Laser frequency translation: a new method

Matthew Poelker, Prem Kumar, and Seng-Tiong Ho

Department of Electrical Engineering and Computer Science, Robert R. McCormick School of Engineering and Applied Science, Northwestern University, Evanston, Illinois 60208

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We demonstrate how the frequency of a single-mode cw dye laser can be translated by 1.772 GHz using stimulated Raman scattering in sodium vapor. The output of a sodium Raman laser, the frequency-translated beam, is shown to be highly correlated in frequency with the dye-laser pump beam. The bandwidth of the 1.772-GHz heterodyne beat signal between the two beams is found to be as narrow as 440 Hz, much narrower than the root-mean-square frequency jitter (~1 MHz) of the dye-laser pump beam. The Raman laser method can be used with materials other than sodium, such as cesium or magnesium, to obtain frequency translations of a magnitude that may not be easily attainable with acousto-optic or electro-optic techniques.

Many experiments require two different-frequency laser beams that are correlated in frequency to a high degree. In a recent experiment, for example, Shahriar and Hemmer showed how the direct excitation of microwave-spin dressed states using a laser-excited resonance–Raman interaction can lead to microwave or millimeter-wave beam-steering applications.[1] The success of their method relied on the frequency-correlated nature of the two laser beams used to excite the resonance–Raman transition.[2] To obtain the second beam, Shahriar and Hemmer translated the frequency of a portion of a single-mode cw dye-laser beam by 1.772 GHz using an acousto-optic modulator. In another experiment, Hemmer *et al.*[3] stabilized a microwave oscillator by using a resonance–Raman transition in a sodium atomic beam. In this experiment Hemmer *et al.*[3] also obtained the second beam using an acousto-optic modulator. Based on this experiment, they argued that, for optical clock applications, better results could be obtained by using an atomic beam of cesium. In the case of cesium, however, correlated laser beams differing in frequency by 9.1 GHz would be required.[3] A 9.1-GHz frequency translation can be quite difficult to obtain with conventional acousto-optic or electro-optic techniques. In this Letter we demonstrate a new method to translate the frequency of a single-mode cw dye-laser beam. In particular, we demonstrate a frequency translation of 1.772 GHz using stimulated Raman scattering in sodium. Our method can be used with Raman media other than sodium, for example, cesium for a 9.1-GHz shift or magnesium for a 601-GHz shift,[4] to obtain frequency shifts that are difficult to obtain with acousto-optic or electro-optic techniques.

We reported in a previous Letter[5] that when sodium is enclosed in an optical cavity and pumped with the output of a single-frequency cw dye laser tuned near the D_1 line, Raman-shifted oscillation builds up within the cavity. The oscillation is blue (red) detuned from the pump laser by the 1.772-GHz ground-state hyperfine splitting of sodium when the pump laser is on the blue (red) side of the D_1 line. (Similar results occur when the laser is tuned near the D_2 line.) As explained in Ref. 5, the gain mechanism for this lasing can be understood by modeling sodium as a three-level atom; levels 1 and 2 are the $F = 1$ and $F = 2$ sublevels of the $S_{1/2}$ ground state, separated by $\Delta = 1.772$ GHz, and level 3 is the $P_{1/2}$ excited state. When the pump laser of frequency ω_p is tuned to the blue side of the D_1 line, the $F = 2$ ground state is optically pumped. The subsequent inversion created between the ground-state sublevels leads to gain at frequency $\omega_p + \Delta$ as a result of stimulated Raman scattering of the pump beam. Similarly, when the pump frequency is red detuned, the $F = 1$ sublevel gets optically pumped and the Raman gain exists at frequency $\omega_p - \Delta$. Because the Raman gain occurs when the atom makes a transition between the two long-lived ground-state sublevels, a strong correlation is expected between the frequency jitters of the pump laser and that of the Raman-shifted oscillation created in the sodium-filled cavity, the sodium Raman laser. This frequency correlation can be demonstrated by heterodyning the pump beam with the Raman-shifted beam and observing the bandwidth of the 1.772-GHz beat signal.

A schematic of our experimental setup is shown in Fig. 1. An argon-ion laser is used to pump an externally stabilized cw ring dye laser of approximately 1-MHz root-mean-square linewidth. The linearly polarized output beam is transversely expanded and made *p* polarized by using a half-wave plate ($\lambda/2$). The pump beam is then directed through a polarization beam splitter (PBS) into a heat-pipe oven containing sodium vapor maintained at approximately 280°C. Approximately 5 Torr of helium is added in the heat pipe as a buffer gas. Counterclockwise-propagating, *s*-polarized, Raman-shifted oscillation builds up in the ring cavity formed by flat mirrors M1 and M2 and PBS for pump frequencies near the D_1 line.[5] Because the Raman gain is extremely narrow band,[6] the cavity length must be an integral multiple of the well-defined wavelength over which

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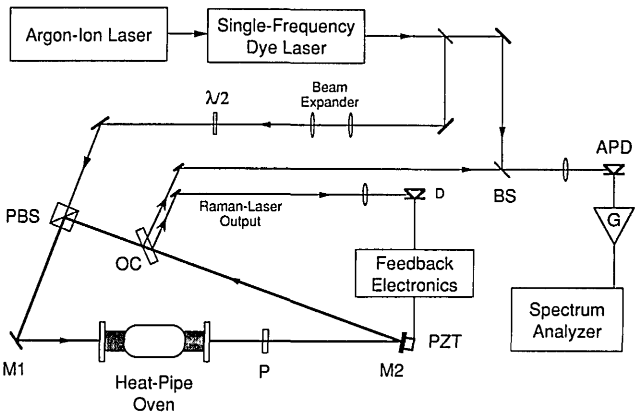

Fig. 1. Schematic of the experimental setup. G, electronic amplifier.

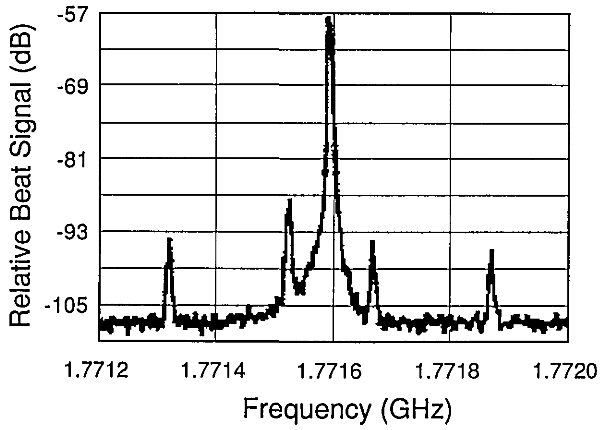

Fig. 2. Spectrum of the beat signal between the Raman-laser beam and the pump beam in the vicinity of 1.772 GHz. The horizontal scale is 200 kHz per division, and the vertical scale is 6 dB per division. The resolution bandwidth of the spectrum analyzer was 3 kHz, and the sweep time was 6.7 s.

the Raman gain occurs. This is accomplished by using a piezoelectric transducer (PZT) on which M2 is mounted. The PBS ensures that the cavity is closed only for *s* polarization; *p*-polarized pump that is not absorbed by sodium escapes through the PBS after a single pass. For alignment purposes, however, it is convenient to attenuate the unabsorbed pump with a linear polarizer (P) directly at the output of the heat-pipe oven. The output coupler (OC), approximately 5% reflection per surface, of the Raman laser is a thick flat piece of glass inserted in the cavity at such an angle as to ensure that the two reflections do not overlap.

As mentioned above, the Raman-laser gain is narrow band. Thermal fluctuations, acoustic noise, and vibrations in the laboratory affect the Raman-laser cavity length, which in turn affects the Raman-laser intensity and frequency. To stabilize the cavity length, one of the output beams is sent to a slow detector (D) whose photocurrent is fed back to mirror M2 through the feedback electronics. For the data presented in this Letter, an ac peak-lock method was employed in which a small dither voltage at 90 Hz is applied to the PZT to modulate the Raman-laser output. The bandwidth of the feedback loop was approximately 30 Hz.

To demonstrate the frequency correlation between the Raman laser beam and the pump beam, the second output beam is sent to a 50/50 beam splitter (BS), where it is combined with a portion of the pump beam of the same polarization and focused onto a fast avalanche photodetector (APD). The photocurrent is monitored with a 2.9-GHz microwave spectrum analyzer. Figure 2 shows a spectrum of the beat signal centered in the vicinity of 1.772 GHz. Although quite prominent in Fig. 2, the side peaks are at least 30 dB below the center peak. At present we do not understand the cause of these side peaks. In Fig. 3 we show an expanded view of the center peak. In this case the spectrum was video averaged over 10 consecutive traces to demonstrate the long-term stability (28 s) of the beat signal. The FWHM of the video-averaged center peak is 440 Hz, which is considerably less than the rms frequency jitter (~1 MHz) of the dye-laser pump beam. This confirms our hypothesis that the frequency variations in the Raman laser follow those of the pump laser.

The plots in Figs. 2 and 3 were obtained with the pump frequency tuned to the red side of the D_1 line, approximately 1.5 GHz from the $(F = 2)$ $S_{1/2}$–$P_{1/2}$ transition. The pump-laser frequency was monitored at all times using the technique of saturation spectroscopy.[7] The pump power was 20 mW, slightly higher than the threshold of the Raman laser with a pump-beam diameter of 3 mm.

Obtaining a beat-signal bandwidth as narrow as 440 Hz required careful choice of the pump-laser power, pump-beam diameter, pump-laser frequency, sodium density, and helium buffer-gas pressure, effects that broaden the Raman-gain profile.[6] Also, the pump and the Raman-laser beams needed to be made collinear in the sodium cell. Power broadening was evident as observed by a marked increase in the beat frequency linewidth when the pump power was increased. Consequently, the narrowest beats

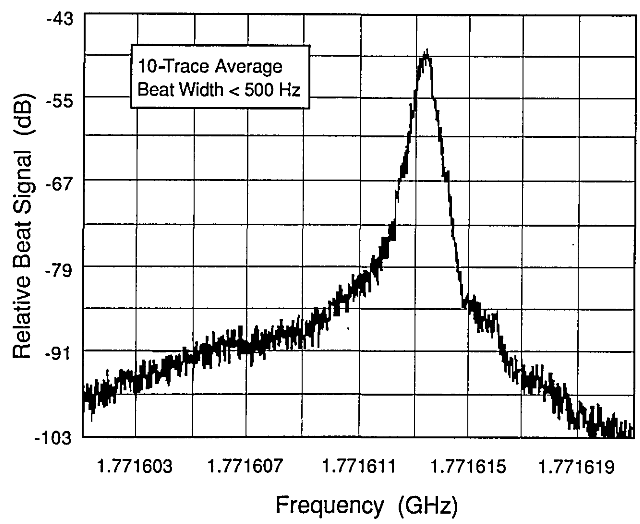

Fig. 3. Expanded view of the center peak in Fig. 2. The horizontal frequency scale is 2 kHz per division, and the vertical scale is 6 dB per division. The resolution bandwidth of the spectrum analyzer was 215 Hz, and the sweep time was 2.8 s. The trace was video averaged 10 times. The FWHM bandwidth of this beat is 440 Hz.

were obtained with near-threshold oscillation conditions. The conversion efficiency of the pump laser to the Raman-laser output with the heat-pipe-oven conditions as specified was approximately 1%. The pump-beam diameter was enlarged to minimize the transit-time effect, which increases the Raman gain bandwidth. The pump-laser frequency was tuned to the red side of the D_1 line to minimize the adverse effects associated with self-focusing in the sodium vapor. To compensate for the low pump intensity, the sodium density and the helium buffer-gas pressure were chosen to yield the highest Raman gain while keeping the effects of collision broadening to a minimum.[6] Approximately 2.5 G of magnetic field was applied parallel to the direction of propagation of the laser beams in the heat-pipe cell to define the quantization axis for the sodium atoms and to remove the degeneracy of the Zeeman sublevels.

The narrow beat width shown in Fig. 3 suggests that this method may be exploited to create an all-optical secondary frequency standard. This is because the beat frequency Δ is directly related to the hyperfine splitting between the two long-lived ground-state sublevels. We have not yet ascertained the absolute accuracy of the beat signal frequency. We realize that extensive studies would need to be undertaken to understand systematic shifts in the beat frequency that are due to, for example, the Stark effect and collision shift. Nevertheless, this scheme is a Raman-laser analog of the all-optical frequency-standard scheme proposed by Hemmer *et al.*[3]

The experiment outlined in this Letter could be extended to other Raman gain media. For example, if cesium were used in place of sodium, a frequency-correlated laser beam shifted by 9.1 GHz from the pump beam would be generated. We are currently working toward improving our results with sodium by reducing the internal cavity losses and thereby lowering the oscillation threshold. This will in turn reduce the power broadening effect and result in a narrower beat signal. Also, the task of locking the cavity length was made more difficult by the presence of three-photon gain[8] that caused oscillation to occur at the pump-laser frequency. We are considering other cavity-locking schemes that would not be affected by this gain. We are also working toward understanding the nature of, and, if possible, the removal of, the modulation sidebands that are visible in Fig. 2.

It is worth noting that the sodium Raman laser provides an example of lasing without excited-state (the $P_{1/2}$ state in this case) population inversion.[9] It may serve as a test of recent theoretical models describing lasing without inversion in three-level systems.[10]

A preliminary account of this research was presented at the 1985 Optical Society of America Annual Meeting.

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