Low-noise optical injection locking of a resonant tunneling diode to a stable optical frequency comb

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Optical injection locking of a resonant tunneling diode (RTD) oscillator has been demonstrated using ultrashort pulses from a mode-locked Ti:sapphire laser operating at a 1 GHz pulse rate. The source of the optical signal is a mode-locked femtosecond laser whose optical frequency comb is phase locked to a H-maser stabilized frequency synthesizer. An exceptionally large capture range of more than 5 MHz is observed. The system produces stable microwave signals with low phase noise, which at 1 GHz is less than −74 dBc/Hz for a 10 Hz offset. The noise of the microwave injection-locked RTD signal matches that of the input optical pulses.
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This letter demonstrates optical injection locking of a resonant tunnel diode to convert the ultrashort, high stability pulses from a self-referenced optical frequency comb into microwave signals with an unprecedented capture range and low phase noise. Research of recent years has yielded unmatched frequency stability and low phase noise from oscillators based on self-referenced optical frequency combs locked to narrow optical transitions in laser-cooled atoms.[1,2] The repetition rate of the optical pulses from the self-referenced mode-locked laser is then essentially a subharmonic of the optical atomic frequencies, $f_{rep}=f_{atom}/N$, where N is a large ($\sim 10^5$) integer. Bartels and co-workers have shown that the fractional frequency instability of these optical clock pulses relative to the input reference is $\sim 10^{-17}$ with 1 s averaging and providing subfemtosecond timing jitter.[2,3] However, detection of the same signals on a GaAs *p-i-n* photodiode generates some excess timing jitter and phase noise, resulting in stability that is ten times[3] worse in the electrically detected f_{rep}. Because of this and other limitations of traditional photodetectors such as nonlinearities, saturation, and bandwidth limits, we are interested in alternatives to the photodiodes for f_{rep} detection.

Resonant tunneling diodes (RTDs) are interesting candidates for transferring f_{rep} to high frequency microwaves that could be controlled with stabilized femtosecond pulses and could be remotely located at the end of a fiber link. Their quantum mechanical tunneling mechanism and small size result in very fast devices, and oscillation frequencies up to 712 GHz have been demonstrated.[4] Optical injection locking of RTDs provides the high speed connection between fast, short optical pulses and fast, short electrical pulses. We demonstrate here that this approach can cleanly transfer the stability of high Q (10^{12}–10^{14}) optical transitions to microwave electronic signals.

Optical injection locking of a RTD was first demonstrated by Higgins *et al.*[5] using a modulated laser diode optical signal at a 2.8 GHz oscillation frequency and with a 150 kHz locking bandwidth. Kahn *et al.*[6] have shown optical injection locking of a RTD with 1.5 μm rf-modulated cw light source and demonstrated a 300 kHz capture range of a 360 MHz rf signal. Lasri *et al.*[7] and Eisenstein and co-workers[8,9] have converted modulated cw lasers and mode-locked diode lasers into very low phase-noise rf oscillations and have provided very useful and advanced models for the analysis of the noise in optically injection-locked microwave oscillators.[8,9] This letter reports optical injection locking of a RTD at 1 GHz oscillation frequency. Here we have taken advantage of a high stability signal from an optical frequency comb phase locked to a narrow optical transition in laser-cooled atoms. We show locking ranges of ⩾5 MHz, which is a more than ten times greater range than previously reported.[5,6] The injection-locked RTD oscillator produces microwave signals with noise characteristics that match those of the input signal and limited by the measurement instrument noise floor, yielding a single sideband phase-noise density of less than −74 dBc/Hz at 10 Hz offset.

The inset of Fig. 1 shows a schematic of the RTD circuit used for injection locking. The InGaAs/AlAs RTD material structure was the same as that in Ref. 10. Mesa devices (8 μm diameter, 0.4 μm height) were formed by use of a

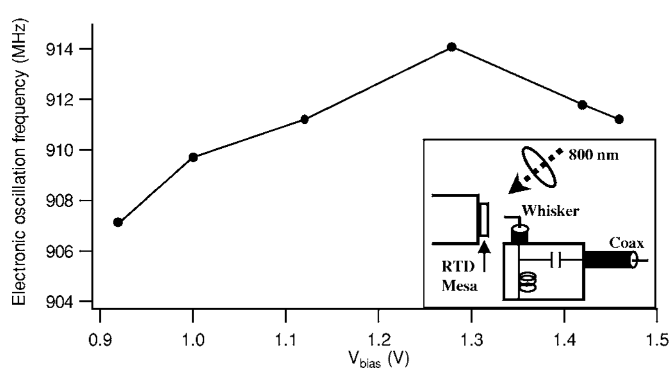

FIG. 1. Typical variation of electronic RTD oscillation frequency with dc bias voltage. Inset: Schematic of experimental setup.

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self-aligned contact and bromine ion-beam assisted etching. The top and bottom Ni/Ge/Au contacts were annealed at 720 K (~450 °C) for 30 s. The grounded RTD is contacted through an etched tungsten whisker and is dc biased into the negative conductive region (NCR) using an 18 GHz bias tee. The RTD is bonded to the center conductor of a copper coaxial resonator that is approximately 4 cm long and that resonates at about 911 MHz. The electrical pulses from the resonator are coupled out using a small electrical probe brought close to the open end of the coaxial resonator and are then amplified (15 GHz bandwidth and 10 dB gain) and monitored with a microwave spectrum analyzer.

When the RTD is biased into the NCR, the free-running oscillation frequency is determined to a first approximation by the resonant frequency of the coaxial resonator. The oscillation frequency depends to a smaller degree on the nonlinear RTD impedance, which is a function of the dc bias voltage. As is shown in Fig. 1, the oscillation frequency does not vary monotonically with bias voltage. Instead, it increases with the bias voltage, reaches a maximum frequency, then decreases until the RTD is no longer biased in the NCR region and the oscillations cease. The oscillation frequency and range vary over a few megahertz for different whisker contacts. Harmonics of the fundamental were observed to the 20th harmonic, indicating the approximate temporal width of the electrical pulses. Our experiments were carried out with RTDs that were not in any way optimized for responding to optical signals, and over the bias voltage range corresponding to electronic oscillations showed a dc optical-to-electrical responsivity of around 9 mA/W.

Optical injection locking was achieved with optical pulses from a high repetition rate mode-locked Ti:sapphire laser (central wavelength of ~800 nm). Pulses of ~30 fs were coupled into a single mode fiber (~5 m) and then focused onto the RTD at about 45° by a 13 mm focal length microscope objective. The laser repetition rate f_{rep} was tuned near the coaxial resonator frequency (911 MHz) using a piezoelectric transducer on the laser cavity which also allowed f_{rep} to be phase locked to a low-noise synthesizer referenced to a hydrogen maser.

The rf spectra of the free-running and injection-locked RTD oscillator were measured on a rf spectrum analyzer (Fig. 2). The free-running signal has a single-sided noise power density of −86 dBc/Hz at 100 kHz offset, compared to the −78 dBc/Hz previously reported.[6] Adding laser light with a pulse repetition frequency close to the free-running oscillation frequency pulls the electronic oscillation to the laser repetition rate f_{rep}, and the spectrum collapses to match that of the laser light pulses with 10 dBc/Hz noise suppression at 10 kHz offset when injection locked. Phase locking f_{rep} to a maser-referenced synthesizer further reduces the noise on f_{rep} and likewise the injection-locked signal. Figure 2 bottom panel) shows the injection-locked signal with a 1 Hz resolution bandwidth with f_{rep} phase locked to a low-noise rf synthesizer referenced to a 5 MHz signal derived from a Hydrogen maser. The output power is −30 dBm after a 10 dB amplifier, but we expect this number to increase after optimization of the outcoupling. Under some conditions, signal levels of −30 dBm in a 100 kHz bandwidth were measured without an amplifier. We verified that the noise on the injection-locked signal follows the noise introduced from the input synthesizer signal. As the noise level of the input changes when different synthesizers are used with

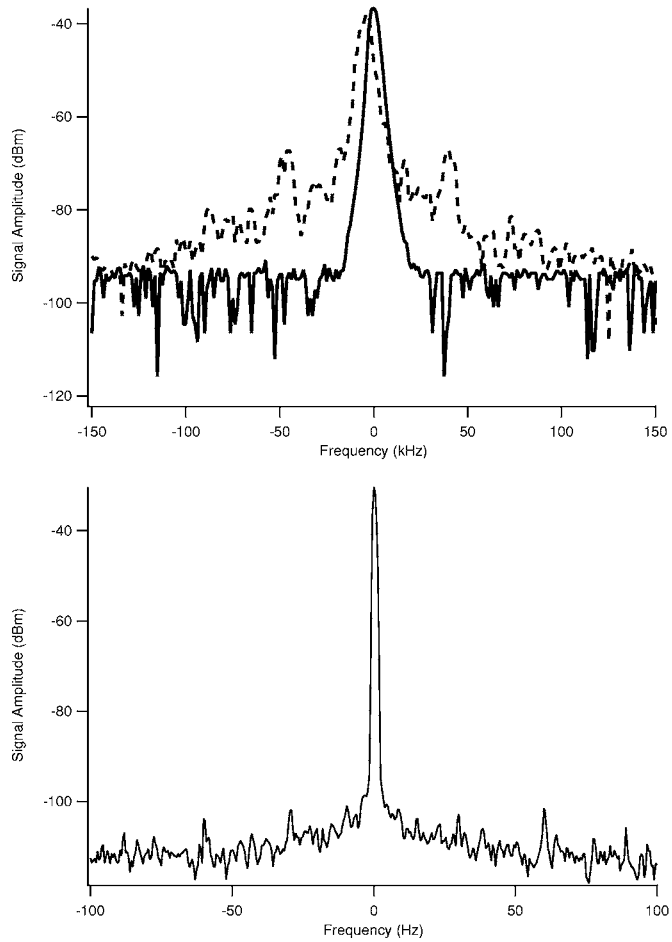

FIG. 2. Top panel: Free-running (dotted line) and injection-locked (solid line) oscillators at 1 GHz measured with a spectrum analyzer at 3 kHz RBW and 5 dB attenuation. Bottom panel: Injection-locked signal at 1 Hz RBW where laser repetition rate is phase locked to a low-noise synthesizer (0 dB attenuation). Note the different frequency scales.

and without the maser reference, the injection-locked signal changes accordingly. Any noise introduced by the injection-locked RTD is therefore less than that of the low-noise input signal and the noise floor of the spectrum analyzer [−147 dBm in 1 Hz resolution bandwidth (RBW)].

To examine the variation of the capture range, a whisker contact was chosen such that the electronic oscillation frequency range was approximately centered about f_{rep}. Keeping f_{rep} constant, the dc bias voltage was varied to determine the voltage where the signal ceases to be injection locked. This process was repeated for various incident laser powers (see Fig. 3). As expected, the capture range increases for increasing laser power, approaching an asymptote at high incident laser powers. A particularly interesting result is that for incident laser powers of 5 mW and greater, the injection locking range extends to higher voltages than those for the electronic oscillation range. For this reason, the dc bias voltage axis can be directly mapped onto a frequency axis only for data taken at laser powers less than 5 mW (e.g., Fig. 1). Even for the data taken at the lowest incident laser power, the capture range is on the order of 1 MHz, which is considerably larger than the 100–300 kHz capture range previously reported.[5,6] The improvement in locking range and spectral purity is likely due to the relatively large charge densities created in the RTD by the optical pulses and perhaps the significant differences in device structures and materials.

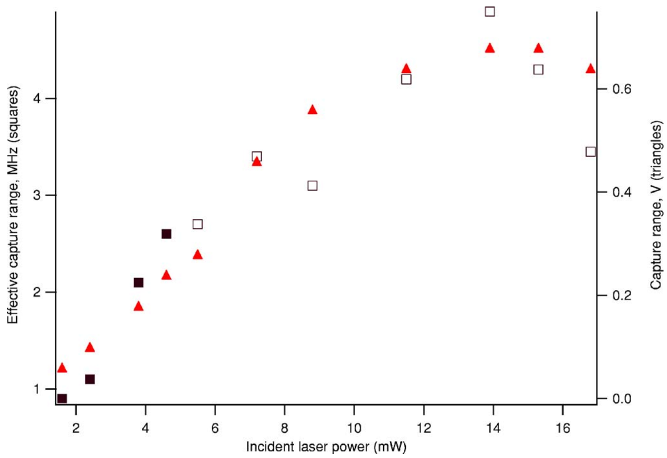

FIG. 3. Injection locking capture ranges vs incident laser power. Capture range in dc bias voltage is indicated by triangles. Capture range in megahertz is indicated by squares. The actual capture range (MHz) can only be measured for incident laser power ≤5 mW (filled squares). Effective (lower limit) capture range is shown by empty squares.

The temporal wave form of the RTD signal was recorded on a sampling oscilloscope with 15 GHz bandwidth. No significant difference was seen between the injection-locked and free-running wave forms, although the phase noise and hence timing jitter, is greatly improved. A narrow 70 ps feature, which we attribute to the RTD, was observed on top of the 700 ps response due to the other electronics in the circuit. In addition, the amplitude of the free-running and injection-locked signal harmonics was not altered.

In conclusion, we have shown the conversion of stable optical frequencies to low phase-noise microwave signals by injection locking a RTD oscillator. An exceptionally large capture range of 5 MHz was demonstrated, with noise on the injection-locked RTD signal matching that of the input femtosecond optical frequency comb.

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[1] L. Hollberg, C. W. Oates, E. A. Curtis, E. N. Ivanov, S. A. Diddams, T. Udem, H. G. Robinson, J. C. Bergquist, R. J. Rafac, W. M. Itano, R. E. Drullinger, and D. J. Wineland, IEEE J. Quantum Electron. **37**, 1502 (2001).
[2] L. Ma, Z. Bi, A. Bartels, L. Robertsson, M. Zucco, R. S. Windeler, G. Wilpers, C. Oates, L. Hollberg, and S. A. Diddams, Science **303**, 1843 (2004).
[3] A. Bartels, S. A. Diddams, T. M. Ramond, and L. Hollberg, Opt. Lett. **28**, 663 (2003).
[4] E. Brown, J. R. Soderstrom, C. D. Parker, L. Mahoney, and K. M. Molvar, Appl. Phys. Lett. **58**, 2291 (1991).
[5] T. P. Higgins, J. F. Harvey, D. J. Sturzebecher, A. C. Paolella, and R. A. Lux, Electron. Lett. **28**, 1574 (1992).
[6] M. Kahn, J. Lasri, M. Orenstein, D. Ritter, and G. Eisenstein, Solid-State Electron. **45**, 1827 (2001).
[7] J. Lasri, P. Devgan, R. Tang, and P. Kumar, Opt. Express **11**, 1430 (2003).
[8] J. Lasri and G. Eisenstein, J. Lightwave Technol. **20**, 1924 (2002).
[9] E. Shumakher and G. Eisenstein, IEEE Trans. Microwave Theory Tech. **52**, 1523 (2004).
[10] C. Chen, R. H. Matthews, L. J. Mahoney, S. D. Calawa, J. Sage, K. M. Molvar, C. D. Parker, P. A. Maki, and T. Sollner, Solid-State Electron. **44**, 1853 (2000).