Self-Injection Locking of a Microwave Oscillator by Use of Four-Wave Mixing in an Atomic Vapor

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***Abstract*—We demonstrate self-injection locking of a low-power, compact microwave oscillator by use of feedback generated from four-wave mixing in an atomic vapor. The four-wave mixing process creates an effective microwave filter with extremely high off-resonant signal suppression. This type of locking results in a shorter locking time, increased short-term stability, improved close-in phase noise, and reduced spurious signals as compared to current techniques used in miniature atomic clocks. Other possible benefits and drawbacks are mentioned.**

I. Introduction

The promise of ultra-miniature atomic frequency references has gained recent interest, driven by the goal of achieving frequency stability comparable to that of existing miniature atomic references but with greatly reduced size, power consumption, and production cost. Such devices would have broad applicability in military [1] and civilian [2] applications, including reliable GPS position tracking and secure communications. To date, progress in this direction has involved mostly the use of coherent population trapping (CPT) of atoms [3]. In this method, the high-Q atomic resonance is observed as an increase in light transmission through the atomic vapor cell when a laser light field is modulated so as to have spectral components precisely separated by the ground state hyperfine splitting frequency of the atoms.

CPT-based clocks are currently made by use of either active or passive locking techniques. In the case of a passive frequency reference, the output of a local oscillator (LO) is used as the modulation source and the LO frequency is tuned onto the resonance by use of lock-in detection, which requires modulating the LO. Phase-locking techniques based on a detected increase in the microwave signal have also been shown [4]. Passive systems are limited in both locking range and correction bandwidth, requiring the LO to be precisely tunable, to have minimal drift, and to have minimal high-frequency fluctuations. These specifications usually imply a high-power, large LO. Active locking [4, 5] eliminates the LO and much of the locking electronics by modulating the laser with its own microwave beat note, which is filtered by the atoms and is detected by a fast photodiode. However, these systems are sensitive to phase shifts in the oscillating loop and can be difficult to lock since the resonance is observed merely as an increase in an existing signal, often by less than 10 %. Also, increased complications in the locking dynamics can lead to instability and several possible resonances [5].

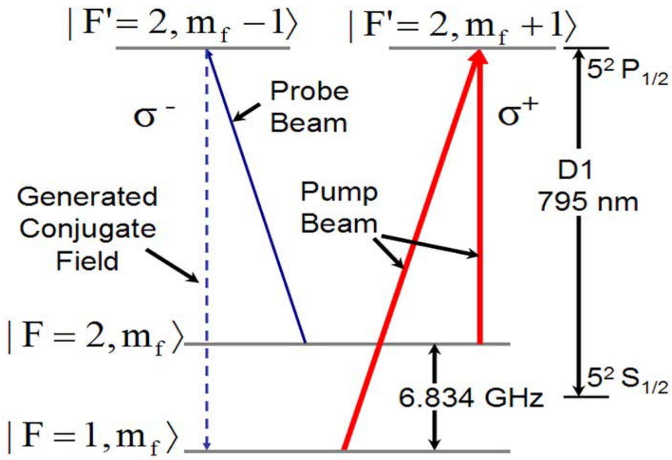

Fig. 1. Depiction of the level scheme used in CPT four-wave mixing experiments. The light field that is represented by the dotted line is generated with four-wave mixing. A clock is created by use of the ground state sublevel where $m_F = 0$ and a magnetometer is created by use of the magnetically sensitive sublevels $m_F = \pm 1$.

Recently, we demonstrated a passive frequency reference [6] that used a miniature, low power local oscillator [7]. Problems regarding the long-term instability of similar devices are largely due to temperature fluctuations and aging of the VCSEL [8-10]. The short-term frequency instability can be limited by the LO, which is itself limited in performance by stringent size and power consumption requirements. In particular, the phase noise of the LO at twice the modulation frequency has been shown to limit performance [11]. We demonstrate here a simple, robust, and potentially low-power lock to the atomic hyperfine transition. The approach requires no modulation of the LO and results in a design that can be easier to implement than recent active designs, has a larger locking range and correction bandwidth than passive methods, and presents improved phase noise and short-term instability versus comparable examples using both methods.

II. Method

The RF output signal from a compact local oscillator is sent to an optical system described in more detail below. This optical system acts as a narrowband RF filter and frequency doubler; it generates as its output a phase-coherent RF signal at twice the input frequency. This signal is used to self-injection lock the LO at the second harmonic, stabilizing its frequency. First we discuss the generation of the signal in the atoms.

Fig. 1 shows the atomic energy level diagram that can be used to describe CPT and four-wave mixing. Here, the ^{87}Rb atom is used as an example. The ^{87}Rb atoms are excited by the pump beam, a 795-nm circularly-polarized laser beam containing two optical components separated by 6.8 GHz. Each optical component is resonant with a transition between a ground-state component and the excited state. This results in coherent population trapping, or pumping of the atoms into a superposition of the two ground states. This superposition is uncoupled from the two light fields. When this occurs, a decrease in photon absorption is detected by a photodiode as an increase in total transmitted light. Because the spectral difference of the two optical components is a precise microwave frequency, one observes a very narrow resonance with a microwave Q typically greater than 1 million. However, the low contrast of the signal (of a few percent) is often a practical limitation. It has recently been shown [12] that a large improvement in contrast can be achieved with use of a four-wave mixing process that generates a new, phase-conjugated light field when CPT resonance occurs. In this process, a non-modulated probe beam is tuned to the $F = 2 \rightarrow F' = 2$ transition. This beam is identical to the pump beam in wavelength and spatial orientation but has opposite circular polarization. Due to the nonlinearities of the CPT process, a fourth phase-conjugated light field, separated from the probe by 6.8 GHz, is generated by the atoms. In [12] all the light fields except the generated field are removed and the signal is detected against a near-zero background. In our technique, we remove only the pump beam with a $\lambda/4$ waveplate and a polarizer. Both the probe beam and the generated field impinge on a fast photodiode. The output, a precise 6.834-GHz signal that is equal to the frequency difference between the ground state components, is then used to stabilize the LO. Whereas the process in [12] results in a large contrast in a DC photodetector signal, our process results in a large microwave contrast observed by a fast photodiode.

The primary advantage over the conventional techniques is that, rather than observing a small increase in an existing signal, this signal is observed only when the LO is tuned in the vicinity of the CPT resonance. This signal could be used to directly modulate the pump laser, forming an active system similar to [5]. However, several stages of amplification would be required to achieve the -6 dBm of power required to modulate the diode laser. Additionally, it has been shown [5] that signal power fluctuations in similar active frequency

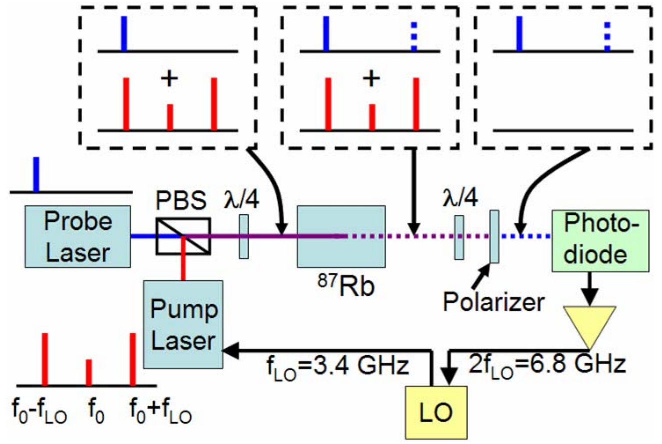

Fig. 2. Diagram of the experimental setup. The pump laser is modulated by the LO such that the two first-order sidebands are separated by 6.8 GHz. Additional filtering of the pump carrier wavelength is not needed. The probe laser is tuned to the same (795-nm) wavelength as the pump but has orthogonal polarization. $\lambda/4$ waveplates result in circular polarizations of the beams. When the LO is tuned to the CPT resonant frequency, a phase-coherent 6.8-GHz frequency is observed at the output of a fast photodiode. This is used directly (without frequency division) to injection-lock the LO.

references can cause instability due to power-sensitive phase shifts. Here, we use a low-power LO to modulate the laser with a relatively stable power and the generated signal is used to injection-lock the LO, stabilizing its frequency. Although the injected signal is at twice the frequency of the LO output signal, this harmonic injection locking occurs effectively with injected powers as low as -70 dBm. The LO output power remains largely unaffected by changes in injection-locking power, eliminating some of the problems caused by the unstable loop power in active self-locked systems.

III. Experimental Setup

Fig. 2 shows the setup used as a proof-of-principle experiment. The pump and probe lasers are vertical-cavity surface-emitting lasers (VCSELs) tuned to the 795 nm D1 line of ^{87}Rb. The pump laser is modulated with the 3.417 GHz, 0 dBm output of a miniature LO like that designed in [7] and that consumes less than 10 mW. The modulation produces sidebands in the optical spectrum, with the two first-order sidebands separated by 6.8 GHz. This light is then circularly-polarized by a $\lambda/4$ waveplate and then it passes through a 1 cm diameter glass cell containing ^{87}Rb atoms with a 50 Torr buffer gas pressure in a ratio of 1.44 argon to nitrogen. The incident optical intensity on the cell is approximately 50 $\mu W/mm^2$ for the pump. Then, a second but non-modulated probe beam is spatially aligned with the pump beam and its polarization is aligned perpendicular to the pump beam polarization. The probe has intensity, incident on the cell, of approximately 5 $\mu W/mm^2$. It interacts with the atoms that are pumped with the first beam, resulting in the generation of a phase-conjugated signal with the same polarization as the probe beam but separated from the probe in frequency by 6.834 GHz. The two beams are then linearly polarized by another $\lambda/4$ waveplate and the pump beam is removed with a polarizer. The combined probe and generated light field impinge on the fast photodiode, resulting in a 6.834-GHz oscillating current that yields -90 dBm when output from the photodiode. This signal is then amplified by as much as 50 dB and is fed directly into the output of the LO, which locks to the signal by harmonic microwave injection locking. We have observed that the LO output power remains stable over a wide range of injection-locking power, and levels less than -70 dBm are strong enough to lock the LO. Since this injection-locking is achieved at the second harmonic, no power-consuming frequency conversion is required. Also, because electromagnetic radiation at the hyperfine splitting frequency can destroy the CPT pumping of the atoms, operating at half this frequency can allow the LO to be placed very close to the atoms with no harmful effect. Since the LO in this experiment occupies less than 0.5 cm^2 on a substrate, and the VCSEL diodes and photodiode are much smaller, the system is well suited for ultra-miniature frequency references. The microwave amplifier can be built for low power consumption since its output power remains small.

IV. RESULTS

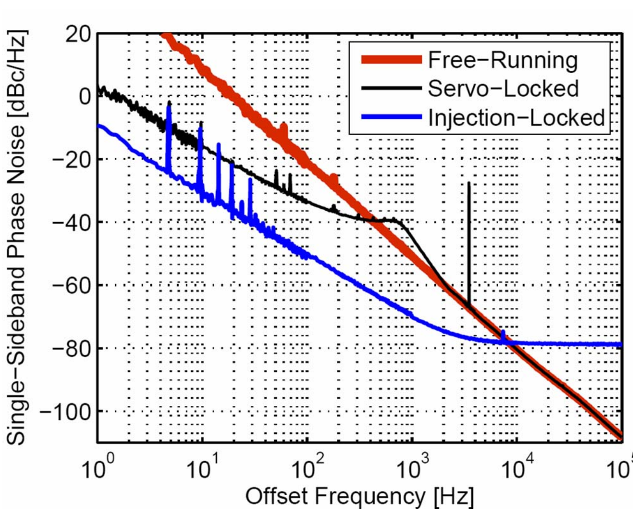

Fig. 3. Phase noise plots comparing the unlocked LO to typical servo control and to our injection locking method. Injection locking is shown to improve the close-in phase noise and removes the noise spike at 3.49 kHz, since modulation is not necessary.

Fig. 3 shows phase noise measurements of the output of the LO at 3.417 GHz. To obtain these measurements, the LO frequency was down-converted to 17.3 MHz by mixing against the output of a low noise synthesizer that was stabilized to a hydrogen maser reference. A commercially-available phase noise test set was then used to compare the 17.3-MHz signal against a low-phase-noise, oven-controlled quartz crystal reference. The free-running phase noise of the LO is considerably worse than that given by recently-used designs [6]. Nonetheless, lock-in amplification and detection (servo-locking) improved the phase noise by more than 40 dB at one Hertz offset, and the noise becomes worse than the free-running LO only around the locking bandwidth near 1 kHz. Here, the phase noise plateau characteristic of lock-in detection is observed, and so is the phase noise spike at 3.49 kHz, due to the required modulation. At frequency offsets larger than the locking bandwidth, we observe that the servo-locked LO matches the free-running LO in performance, as expected.

While keeping the LO bias and tune voltages the same, and while maintaining the same laser intensities and physical setup, the LO was injection-locked to the generated four-wave mixed output of the atoms. This method did not require modulation or lock-in servo electronics for the LO, and we observed a phase noise improvement of 10 dB at 1 Hz offset and 30 dB at 1 kHz offset. The slope of the noise data follows 20 dB per decade until hitting an apparent noise floor at -79 dBc/Hz. This floor is actually due to the injection locking of the LO to the noise floor of the amplified signal from the photodetector. It is consistent with the 1-Hz bandwidth signal-to-noise ratio of -79 dB, measured at the output of the amplified photodetector. For frequencies greater than the injection-locking bandwidth, this noise appears to roll off to the original noise floor of the LO, as expected. Using a spectrum analyzer, we observed a locking bandwidth greater than 20 MHz, depending on injection-locking power. The phase noise at large offsets can be improved by increasing the signal-to-noise ratio from the photodiode or by reducing the injection-locking power. However, this latter method reduces the locking bandwidth. Maintaining a high-bandwidth lock should permit stabilization of the LO during fast perturbations and over a wide range of frequency drifts. There are possible benefits in addition to improved close-in phase noise. For example, the removal of modulation of the LO reduces the requirement of low phase noise at twice the modulation frequency, which was due to a unique aliasing effect [11].

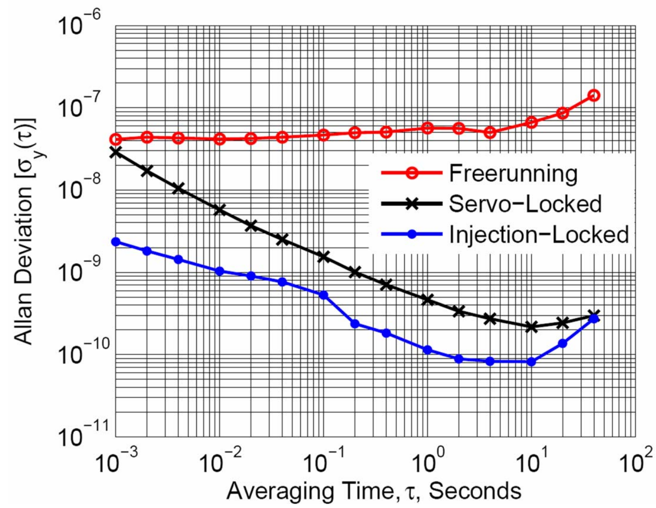

Fig. 4. Frequency instabilities using the different methods. Injection locking is shown to improve the short-term Allan deviation. The servo-locking correction time is shown at approximately 1 ms, and the injection-locking method provides much faster correction. Frequency drift at times greater than 10 s is observed in each method.

Fig. 4 shows the time-domain data that were measured under the same conditions (in fact, simultaneously) as the data in Fig. 3. Notice that the typically used servo lock begins improving the fractional frequency instability at 1 ms. The slope follows $1/\tau^{1/2}$, due to the white frequency noise of the atoms, until a drift, which is assumed thermal in nature, is observed after 10 seconds. When the system is configured for four-wave mixing and injection locking, the signal shows significant improvement in short-term instability. With good temperature stabilization, it is expected that this method will improve the overall stability of ultra-miniature atomic frequency references.

V. CONCLUSION

We have demonstrated the injection locking of a small, low-power LO to the phase-coherent signal generated from four-wave mixing in an atomic vapor. As with other atomic frequency references, the atoms provide a large effective microwave Q, which stabilizes the LO frequency. Our method achieves a simple, fast and robust lock to this signal, resulting in improved close-in phase noise and short-term frequency instability versus other methods used in similar systems. The components consume little power (several mW for the LO, less for the lasers and potentially less for the RF amplifier) and can be made small, showing promise for use in ultra-miniature frequency references. This method can be adapted for use in miniature atomic magnetometers by using the magnetically sensitive sublevels $m_F = \pm 1$ instead of the clock transition $m_F = 0$ to set the oscillation frequency. An adjustable phase shift in the microwave loop will switch the oscillating frequency between the clock and magnetic transitions, allowing for accuracy calibration by comparing the magnetically sensitive frequency to the magnetically insensitive one. It should be determined whether the method described here represents a stronger dependence on the atoms, resulting in a frequency reference that is less sensitive to vibration and acceleration than standard servo-locked clocks. The system is sensitive to microwave phase shifts in the loop, which could make it more sensitive to vibration and acceleration, depending on implementation.

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