USING LASER DIODE INSTABILITIES FOR CHIP-SCALE STABLE FREQUENCY REFERENCES

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Abstract

Semiconductor lasers are known to undergo significant changes in their output characteristics when subjected to external optical perturbations such as near-resonant injection from an external source or optical feedback. Over a range of operating conditions, the perturbations can induce a periodic pulsating output where the pulsation frequency can be controlled by the bias point of the laser(s), and amplitude (and frequency offset) of the injection. The output optical spectrum can be adjusted to be dominated by two strong frequency components with a controllable offset. Adding a weak microwave modulation to the bias can lock the pulsation frequency to this reference. Such a spectrum is nearly ideal for the excitation of Coherent Population Trapping (CPT) resonances of gas-phase atomic media such as cesium (Cs) and rubidium. We describe the double locking of a laser diode to the CPT optical (852 nm) and microwave (9.2 GHz) resonances in Cs gas in a cell containing Cs and a buffer gas. The microwave power required for the modulation reference is a small fraction of the dc-bias power, unlike a directly modulated laser diode. The combination of all-optical excitation of the Cs gas and reduced microwave electronics specifications is very useful for the fabrication of ultra-small frequency references.

INTRODUCTION

Interest in the fabrication of chip-scale atomic clocks (CSACs) has been spurred by recent work showing that all-optical excitation and probing of cesium (Cs) and rubidium (Rb) atomic vapors can be scaled down to very small sizes **[1-3]**. This work has made use of the novel nonlinear optical properties of the atomic medium that allow the creation of long-lived atomic coherences through Coherent Population Trapping (CPT) that alters the transmission properties of resonant light **[4]**. Because the atomic medium can be both excited and probed optically, the gas cell can be very small, sub-mm^3, and requires no direct microwave excitation, opening up the possibility of very small physics packages with low power budgets.

The all-optical excitation requires light at two resonant optical frequencies with a very high mutual coherence. To date, this has been achieved principally by direct modulation of a semiconductor laser. The modulation causes sidebands to be generated about the carrier frequency. While the absolute

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coherence of each of the laser frequency components is relatively large, with optical linewidths in 1-100 MHz range, the mutual coherence is determined by the linewidth of the microwave modulation source. Laboratory instruments that can generate highly coherent microwave signals are readily available. However, these units are bulky and consume excessive power for chip-scale implementation. Further, direct modulation requires that the modulation power be similar to, or larger than, the dc-bias power to the excitation laser **[1]**.

It is well known that semiconductor lasers can be very sensitive to perturbation by near-resonant light due to strong nonlinear optical interactions within the semiconductor gain medium **[5]**. Incident light levels as low as 10^{-4} of the output level are sufficient to destabilize monochromatic laser output and induce a pulsating, multi-frequency output. Here, we wish to show that such pulsating output can be simultaneously locked to optical and microwave references, a double-locked laser diode (DLLD), with sufficient precision to be a useful excitation and probing source for CSACs that use CPT.

NONLINEAR DYNAMICS IN SEMICONDUCTOR LASERS

The semiconductor laser is an important physical system both because of its wide-ranging applications and because it is an excellent test system for investigations of the predictions of laser theory and nonlinear dynamics theory. It is a highly nonlinear system due to the nature of the coupling between the optical fields and the gain medium. For most applications, the laser is simply a source of coherent optical power and its nonlinear characteristics are suppressed. However, the nonlinear response of the system to an external perturbation, such as an injected optical field or feedback from a distant reflector, can lead to potentially useful changes in its output characteristics. Past experimental work on the semiconductor laser subject to external optical injection has established that a range of optical outputs can be produced. For a laser operating at a given bias current, external optical injection can induce stable locked output, multiwave mixing, oscillatory power output due to an undamping of the carrier-field resonance of the system, and chaotic dynamics depending on the amplitude and offset frequency of the external optical field **[5]**. It has been found that a relatively simple model describing the coupling between the external and circulating optical fields and the free carriers of the gain medium can reproduce the observed characteristics observed experimentally. Because the key dynamic parameters of the model can be determined experimentally, a quantitative comparison can be made between experimental data and model calculations. Recently, a full comparison of experimental observations and model calculations has been made where excellent agreement between experimental data and model calculations was observed **[6]**. Typically, the laser output power changes from cw, monochromatic output to a periodically modulated output for resonant injection levels on the order of 10^{-4}, to chaotic output for power levels on the order of 10^{-2}, and back to oscillating or pulsating output for injection levels on the order of 10^{-2}. Because the pulsation frequency is easily controlled in this latter region and can be locked to a microwave reference, the nonlinear dynamics makes the laser an appropriate source without strong current modulation. However, no measurements have been made to show that excitation of the CPT resonance is possible with such a source.

Figure 1 shows a mapping of the output dynamics of a semiconductor laser subject to external optical injection with transitions between different output characteristics identified using the model. The particular laser is a 1.55-micrometer Distributed Feedback (DFB) laser diode, but similar characteristics have been observed for conventional edge-emitting Fabry-Perot laser diodes and Vertical Cavity Surface Emitting Laser Diodes (VCSELs) **[5]**. The output characteristics are shown as a function of the amplitude and offset, with respect to the free-running characteristics, of the laser. The mapping is asymmetric with respect to the offset due to the fact that both the gain and the refractive index of the semiconductor medium are sensitive to the external injection. There is a region of stable injection locking of the slave laser to the injected signal, plus regions where the output power is oscillatory or erratic. Of particular interest to the CSAC application is the transition across a Hopf Bifurcation to a region where the laser output is dominated by two optical field components whose offset can be precisely controlled. The optical frequency of one of the two components is locked to the external injection, while the other strong component can be locked at a precise offset using a microwave current reference creating the double-locked output **[7]**. In the CSAC application, the two frequency components are precisely locked to the optical and microwave resonance frequencies of the atomic medium.

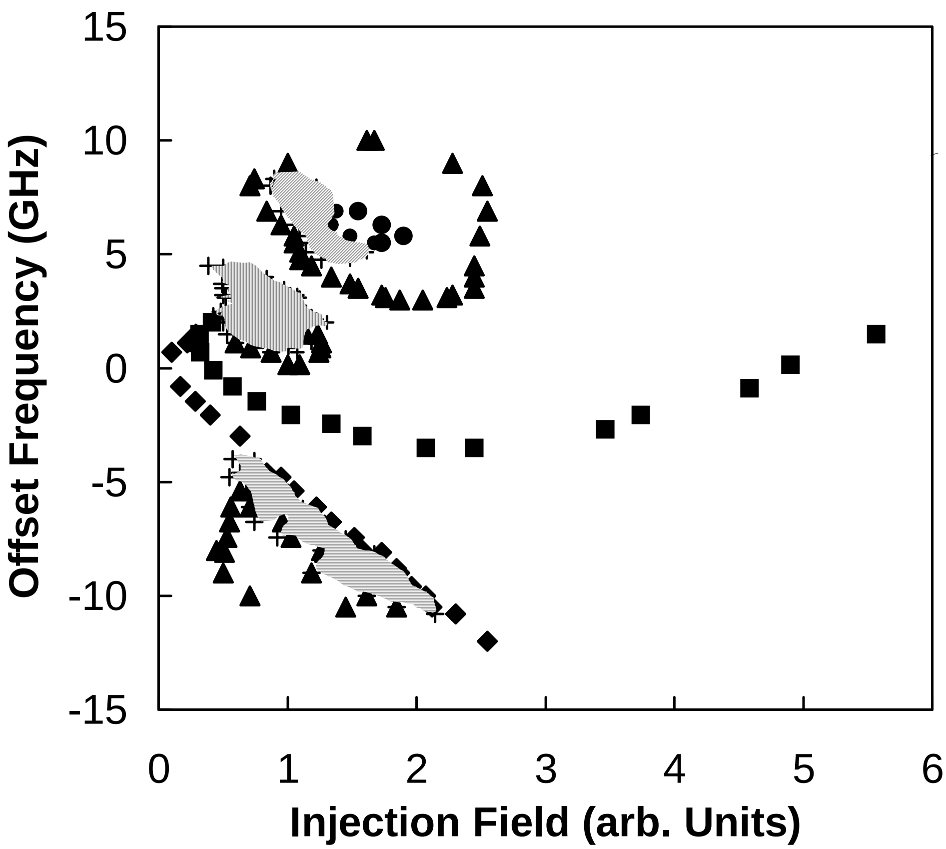

Figure 1. Transitions between regions of different operating characteristics in a single-mode DFB semiconductor laser subject to external optical injection. The injection field is proportional to the square root of the injected signal power, and the offset frequency of the injected optical beam is with respect to the free-running frequency of the slave laser. Diamonds mark the transition from unlocked to stable locked operation and squares from stable to pulsating output. Triangles mark transitions where the pulsation or unlocked power oscillation frequency is halved (period two) and circles a transition to period four oscillating output. The hashed regions mark regions where the output is chaotic.

EXPERIMENTAL APPARATUS

To demonstrate that the DLLD has sufficient stability to act as the pump and probe of the atomic medium for a CSAC, we constructed the experimental apparatus shown schematically in Figure 2. The semiconductor laser output is perturbed from steady-state free-running output by the injection of light from another laser. Both lasers used were commercially available VCSELs operating at 852 nm, resonant with the D2 absorption peak in Cs. Due to their small size, the optical frequency of VCSELs is very sensitive to current and temperature fluctuations, typically tens of GHz per mA of bias current and degrees C, respectively. Both lasers are under current and temperature control, with fluctuations below ± 1 µA and ± 0.01 C, respectively. The master laser is isolated from the output of the slave, so that it maintains stable, single-frequency output. The injection into the slave causes its output to oscillate in time at a frequency determined by the injection level and offset frequency of the master laser. It is adjusted to cause the slave laser to have an output dominated by two frequency components offset by the 9.2 GHz frequency of the Cs clock transition. The slave laser output is monitored by a fast photodiode connected to a microwave spectrum analyzer. Part of its output is split off and passed through a 1 mm thick cell containing Cs and 100 torr of argon buffer gas. The buffer gas limits the diffusion of the Cs vapor out of the beam and into contact with the cell walls without destroying the coherence set up by the optical excitation. A second, low-frequency photodiode monitors transmission through the cell.

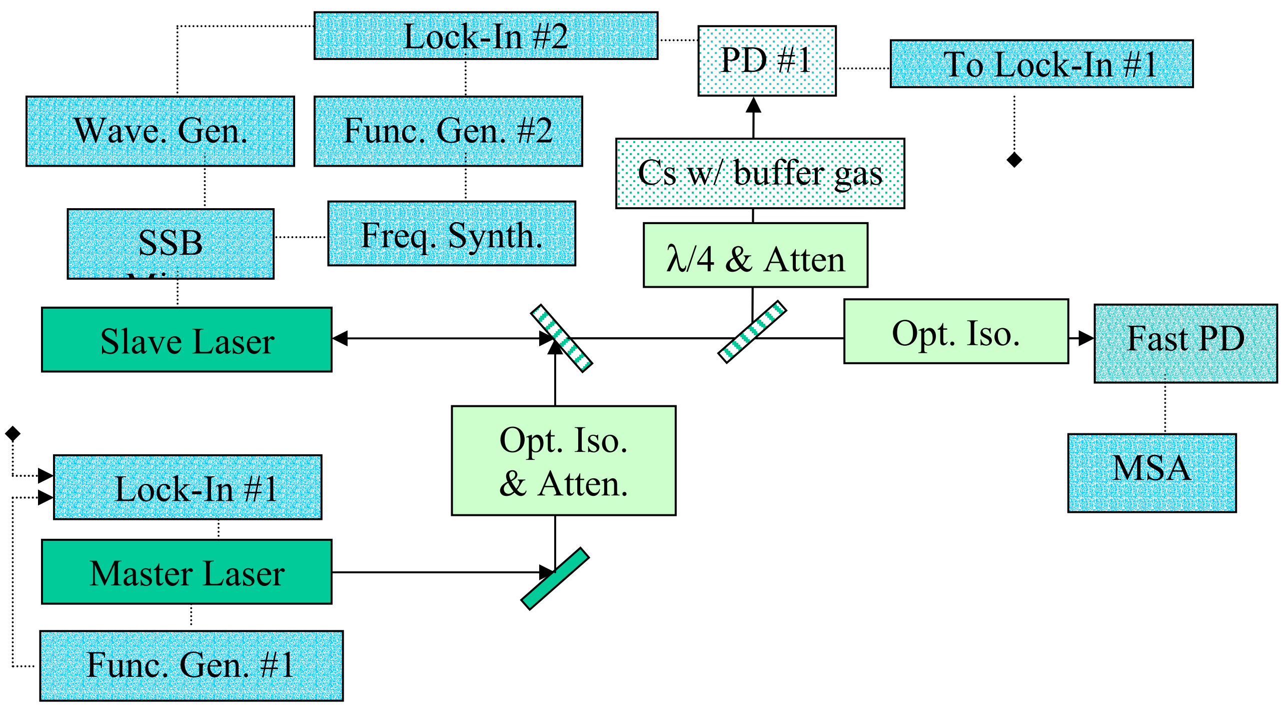

Figure 2. Schematic of the experimental apparatus. The attenuated output from an injection, or master, laser is used to perturb the output of a slave laser. After passing through beamsplitters, part of the slave laser output is transmitted through a shielded, temperature-controlled cell containing Cs and 100 torr of argon buffer gas to a photodiode. The other part is incident on a fast photodiode whose output is monitored by a microwave spectrum analyzer. The optical frequency of the master laser is locked to the Cs D2 resonance, while the induced pulsation frequency of the slave laser is locked to a weak, microwave-frequency current modulation generated by a microwave frequency synthesizer and an RF waveform generator, both locked to a stable frequency reference. The frequency of the synthesizer is modulated so that the laser pulsation can be locked to the CPT resonance by controlling the frequency of the waveform generator. Optical isolators are used to prevent back reflections.

To lock the lasers to the Cs D2 absorption feature a weak 100-kHz modulation (sidebands < -20 dBc in the optical spectrum) is placed on the master laser. This modulation is transferred to the slave. A lock-in amplifier is used to detect the dispersion-like modulation feature that occurs at the optical resonance. The output of the lock-in is fed back to the master laser bias current to lock the output to the optical resonance. To complete the double locking, a weak, <100 µW, modulation at the 9.2 GHz frequency of the Cs clock transition is applied to the slave laser by the combination of a microwave frequency generator and an RF waveform generator. This locks the frequency of the power oscillation set up by the injection from the master laser. The signal from the frequency synthesizer is frequency modulated at 12 kHz. A second lock-in amplifier detects the dispersion-like feature due to the CPT resonance, and the output of the lock-in is used to control the frequency of the RF waveform generator to lock the output power oscillation to the atomic resonance. Not shown in Figure 2 is a third VCSEL that is used as an optical local oscillator so that optical spectra can be generated using the fast photodiode and microwave frequency synthesizer.

When free running and biased about 1.5x threshold, the slave laser emits a single-frequency output with a linewidth of less than 50 MHz. The changes in the output characteristics due to the double locking are summarized in Figures 3 and 4. Figure 3 shows low-resolution optical spectra (resolution bandwidth ~100 MHz) for the laser under weak current modulation with and without external optical injection. With no optical injection, the current modulation induces weak sidebands. The optical injection causes the output to be dominated by two strong optical frequency components with a controllable offset and relative amplitude. By adjusting the dc-bias current to the two lasers, the output is optimized so that the two strong components are of equal amplitude and are offset by 9.2 GHz. Figure 4 shows that the beat frequency of the laser output is broad, approximately 32 MHz when there is no microwave reference frequency. However, the beat signal sharpens into a feature with a width less than the 1 Hz minimum resolution bandwidth of the spectrum analyzer. This is achieved with a microwave modulation power of ~ 30 µW, approximately two orders of magnitude less than the dc-bias power to the slave laser. This contrasts sharply with the case of direct modulation, where the modulation power is similar to, or greater than the dc-bias power.

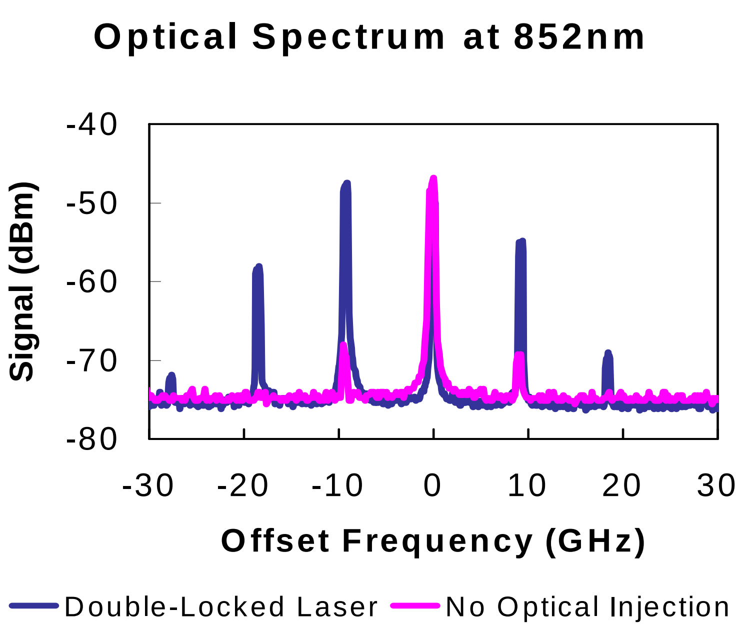

Figure 3. Optical spectra comparing the perturbed output power due to external optical injection with the free-running case when there is a simultaneous weak current modulation at 9.2 GHz. Under external injection, two strong optical frequency components are generated.

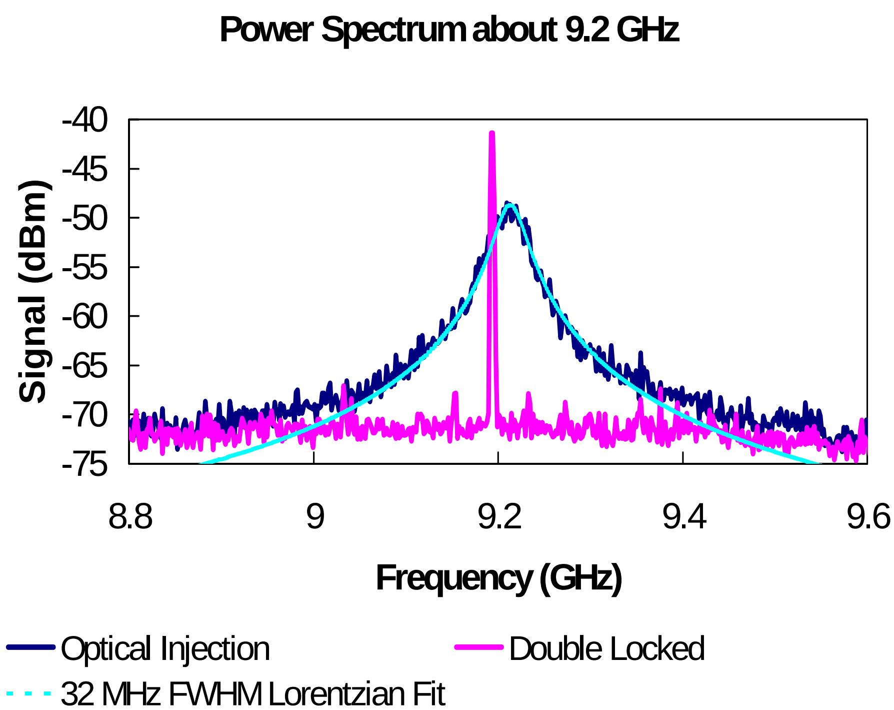

Figure 4. Microwave spectrum of the fast photodiode output at the laser power oscillation frequency. With no weak current modulation, the beat signal between the two optical field components generated by the external optical injection and nonlinear optical interactions is relatively broad and well fit by a Lorentzian curve. With simultaneous weak current modulation, the signal locks to the microwave reference with a width less than the resolution of the spectrum analyzer.

PROBING THE CPT RESONANCE

To demonstrate that the DLLD was a useful excitation and probing source for a CPT-based chip-scale atomic clock, the output of the perturbed laser was focused to a diameter (i.e. twice the beam waist) of slightly below 1 mm and passed through the 1 mm thick cell containing the Cs and buffer gas. This produced an interaction volume of ~ 1 mm^3, as shown in Figure 5. The frequency of the RF waveform generator was then scanned so that the modulation reference frequency to the laser would cross the CPT resonance. Figure 6 shows the modulation spectroscopy signal measured by the lock-in amplifier, with a resonance width of 1 kHz. More tightly focused beams yielded a larger resonance width, indicating that the residence time of the Cs atoms in the beam was a significant lifetime-limiting factor for this measurement. Clearly, the DLLD has the necessary stability to excite and probe the resonance.

The feedback loop controlling the frequency of the modulation reference was then closed and the DLLD was locked to the CPT resonance. Data runs taken over several hours produced short-term Allan deviations of 1.47×10^{-10} for a 2.5-second integration time, and 5.8×10^{-11} for a 25-second integration time. For longer times, drifts due to the temperature sensitivity of the Cs resonance, -100 Hz/C, and fluctuations in the bias points and the mechanical pointing of the lasers caused the stability to deviate from the ideal $\tau^{-1/2}$ curve. The signal-to-noise ratio of the error signal generated from the resonance signal of Figure 6 was not strong enough to sufficiently control phase fluctuations of the laser power oscillation/pulsation to maintain locking tong-term locking precision. We believe that this limitation can be overcome by switching to a D1 resonance in either Cs or Rb, where the CPT resonance signal has been measured to be approximately an order of magnitude stronger **[8]**. Work to demonstrate this is underway.

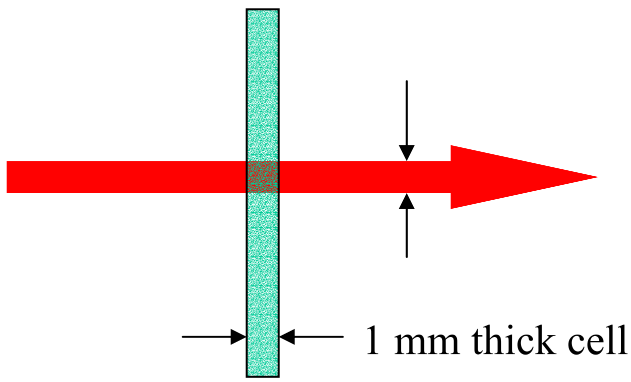

Figure 5. A representation of the interaction geometry used to simulate a very small cell. A narrow, sub-mm beam width excitation/probing beam is passed through a thin, 1 mm path length, spectroscopy cell containing Cs and Ar buffer gas.

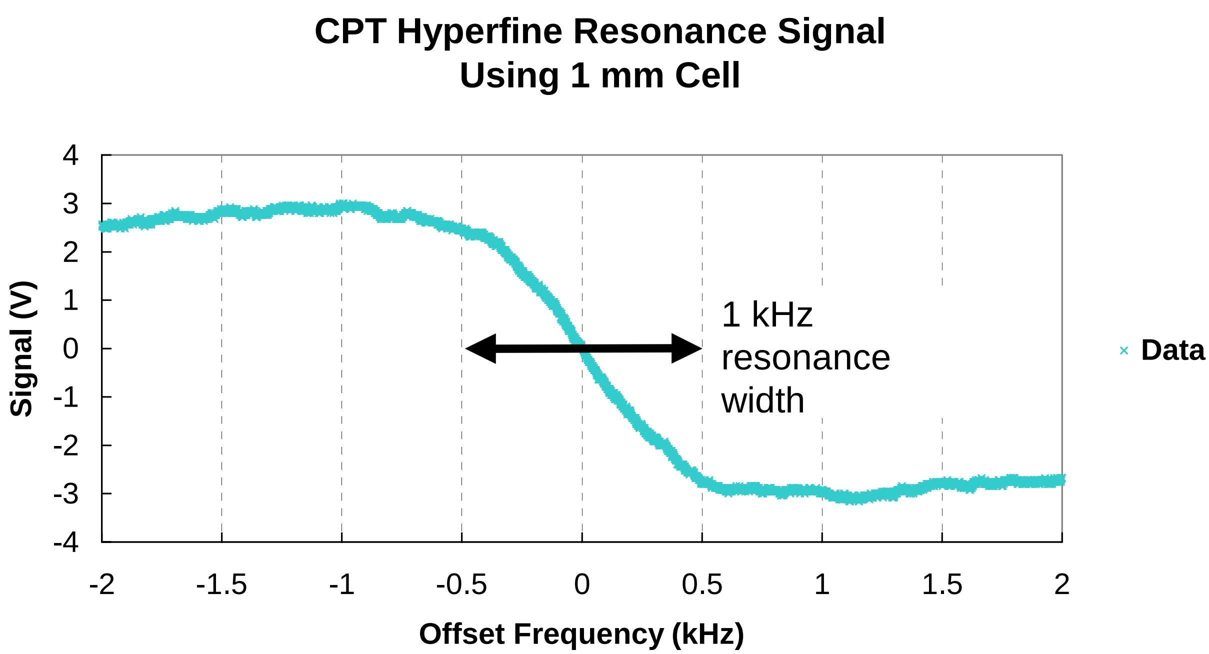

Figure 6. The modulation spectroscopy spectrum of the transmitted laser beam as the frequency of the weak current modulation to the laser is swept across the CPT resonance. The frequency of the modulation signal is itself modulated at 12 kHz and the spectrum is the lock-in output of the photodiode signal component at the frequency. The dispersion-like characteristic can be used to lock the laser to the resonance.

SUMMARY

The nonlinear optical interactions within a semiconductor laser can be used to generate an instability in the laser output. This instability can be controlled to yield a periodically oscillating power output and an optical spectrum dominated by two optical frequency components. This is ideal for implementing the CPT-based excitation/probing of atomic media. Because the CPT implementation involves only optical excitation and probing, sub-mm^3 interaction volumes generate useful signals for locking the optical output to the atomic resonance. We have demonstrated that approximately 30 µW of microwave power is sufficient to lock the laser power oscillation to the atomic resonance. The clock signal is generated directly on the optical carrier so that, potentially, it can be distributed with lower susceptibility to electromagnetic interference. Further work is underway to investigate the advantages of implementing a DLLD-based configuration using the stronger D1 resonances in Cs and/or Rb.

ACKNOWLEDGMENT

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