.5 THz, a 50 kHz frequency shift corresponds to a 6 nm change in a cavity length. In a typical laboratory environment, temperature changes and mechanical and acoustic vibrations can alter cavity lengths by more than the nanometer level, so these factors are significant and their effects need to be minimized.

A laser's frequency can be stabilized by comparing it to the frequency of another, more stable, reference source. An ideal reference source is known to be the high harmonic of an ultrastable microwave frequency, since microwave synthesizers are widely available. However, the signal-to-noise (S/N) of a beat signal decreases rapidly with increasing harmonic number and regular corner-cube-mounted (CCM), whisker-contacted Schottky diodes cannot produce a sufficiently strong intermediate frequency (IF) signal for laser frequency locking above 1 THz. For example, a 671 GHz OPFIRL has been successfully stabilized using the 7th harmonic of a phase-locked Gunn oscillator generated in a CCM Schottky diode [4]. A planar Schottky diode, used [5] as a harmonic mixer, allowed the authors in [6] to stabilize frequencies above 1 THz. They successfully frequency-locked a 1626.6 GHz OPFIRL to the 10th harmonic of a 163 GHz signal, achieving an S/N of 20 dB at a resolution bandwidth (RBW) of 1 kHz. Prior to this the authors similarly frequency-locked an 803 GHz OPFIRL ($S/N = 40$ dB, $RBW = 1$ kHz), so frequency doubling led to a 20 dB S/N reduction, implying that these harmonic mixers had reached a high-frequency limit. Thus, a more efficient Schottky diode harmonic mixer is needed to implement laser frequency stabilization at frequencies above 1.5 THz.

In this paper, detection of the downconverted IF between the laser and the harmonic of the microwave source is made in a novel planar THz Schottky diode and the IF signal ($S/N = 55$ dB, $RBW = 1$ kHz) is electronically processed for frequency locking of a 1.56451 THz OPFIRL. Moreover, we demonstrate that these devices provide strong harmonic mixing signals at much higher THz frequencies.

2. EXPERIMENTAL SETUP

Figure 1 is a schematic of the setup that is used to lock the 1.56451 THz laser line in methanol, CH_3OH. A frequency tripler operating from 70 to 120 GHz is driven by a microwave

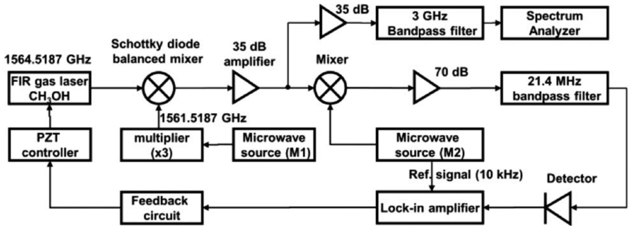

Fig. 1. Circuit configuration used in frequency locking the OPFIRL to the 19th harmonic of the microwave source (M1). The modulated microwave source (M2) and 21.4 MHz bandpass filter provided an error signal that stabilized the IF, ($\nu_{OPFIRL} - \nu_{M1} \times 3$), and locked the OPFIRL to the microwave reference source.

synthesizer (M1). The multiplier output at 97.594 GHz is coupled by the WR 10 waveguide into a 1.5 THz fundamental waveguide balanced mixer developed by Erickson [7], using THz Schottky monolithic membrane-diode (MOMED) devices provided by JPL [8]. The mixer block, shown in Fig. 2, was designed with a separate waveguide port for injecting the millimeter wave signal, leaving the IF port of the mixer block free for coupling out the 3 GHz IF beat signal between the 19th harmonic of the multiplier frequency and the laser frequency. The THz balanced mixer has been previously shown to provide superior performance to CCM, whisker-contacted Schottky diodes, both as downconverters and sideband generators [9]. Here, the 3 GHz IF signal is measured on a spectrum analyzer with an observed S/N of ~40 dB using a 30 kHz RBW, a S/N level that cannot be achieved using CCM or earlier planar diodes.

To generate a frequency discriminator signal, the IF signal is amplified by 35 dB and downconverted to 21.4 MHz using a microwave mixer and synthesizer. The 21.4 MHz signal is amplified by 70 dB and passed through a 100 kHz wide RF bandpass filter centered at 21.4 MHz. The synthesizer frequency is sinusoidally modulated at 10 kHz with a modulation depth of 120 kHz, and the 10 kHz modulation frequency is used as a reference frequency for the lock-in amplifier (LIA), whose input is the RF-rectified 21.4 MHz signal. The lock-in output at the reference frequency is proportional to the first derivative of the bandpass spectrum and thus provides a basis for locking the laser frequency to the harmonic of the microwave reference. The lock-in output is input to a typical proportional/integral (PI) feedback circuit, and the output of the PI circuit is used as the error-correcting signal. The same mixer, downconversion electronics, and discriminator circuit were earlier used to frequency lock a 2.324 THz quantum cascade laser [10].

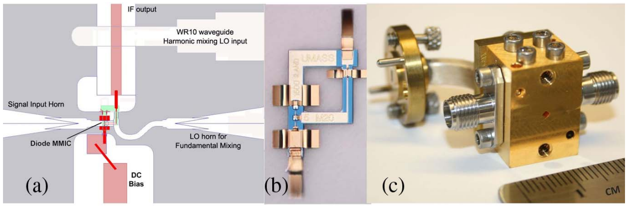

Fig. 2. (a) Schematic diagram of the balanced mixer showing the WR10 waveguide that is used as the local oscillator (LO) input as well as the LO feedhorn that is not used for harmonic mixing. The horn on the left side is used for the OPFIR signal input. (b) Photograph of the device (taken from Ref. [7]). Green areas are the GaAs substrate and gold areas are metal on the MMIC chip. (c) Photograph of the mixer block with the W-band waveguide input.

Locking the OPFIRL to a harmonic of the microwave reference requires a mechanical adjustment of the gas laser's cavity length. This is best accomplished by translating the output mirror (aka output coupler) with a piezoelectric translator (PZT) assembly. More precisely, both the output coupler holder and coupler need to be translated. Ideally, the movement should be fast enough to respond to, and correct for, the mechanical and acoustic "noise" that perturb the cavity length, but rapid mechanical movement of an object of finite mass will always involve trade-offs. Based on our observations of laser frequency fluctuations and drift we chose a set of parameters that would not stress the limits of the commercially available PZT hardware; namely, the cavity should be translatable over a distance of 1 μm in a time as short as 5 ms. This corresponds to a frequency shift of approximately 750 kHz and noise spectra out to 200 Hz. In addition to being able to operate in a high-vacuum environment, we needed a versatile PZT assembly that could translate both uniform (Si-coated dielectric) output couplers and hole (metallic) couplers. The feedback loop for locking the laser frequency to the harmonic of the microwave reference is completed by feeding the output of the PI circuit to the PZT voltage controller input.

3. LONG-TERM STABILITY AND SPECTRAL PURITY MEASUREMENTS

The proportional and integral parts of the feedback circuit ensure the spectral purity and the long-term stability of the gas laser, respectively. The obtained long-term OPFIRL stability results are shown in Fig. 3, where data were recorded with a counting time of 2 s using a frequency counter. The blue curve drift of 250 kHz which represents the free-running gas laser stability over 4.5 h is significantly larger than the one of the red line which represents the locked laser's frequency stability. Zooming in on the red line reveals a frequency drift of 80 Hz within a 260 min timeframe (0.3 Hz/min) (Fig. 4). The drift is

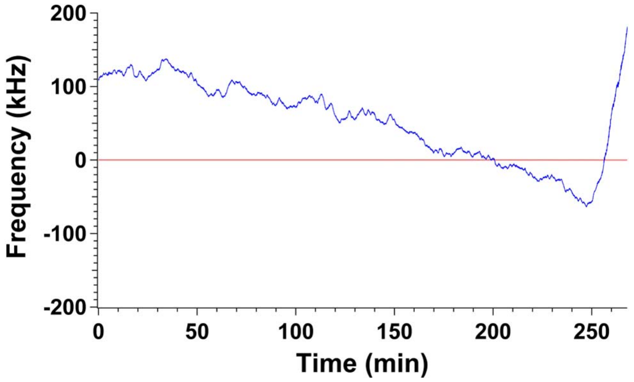

Fig. 3. Long-term frequency fluctuations of the 3 GHz beat signal recorded (2 s/point) during a 4.5 h time interval of the free-running (blue curve) and locked (red curve) OPFIRL.

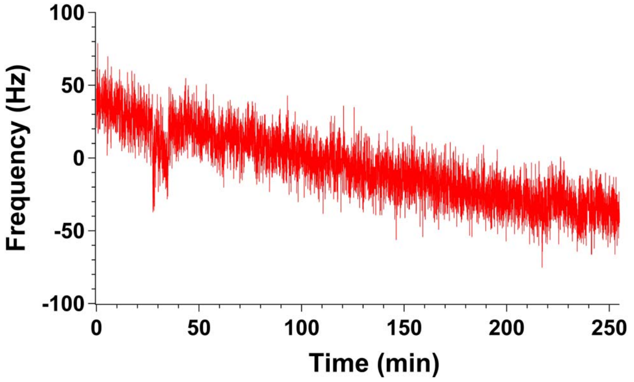

Fig. 4. Long-term drift of the 3 GHz beat signal recorded (2 s/point) when the laser was stabilized.

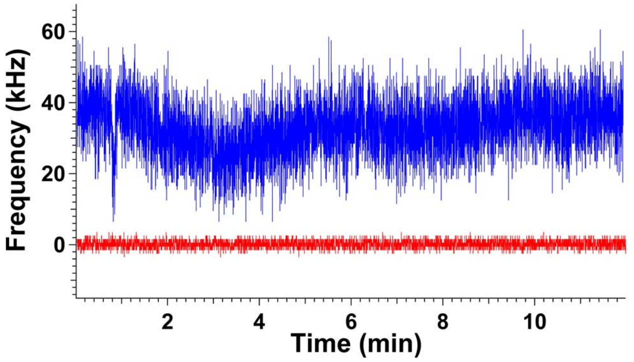

Fig. 5. Long-term frequency fluctuations of the 3 GHz beat signal recorded (20 ms/point) during a 15 min time interval of the free-running (blue curve) and locked (red curve) OPFIRL.

due to a lack of sufficient loop gain in combination with the slow drift of the reference source. The presented results were achieved with an integrator bandwidth of approximately 1 Hz and a proportional circuit bandwidth of 1 kHz, determined by the LIA time constant.

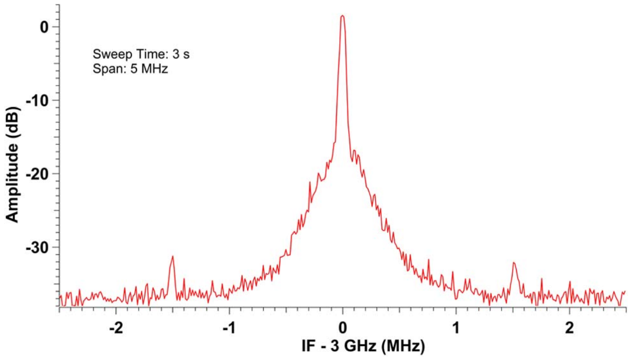

Fig. 6. Frequency spectra of the 3 GHz beat note recorded from the spectrum analyzer under locked conditions with 3 s scan time (resolution bandwidth of 30 kHz).

Table 1. OPFIRL Downconversion Results using the 2.3 THz Harmonic Mixer

OPFIRL Line (THz)	Power (mW)	N	S/N (dB) (RBW 30 kHz)
2.52	4	22	42
3.1	20	27	47
4.25	7	37	27

In order to see the spectral purity (linewidth) of the beat signal when the laser was locked and unlocked, the 3 GHz IF signal was recorded with a counting time of 20 ms over 15 min using the frequency counter (Fig. 5). Linewidth narrowing from 40–50 kHz to 3–5 kHz for the optimum parameters of the feedback circuit is seen in the figure. The locked beat note width of 3–5 kHz is due to residual noise, which is not removed by the feedback loop.

Figure 6 shows the beat note between frequencies of the stabilized laser and 19th harmonic of the microwave source which was recorded using the spectrum analyzer with resolution bandwidth of 30 kHz and sweep time of 3 s. It demonstrates the signal-to-noise ratio of 40 dB achieved in the system. A secondary transverse mode of the OPFIRL is responsible for the 1.5 MHz offset beat signal seen in the plot.

Measurements were made to evaluate the high-frequency limits of the mixers. A similar 2.3 THz Schottky diode balanced harmonic mixer with a microwave source was used to downconvert free-running OPFIRL lines at 2.52, 3.10, and 4.25 THz. The achieved results are shown in Table 1, where N stands for a harmonic number. The S/N data indicates that these mixers will enable OPFIRL frequency stabilization by microwave harmonic mixing up to above 4 THz.

4. CONCLUSION

The far-infrared molecular laser frequency has been locked to the harmonic of the microwave reference using a THz Schottky diode balanced mixer. Short-term frequency jitter was reduced by an order of magnitude, from approximately 40 to 4 kHz and long-term drift was reduced by more than three orders of magnitude, from approximately 250 kHz to 80 Hz.

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