

## 21.0 Quantum Optics and Photonics

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## 21.1 Investigation of Error Sources in a Laser Raman Clock

We have continued our precision studies of laser induced stimulated resonance Raman interactions in a sodium atomic beam with emphasis on Ramsey's method of separated oscillatory fields. We observed Raman-Ramsey fringes for a field separation of up to 30 cm, and the data were consistent with theoretical predictions. We have also been investigating the performance of a clock based on this interaction in a sodium atomic beam to determine the feasibility of such a scheme and to demonstrate any possible advantages over conventional microwave excited clocks. Recent performance showed a stability of  $1 \times 10^{-11}$  for a 5000 second averaging time. This compares favorably with commercial cesium clocks when difference in atom transit time and transition frequency are taken into consideration.

Currently we are studying potential sources of long term frequency error in the Raman clock. Some of the error sources are similar to those in microwave clocks, such as the effects of path length phase shift, external magnetic fields, background slope, atomic beam misalignment and second order Doppler. The other error sources are unique to the Raman clock and include laser frequency detuning, laser intensity changes, laser beam misalignment, optical atomic recoil, the presence of nearby hyperfine levels, and other smaller effects.

Our present investigations have centered around error sources that are unique to the Raman process. For example, we have found that laser detuning from resonance by 1% of the atomic linewidth can cause a fractional error of  $2.4 \times 10^{-11}$ . Also a 1% change in laser intensity can generate an error of  $2.5 \times 10^{-12}$ . Efforts are underway to find ways of reducing both detuning and intensity errors. In addition, laser misalignment can also be a source of significant error. A laser beam translation of 0.1 mm can cause an error

of  $3 \times 10^{-11}$ . The use of fiberoptics is being investigated for the minimization of misalignment error.

### **Publications**

Hemmer, P.H., G.P. Ontai, and S. Ezekiel, "Precision Studies of Stimulated Resonance Raman Interactions in an Atomic Beam," *J. Opt. Soc. Am. B* (1986).

Hemmer, P.H., V.D. Natoli, M.S. Shahriar, B. Bernacki, H. Lamela-Rivera, S.P. Smith and S. Ezekiel, "Study of Several Error Sources in a Laser Raman Clock," *Proceedings of 41st Annual Frequency Control Symposium, Philadelphia, Pennsylvania, 1987.*

## **21.2 Physics of Stimulated Resonance Raman Effect**

In conjunction with our experimental studies of the stimulated resonance Raman effect for potential clock applications, we have also performed detailed theoretical studies. Among other things, these theoretical studies have resulted in the development of a classical mechanical model for the quantum mechanical resonance Raman process, namely a set of three classical coupled pendulums.

In this pendulum model, individual pendulum oscillations correspond to atom field composite states and the coupling springs serve to couple the pendulum oscillations in the same way that the laser field couples atom field composite states. Using standard approximations for atom field calculations, it is found that a one to one correspondence exists between the (complex) pendulum oscillation amplitudes and the (complex) composite state amplitudes. Moreover, it is also found that the familiar atom field "dressed" states are analogous to normal modes of the coupled pendulum system.

Thus, the pendulum system provides the means to actually "see" what happens in the resonance Raman interactions. This allows us to give simple physical interpretations to many of our more puzzling experimental observations. For example, in our two zone Raman studies in an atomic beam, we find that the effects of laser detuning becomes smaller at higher laser intensities. Using pendulums, we find that this occurs because the Raman interaction generates a single atom field superposition dressed state at high laser intensities, (single pendulum mode); but laser detuning effects result from the interference of two superposition states in the region between interaction zones.

In addition to the pendulum analogy, we are also performing density matrix calculations of the Raman lineshapes and comparing these to our experimental results.

## **21.3 Observation of Raman-Ramsey Fringes in a Cesium Atomic Beam Using a Semiconductor Laser**

Stimulated resonance Raman interactions have been observed in a cesium atomic beam using a semiconductor laser at 852 nm. The semiconductor laser, which has a linewidth of 30 MHz, was amplitude modulated at about 4.6 GHz and the resulting sidebands were used to excite the Raman transition at 9.212 GHz. Using separated field excitation, Ramsey fringes for a separation of 8 cm have been observed with a linewidth

of approximately 2 kHz. This fringe width is consistent with the theoretically predicted value. Work is under way to use the Raman/Ramsey fringe to stabilize a microwave oscillator in a way similar to our sodium Raman clock employing a dye laser.

The interest in the semiconductor laser excited Raman cesium clock is based on its potential small size, light weight, and low cost, as well as high performance.

## 21.4 Influence of Atomic Recoil on the Spectrum of Resonance Fluorescence From a Two-Level Atom

The fluorescence spectrum of a two-level atom, which is of fundamental importance to the understanding of atom-field interaction, has received considerable attention during the past few years. Calculations show that for a stationary two-level atom in a monochromatic excitation field, the fluorescence spectrum is composed of three peaks which are symmetric with respect to the excitation-field frequency. A number of experiments have been conducted to measure this spectrum, and such symmetric spectra have indeed been observed. However, under certain conditions, asymmetric spectra were also observed. In particular, we observed a symmetric spectrum for atoms in a uniform field and an asymmetric spectrum in a field gradient.

We have recently investigated the cause of this asymmetry which has been hitherto unexplained and we now feel confident that it is caused by atomic recoil. We have performed a detailed calculation that takes into account atomic recoil, the field gradient and the direction of the observation of the fluorescence and showed that the spectrum of resonance fluorescence becomes asymmetric consistent with observations. Moreover, we also showed that by including the forces on the atoms due to the laser field, asymmetry can also occur in a uniform field.

### Publications

Prentiss, M.G. and S. Ezekiel, "Influence of Atomic Recoil on the Spectrum of Resonance Fluorescence From a Two-Level Atom," *Phys. Rev. A* 35, 922 (1987).

## 21.5 Studies in a Passive Resonator Gyroscope

A passive resonator rotation sensor or "gyroscope" is a ring resonator in which counter-propagating light beams within the resonator experience a non-reciprocal phase shift due to an applied rotation rate. Because of this phase shift the resonance frequency of the resonator for the counter-propagating directions are not identical. This difference in resonance frequency,  $\Delta f$ , is measured by means external to the resonator, e.g., by locking the frequencies of the external laser beams to corresponding resonances of the cavity.

Our research demonstrated that because of backscattering within the cavity, the difference in resonance frequency  $\Delta f$  cannot be measured as long as the applied rotation is below a certain value determined by the degree of backscattering. This behavior which is called "lock-in" has long been observed in ring laser gyros where a laser amplifier is placed within the resonator. In our passive approach, lock-in occurs if all the

information about backscattering is fed faithfully to the servo loops which hold the external laser frequencies to the cavity resonance.

Lock-in was observed using mechanical rotation and also non-mechanical rotation, e.g., by sweeping the frequency of one of the external lasers. The theory of lock-in relative to our passive set-up was developed and used to understand the observed behavior in the neighborhood of lock-in. Finally, we demonstrated several non-mechanical schemes of eliminating lock-in in passive resonator gyroscope.

The operation of servo loops which lock the external laser frequencies to the cavity resonance requires the generation of discriminants from the resonances of the cavity. These discriminants are produced by modulating the perimeter of the cavity sinusoidally at 30 kHz and demodulating the output intensity of the cavity using a phase sensitive detector (lock-in amplifier). In normal operation of the gyroscope the phase of the lock-in amplifier is adjusted to yield the largest demodulated output. In this case the lock-in amplifier is in phase with respect to the modulation on the perimeter of the cavity. When we set the phase of the lock-in amplifier to be 90 degrees with respect to the modulation on the cavity (i.e., detecting the quadrature signal) we did not get zero across the resonance lineshape. This indicated that the cavity lifetime influenced the discriminant signal. This is a plausible argument since our cavity linewidth of 50 kHz is comparable to the 30 kHz modulation frequency.

The distortions observed in quadrature were in good agreement with our computer generated models for this process, and furthermore, our model predicts a decrease in the amplitude of this distortion as we either increase the cavity linewidth or decrease the modulation frequency. We have experimentally verified this by first modulating at 1 kHz, and then using a cavity with linewidth of 500 kHz. These distortions in the discriminant are important because they can generate errors in the measurement of  $\Delta f$ .

The short term rms noise of the gyroscope with an integration time of 3 sec is 0.05 deg/hr which is close to the shot noise on the light. Currently we are investigating both short term and long term error sources.

## Publications

Zarinetchi, F., and S. Ezekiel, "Observation of Lock-In Behavior in Passive Resonator Gyroscope," *Optics Lett.* *11*, 401, (1986).

## 21.6 Studies of Nonreciprocal Phase Shift in a Fiberoptic Ring Resonator Gyroscope.

A nonpolarization maintaining fiber optic ring resonator with a finesse of 80 has been used to investigate error sources in a fiber ring resonator rotation sensor. Detailed observations of the resonant backscatter revealed that Rayleigh backscatter was the primary source of offset drift when a cavity modulation technique was used. Using this common modulation technique a long-term variation of offset of  $42^\circ/\text{hr}$  was observed. Short-term noise three times the short noise limit was measured.

By using external acousto-optic modulators to frequency modulate the two counterpropagating beams at different frequencies prior to entering the resonator, the

effect of the backscatter was eliminated. Long-term variation of the offset on the order of  $8^\circ/\text{hr}$  was observed. One possible source of this variation is the change in the birefringence of the fiber. The use of polarization, or better, a single polarization resonator would significantly reduce the effect of this birefringence. The short-term noise was approximately 16 times higher than shot noise. This was attributed to the noise added by the acousto-optic frequency modulators.

Preliminary observations of the optical Kerr effect showed an offset of  $2^\circ/\text{hr}/\text{mwatt}$  input power difference. This is in approximate agreement with the calculated value of the optical Kerr effect and may be eliminated by a simple servo technique.

## Publications

Ezekiel, S., "A Brief History of Fiber Gyros and M.I.T.'s Contributions to Fiber Gyro Development," S.P.I.E. 719, 9, (1987).

## 21.7 Investigation of Noise in a Fiber Interferometer Gyroscope

In a multiturn fiber interferometer gyroscope a broadband light source, e.g., a superluminescent diode (SLD), is used to reduce any undesirable backscatter and also the optical Kerr effect. However, SLDs do not produce a lot of power and their lifetime is limited because they operate at a much higher current density than semiconductor lasers.

We have investigated the use of a chirped frequency semiconductor laser to produce an effectively broad width so as to replace the SLD. The frequency of a semiconductor laser may be chirped by varying the injection current. A number of techniques for chirping the laser have been studied with emphasis on the effect of mode hopping and on any broadband noise created by the chirping.

Using a chirped laser with a width of 28 GHz, we were able to reduce the optical Kerr effect from  $50^\circ/\text{hr}$  to a negligible value. At the same time, we achieved a short term noise close to the shot noise with the intensity on the detector being one hundred times larger than with a superluminescent diode.

## 21.8 Sensitive Techniques for Detection of Residual Higher Order Modes in a Quasi-Single-Mode Fiber

Pure single mode propagation in an optical fiber is important in many applications, such as wideband fiberoptic communication and precision interferometric fiberoptic sensors.

Various methods exist for evaluating single mode fibers that are based on cutoff wavelength measurements. For instance, the cutoff wavelength may be determined by observing the near field pattern or by the rise in bending loss. Other methods are based on mode interference. The cutoff wavelength methods are not able to detect a small contribution of higher order modes and the interferometric schemes either are elaborate,

i.e., require an external interferometer setup, or they need special equipment such as tunable sources. Our scheme is also based on mode interference within the fiber but requires neither a special light source nor an elaborate setup.

In our experiment light from a single frequency He-Ne source is focused into an optical fiber, part of which is wrapped around a 2-cm diameter piezo-electric transducer (PZT). By driving the PZT with a sinusoidal signal at  $f_m$ , we can generate a modulation of the difference between the propagation constants for the fundamental and a higher order mode. The output of the fiber is detected on a movable small aperture photo diode and passed through an amplifier before phase sensitive demodulation by a lock-in amplifier. Using a multi-mode fiber with core diameter of 5.2 microns we were able to demonstrate the sensitivity of this technique. We measured residual higher order mode amplitudes as low as  $10^{-4}$  of the primary mode.

### Publications

Nakajima, Y., and S. Ezekiel, "Sensitive Determination of the Existence of Higher-Order Modes in a Quasi-Single-Mode Fiber," *Opt. Lett.* **11**, 815, (1986).

## 21.9 Investigation of Absolute Stability of Water-Vapor-Stabilized Semiconductor Laser

Single-frequency semiconductor lasers are useful in a number of applications, such as fiber optic communication, interferometry, sensors, and high-resolution spectroscopy. In most of these applications the frequency of the laser must be long-term stable. A simple and convenient method of stabilizing the laser frequency is to lock it to a transition in an atomic or molecular vapor, e.g., cesium, rubidium, or water ( $H_2O$ ) vapor. We have investigated the long term stability of the frequency of a double-heterostructure AlGaAs laser locked to a transition in a simple water vapor cell. We demonstrated that the stability depended on the vapor temperature which influenced the pressure shift in water vapor. Pressure-induced frequency shifts resulting from temperature variations were found to range from 3 MHz/°C at room temperature to 1 MHz/°C at 0°C. We determined that an absolute stability of 1 part in  $10^{10}$  with an averaging time constant of 10 sec could be achieved by controlling the temperature of the water vapor to 0.01°C.

### Publications

Pevtschin, V., and S. Ezekiel, "Investigation of Absolute Stability of Water-Vapor-Stabilized Semiconductor Laser," *Opt. Lett.* **12**, 172, (1987).