Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

OPTICAL FREQUENCY COMB MEASUREMENTS AT 633 nm, 674 nm, AND 1556 nm

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Abstract - **Frequency comb measurements at 633 nm and 674 nm are reported. The absolute frequency of a HeNe/I_2 standard at 633 nm has been monitored and found to vary over a range of approximately 1400 Hz during a period of almost three years. Comb measurements of a travelling HeNe/I_2 standard are in good agreement with measurements performed elsewhere. The frequency of the S-D transition in a single trapped $^{88}Sr^+$ ion has been found to be in good agreement with previous classical frequency chain measurements at NRC and comb results obtained elsewhere. Preliminary results are presented for a laser system locked to transitions in acetylene near 1520 nm.**
Keywords – **Combs, optical standards, single ions**

I. INTRODUCTION

Until recently, optical frequency metrology has relied on harmonic synthesis chains, which are complicated devices requiring years of development and constructed specifically to measure single optical frequencies [1-4]. The development of optical comb generators based on Kerr-lens mode-locked lasers has greatly simplified optical frequency measurements [5-8]. It is now possible to use a single laser source to perform absolute frequency measurements, referenced to a Cs atomic clock, anywhere in the visible and near-infrared region. This new tool has aided in the development of frequency standards in the optical region and may serve a crucial role in their exploitation.

Optical frequency standards in the visible and near infrared are important in the fields of length metrology and optical telecommunications as well as in fundamental atomic physics and the determination of fundamental physical constants. Probably the most important optical standard for length metrology is the iodine-stabilized helium-neon laser (HeNe/I_2) at 633 nm (474 THz). This laser is used worldwide as a practical means of realizing the SI metre. Several comb measurements of this important frequency have been performed in the past [7,9,10]. At the National Research Council of Canada (NRC), we maintain an ensemble of three of these lasers whose frequencies have been tracked through periodic intracomparisons and international intercomparisons. We have previously reported absolute frequency measurements of one of our standard lasers using a harmonic synthesis chain [11]. These results, along with recent optical comb measurements at NRC, have allowed us to monitor the frequency of this laser over a period of almost three years. The results are presented here along with a comparison of recent comb measurements performed at NRC and the Bureau International des Poids et Mesures (BIPM).

Optical frequency standards, based on laser cooled atoms or ions can have superior reproducibility and stability to the best microwave standards. Optical frequency comb measurements have been performed on several single ion transitions with reported uncertainties reaching a value of less than 10 Hz for Hg^+ [12] and Yb^+ [13]. We have been studying the single trapped $^{88}Sr^+$ ion for a number of years and have previously measured the $5s\ ^2S_{1/2}$-$4d\ ^2D_{5/2}$ transition frequency with a harmonic synthesis chain to an uncertainty of 200 Hz [4]. Recent comb measurements of this transition at the National Physical Laboratory (NPL) in the UK have reduced the uncertainty to 100 Hz [14]. We report here, our recent comb measurements of the S-D transition frequency. These measurements have an estimated uncertainty of 50 Hz and are in good agreement with both our earlier chain measurements and the results from NPL.

The laboratory calibration of optical telecommunication frequencies, particularly those associated with emitters and detectors used in dense wavelength division multiplexed (DWDM) systems, requires accurate sources of optical frequencies in the region of 1520 nm (200 THz). For this purpose, we have developed an optical frequency standard based on a diode laser, which is locked to saturated-absorption transitions in acetylene. Absolute frequency measurements of this standard using the NRC comb will be performed in the near future.

II. OPTICAL FREQUENCY COMB

The optical frequency comb used in this work is shown in Fig. 1. It is similar in design to that described in [15]. A GigaOptics GigaJet 20 mode-locked Ti:sapphire laser, pumped by a Coherent Verdi V-8 is used to produce a periodic train of 30-50 fs pulses, centred at 800 nm, at a repetition rate of approximately 695 MHz and an average power of 500-600 mW. The fs laser output passes through a $\lambda/2$ waveplate for polarization control and 100-200 mW is coupled by a single-element aspheric lens into a 25-cm length of microstructured fibre. This fibre, which is described in [16], consists of a 1.7-µm diameter pure silica core surrounded by an array of 1.3-µm-diameter air holes. Light is confined to the core by total-internal-reflection. The combined waveguide and material contributions lead to zero dispersion at 767 nm and a small net anomalous dispersion for wavelengths near 800 nm. As a result, the pulses injected into the fibre remain short and can experience considerable self-phase modulation (SPM) due to their high peak intensities and the long interaction region. The spectrum of each pulse is broadened through SPM to over an octave,

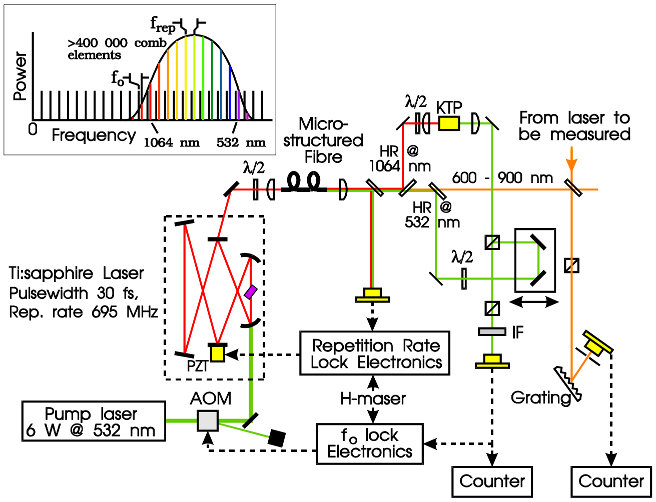

Fig. 1. Setup of the optical comb generator

spanning from approximately 500 to 1100 nm. Since the output from the fibre still consists of a regular series of pulses, the resulting spectrum is made up of a comb of frequencies, separated from one another by the pulse repetition frequency, f_{rep}.

In order to fix the frequency of each comb element, the pulse repetition frequency and the offset of the comb elements from an ideal comb starting at 0 Hz are phase-locked to a 10-MHz signal provided by a hydrogen maser. The maser signal is referenced to an ensemble of Cs atomic clocks maintained at NRC and its frequency is known with respect to the SI second to an uncertainty of approximately 2×10^{-14}. One of the laser cavity mirrors is mounted on a small tube-shaped piezo in order to servo the laser cavity length and pulse repetition frequency. A self-referencing scheme [6-8] is used the fix f_o, the frequency offset of the comb from an ideal comb. The f_o heterodyne beat signal from the photodiode is first bandpass filtered to remove the unwanted signal at f_{rep} and then a combination of ECL and TTL logic chips are used to divide f_o by factors of either 80 or 256 to allow for $>\pi/2$ phase excursions in the phase-locked loop (PLL). An acousto-optic modulator (AOM) controls the pump power and thus modifies the dispersion of the laser pulse in the mode-locked laser. In this way, the frequency of the f_o beat signal is controlled and phase-locked to the signal from the hydrogen maser.

Samples of typical signals from the comb are shown in Fig. 2. Figures 2a and 2b show the self-referencing, f_o heterodyne beat signal. Typically, this signal has a signal-to-noise ratio (S/N) of approximately 35-40 dB. However, the locked or unlocked signal often shows sidebands at 1-2 MHz and rapid fluctuations, as evidenced by the grassy appearance of the signal in Fig. 2a. The cause of these fluctuations is unknown but it is suspected that rapid changes in the power and spectrum from the laser and fibre, as well as incoherent processes in the fibre contribute to the noise. If the resolution bandwidth of the RF spectrum analyzer is reduced below 100 kHz, a narrow spike appears in the signal at the locked frequency as seen in Fig. 2b. The observed width of this spike is below 1 Hz, limited by the resolution bandwidth of the spectrum analyzer. To check the integrity of the offset phase lock, the f_o beat signal is counted directly during all comb measurements. Normally, the counted frequency fluctuates about the lock frequency by approximately the inverse of the counter gate period (typically 1 s).

Figure 2c shows the repetition frequency signal. The

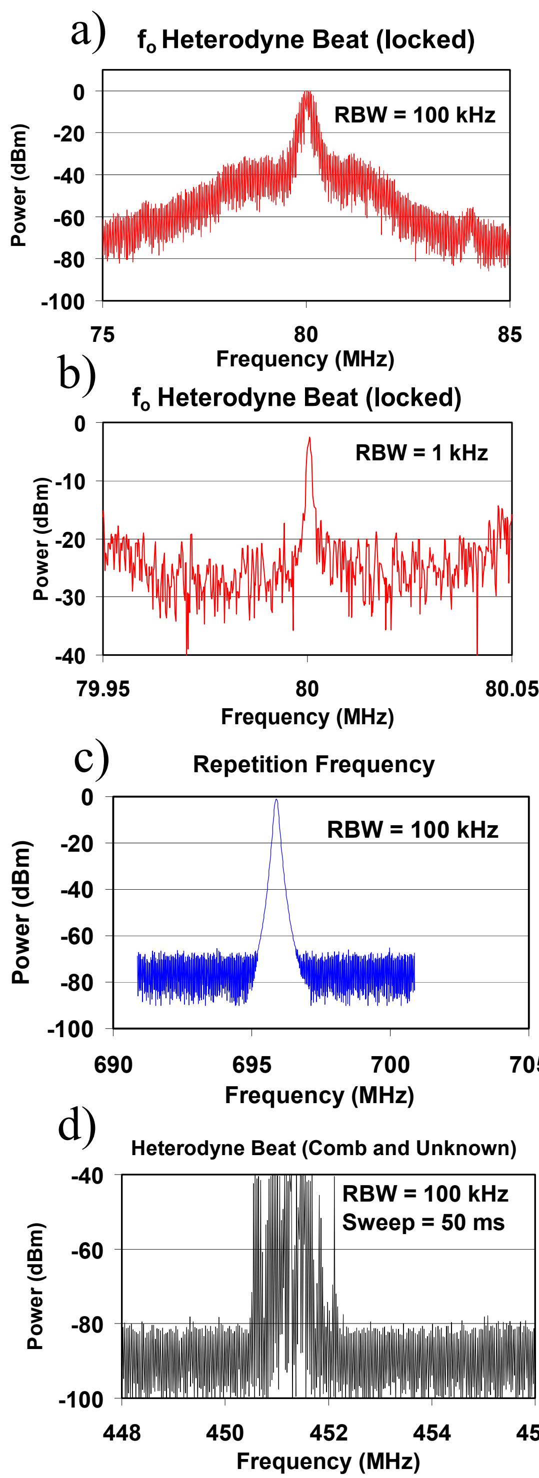

Fig. 2. Examples of the comb signals.

S/N of this signal is always greater than 60 dB and the repetition-rate phase lock is straight forward. An example of the heterodyne beat between a stable laser source at 674 nm and a nearby comb element is shown in Fig. 2d. The S/N usually exceeds 35 dB, permitting direct counting of the beat frequency. To check for counter errors, the signal is counted simultaneously by two different models of counters. Although the 674-nm source was much narrower, the width of the heterodyne beat signal shown in Fig. 2d, obtained with a sweep period of 50 ms, was greater than 1 MHz. Rapid frequency fluctuations in the Ti:sapphire laser carrier frequency and resulting comb elements, primarily due to mechanical vibrations and intensity noise on the pump laser, which are only partly removed by locking the comb to the H-maser, are the likely cause of the excess width. The spectrum of the FM demodulated f_o beat signal fluctuations was in qualitative agreement with the measured mechanical vibrations in the optical table and the power spectrum from the pump laser.

We have recently constructed a new 674-nm laser, which is locked to a high-finesse, ultra-stable Fabry-Perot cavity. It will be used for probing the narrow S-D transition in $^{88}Sr^+$. In early scans of the S-D spectrum, linewidths below 100 Hz for measurement periods of several minutes have been observed. Figure 3 shows a recording of comb measurements of this laser's frequency (not locked to the S-D transition) using a 1-s counter gate period. The laser frequency drifted at a rate of only 0.13 Hz/s. The 1-s counter readings had a standard deviation of 170 Hz for a relative instability of 4×10^{-13}, which was approximately twice the 1-s Allan deviation of the maser signal. Again, the excess noise is likely due to the effect of mechanical vibrations on the stability of the comb elements.

III. MEASUREMENT OF THE HeNe/I_2 STANDARD

The output from HeNe/I_2 standard lasers is typically less than 100 μW and is modulated in frequency by

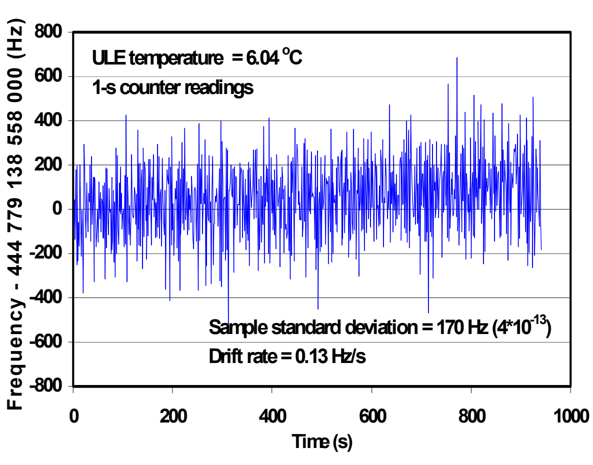

Fig. 3. Measured frequency of the new ultra-stable laser.

6.0 MHz (peak-to-peak) at a rate of approximately 1 kHz. Instead of measuring the frequency of the standard laser directly - a task made difficult by the limited available power - we measure the frequency of a HeNe power laser and the offset of that laser from the standard laser. See Fig. 4. An offset frequency lock with a bandwidth of approximately 200 Hz kept the frequency of the power laser loosely locked to that of the standard laser and reduced the transfer of the 6-MHz modulation. The output from the power laser was sent to the comb via a non-polarization-preserving fibre. A combination of λ/4 and λ/2 waveplates converted the output from the fibre into the appropriate linear polarization for mixing with a comb element. The power of the HeNe laser beam after the combining beamsplitter (see Fig. 1) was normally 75-100 μW. The heterodyne beat frequencies between the power laser and a comb element and between the power laser and the standard laser were measured with counters (1-s gate period) and recorded by a computer. Although the 1-s counter readings of the two heterodyne beats had a scatter of over 10 kHz, the fluctuations were correlated, and 1000-sample runs resulted in a statistical uncertainty in the standard laser frequency of approximately 100 Hz.

The results of comb measurements of the frequency of one of our standard lasers, INMS3, operated on the R(127) 11-5 "f" transition in $^{127}I_2$ are shown in Fig. 5. Also shown is the result of a series of classical harmonic chain measurements performed at NRC in April 2000 [11]. The agreement between the chain measurements and the more-recent comb results is excellent considering the expected reproducibility of the HeNe/I_2 standard. The results shown in Fig. 5 are uncorrected for the operating conditions. Because of practical considerations, this laser is operated at conditions that differ slightly from those that are recommended by the Comité International des Poids et Mesures (CIPM) in the *mise en pratique*. Both the operating conditions and the correction factors for reaching *mise en pratique* conditions varied slightly for the runs shown in Fig. 5. Our series of chain and comb measurements, extending over a period of almost three years, comprise one of the longest absolute frequency records for any HeNe/I_2 laser.

In March 2003, another NRC HeNe/I_2 standard laser, INMS2, was involved in an international intercomparison at the BIPM. Comb measurements of its frequency were performed at NRC both before and after its transportation to Paris, France, where it was measured with the BIPM comb. The results, both uncorrected and corrected for operating conditions, are shown in Fig. 6. The corrected frequency of

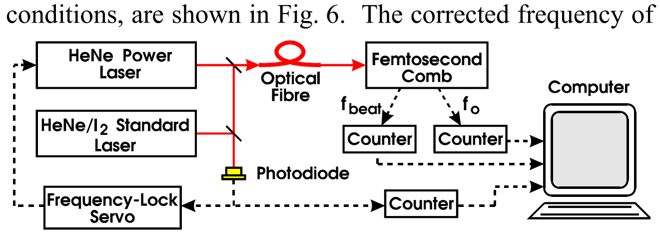

Fig. 4. Setup for measuring the HeNe/I_2 laser frequency.

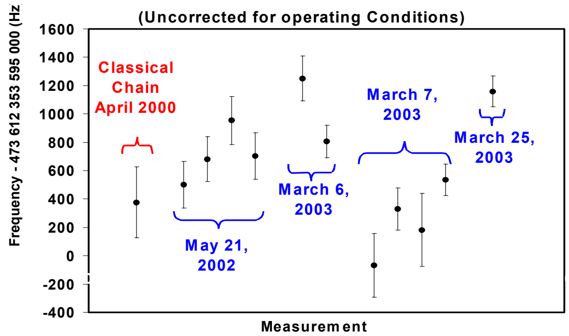

Fig. 5. Measured frequency of INMS3.

INMS2 falls well within the CCL-recommended value for this standard of 473 612 353 604 ± 10 kHz. INMS2 was not realigned during this study. Besides showing the excellent agreement between the NRC and BIPM comb measurements, these results illustrate the reproducibility of this HeNe/I_2 standard after transportation.

IV. MEASUREMENT OF THE S-D TRANSITION FREQUENCY IN $^{88}Sr^+$

The $^{88}Sr^+$ single ion is an attractive system on which to base an optical frequency standard for a number of practical reasons [4,14]. It has a narrow electric quadrupole $5s\,^2S_{1/2}$-$4d\,^2D_{5/2}$ "clock" transition at 674 nm (445 THz), with a natural linewidth of only 0.4 Hz, that can be probed with a diode laser system. It can be efficiently laser cooled on the electric-dipole $5s\,^2S_{1/2}$-$5p\,^2P_{1/2}$ transition at 422 nm either by a diode laser or a frequency-doubled diode laser system. An auxiliary laser, required to pump the ion out of the metastable $4d\,^2D_{3/2}$ level to the $5p\,^2P_{1/2}$ level can be either a diode-pumped fibre laser [4] or a diode laser [14]. The relative simplicity of its probing and cooling laser systems compared to those required for other single ion systems, led to the early development of $^{88}Sr^+$ single ion standards at NRC and NPL. In 1997, the S-D transition was accepted by the Comité Consultatif pour la Définition du Mètre (CCDM) as a recommended radiation for the realization of the metre.

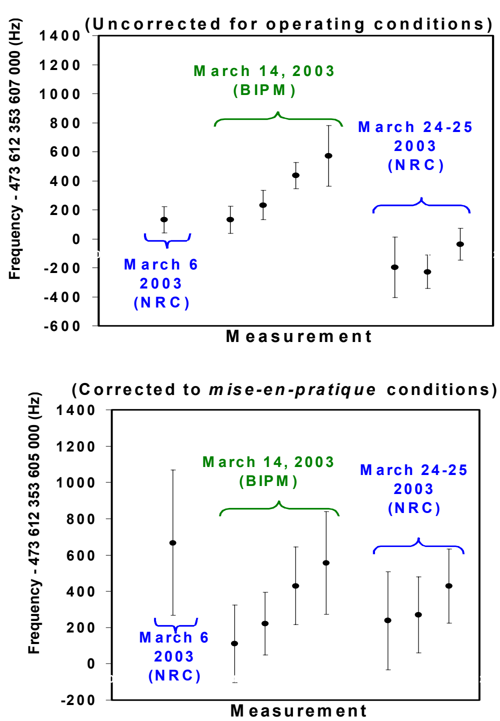

Fig. 6. Measured frequency of INMS2.

Our ion standard apparatus is shown in Fig. 7. The $^{88}Sr^+$ single ion is held in a miniature RF Paul trap, which is surrounded by a mu-metal shield. Pairs of coils, driven by a low-noise current source, are used to control the splitting of the Zeeman components of the S-D transition. Quantum jumps in the fluorescence at 422 nm are detected by a photomultipler and recorded by a computer. The computer controls the AOM and scans four frequencies, one on each side of two symmetrically displaced Zeeman components. From the measured quantum jump rates, the computer calculates the offset of the unshifted probe laser frequency from the centre of the S-D transition and applies a correction to the AOM frequency. By combining these measurements with simultaneous comb measurements of the unshifted probe laser frequency, we have determined the S-D transition frequency. The results are shown in Fig. 8 for several series of comb measurements. Also shown is the result of a series of classical frequency chain measurements performed at NRC in 1997 and 1998 [4] and a recent result from a series of comb measurements at NPL [14].

Although the majority of our comb measurements yielded S-D transition frequencies within 100 Hz of their weighted average value, indicated by the solid line in Fig. 8, there were several outliers. The exact cause of these outliers is unknown, but it is suspected that errors may have occurred due to variations in the linewidth and lineshape of the probe laser system. The optical-feedback-narrowed diode laser source in the probe laser system used in 1997 and 1998 was replaced with a homebuilt, extended-cavity diode laser system for the comb measurements and the servo lock to the ultra-stable, high-finesse cavity was not optimized. This resulted in probe laser linewidths ranging from 700 to 1500 Hz. An average of all the comb measurements shown in Fig. 8, with a weighting inversely proportional to the

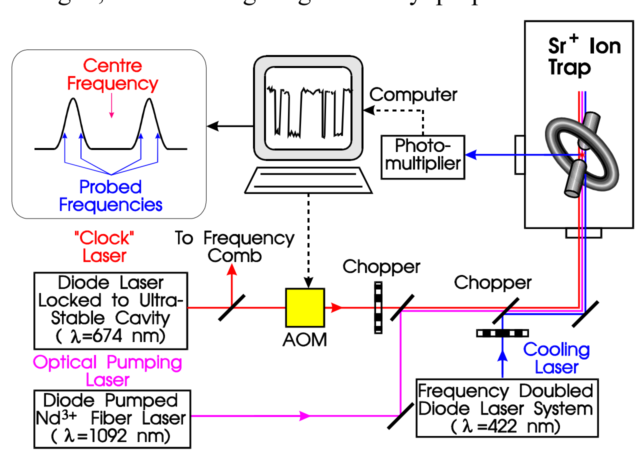

Fig. 7. The Sr^+ ion trap experimental setup.

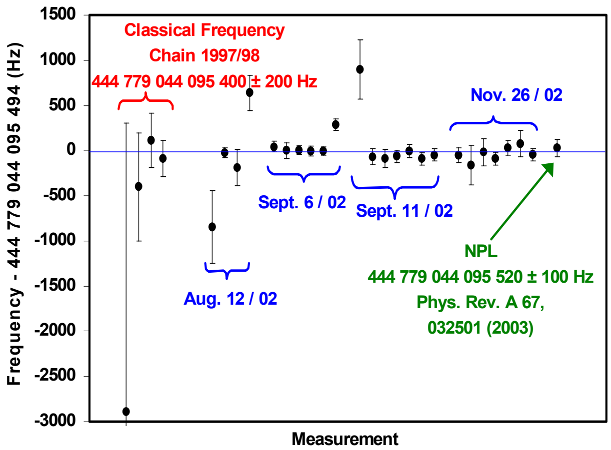

Fig. 8. Measured frequency of the Sr^+ ion S-D transition.

square of the size of the individual error bars, yields a value of 444 779 044 095 494 Hz with a statistical uncertainty of ±25 Hz. A consideration of the distribution of the measured results together with possible perturbations due to fluctuations of the laser line profile has led to an assigned uncertainty of ±50 Hz (1σ). Systematic shifts due to the perturbations of the ion are expected to be less than 1 Hz [4]. The good agreement between these comb measurements and our earlier chain measurements, and especially with the recent results from NPL, is encouraging. As mentioned above, a completely new probe laser has just been constructed at NRC and it is hoped that the scatter in our comb measurements will soon be reduced to a level limited by the stability and accuracy of the hydrogen maser.

V. ACETYLENE-STABILIZED STANDARD AT 1520 nm

Acetylene has many ro-vibrational transitions in the region of 1520-nm making it an attractive system on which to base a frequency standard in this important optical telecommunication region [17-19]. Figure 9a shows our measured linear absorption spectrum for $^{12}C_2H_2$. A similar spectrum, but shifted to slightly longer wavelengths, is obtained for $^{13}C_2H_2$. Each of the linear absorption features is Doppler broadened to a FWHM of approximately 500 MHz while the saturated absorption feature has a natural linewidth of below 800 kHz (see Fig. 9b). We have built two independent laser systems, based on extended-cavity diode lasers, which are locked to the centre of saturated absorption features and have performed a parameter study of their performance [20]. These lasers are found to have a reproducibility of ±5 kHz and a 1-s Allan deviation of 4×10^{-12}.

Preliminary work has been carried out with the aim of measuring the frequency of the acetylene-stabilized lasers. The output has been amplified in a fibre amplifier and focused into a 2-cm-long waveguided periodically-poled lithium niobate (PPLN) doubling crystal. A power of up to 200 μW at a wavelength of 771 nm has been obtained. The resulting heterodyne beat with a nearby comb element had a S/N of 25 dB, which is insufficient for direct counting.

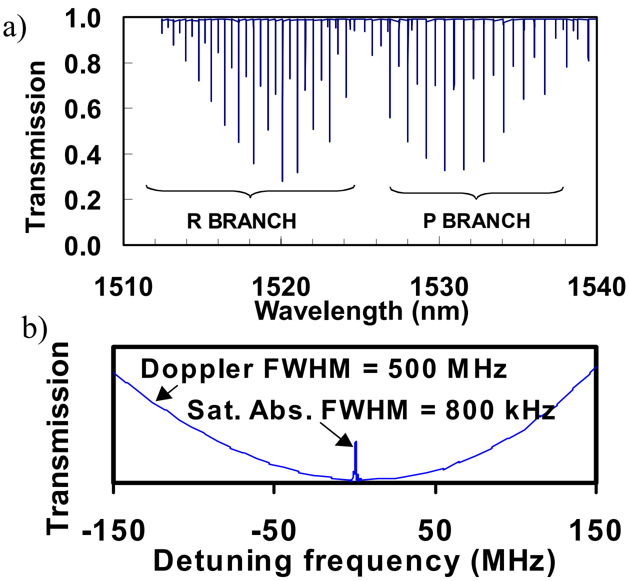

Fig. 9. a) Linear and b) saturated absorption spectrum of acetylene.

Work is continuing and we expect to make comb measurements of the frequencies of several of the acetylene transitions in the near future.

VI. CONCLUSION

We have presented comb measurements of optical frequency standards at 633 nm and 674 nm. The frequency of a HeNe/I_2 standard at 633 nm was found to vary by 1.4 kHz during a period of almost three years. Frequency measurements of a standard laser performed at NRC are in excellent agreement with comb measurements carried out at the BIPM. At 674 nm, we have measured the frequency of the S-D electric-quadrupole transition in a single trapped $^{88}Sr^+$ ion. Our current comb measurements are in good agreement with previous classical frequency chain measurements carried out at NRC and with recent comb measurements reported from NPL. We have recently constructed a new probe laser and it is anticipated that improved measurements of the S-D transition frequency as well as measurements of systematic perturbations will soon be reported.

ACKNOWLEDGEMENT

We would like to thank Jean-Simon Boulanger and Stan Cundy for providing and monitoring the hydrogen maser signal used in this work and Raymond Pelletier for help with the electronics.

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