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13. ABSTRACT (Maximum 200 words) Promising optical frequency/wavelength standards in the visible based on neutral atoms and precise laser sources are studied. In particular we have developed high accuracy systems using diode-lasers with calcium atoms and also diode-pumped Yag-lasers with Iodine molecules. An actual frequency measurement of the Iodine transition at 532 nm is made with the frequency-doubled Yag system. On the calcium transition at 657 nm in the red, optical Ramsey-fringes as narrow as 10 kHz have been observed with a high signal-to-noise ratio using diode lasers. High resolution multi-photon spectroscopy on laser cooled and trapped atoms (Na and Cs) have also been explored. In these pursuits, significant new diode-laser and frequency-measurement technology has been developed, including; highly stabilized diode and Yag lasers, the ability to coherently measure the frequency difference between two lasers to as high as ≈700 GHz, and the extension of the spectral coverage of diode laser sources to the blue (for laser cooling of calcium) and IR spectral regions by using nonlinear optical techniques.		
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Final Report for
grant AFOSR-91-0283

Aug 26, 1994

Period covered; June 15, 1991 to March 14, 1994

Title: Optical Frequency Standards: Hertz-Level Working Standards and their Absolute Frequency Measurement

The accomplishments of our research effort under the AFOSR grant 91-0283 are summarized below. The detailed results are given in specific publications listed as references to this summary.

High resolution diode laser spectroscopy of Calcium

High resolution spectroscopy with diode lasers has been demonstrated on the metrologically important, red transition at 657 nm in calcium. We have observed saturated-absorption Ramsey fringe linewidths as narrow as 10 kHz. Which for comparison is approximately 300 times narrower than that observed on the present iodine stabilized HeNe lasers at 633 nm. Our present performance now allows resolution of the photon recoil splitting of 23 kHz. In addition an alternative high-flux calcium beam/cell system was also developed and gives very high signal-to-noise ratios. This system has the potential to provide outstanding short-term stability ($\sigma_r(\tau) \approx 3 \times 10^{-14} \tau^{-1/2}$) with a saturated-absorption linewidth of as narrow as 65 kHz.

Precision diode laser technology

The application of diode lasers to precision spectroscopy has up to now been a relatively immature science, so much of the actual development of laser technological had to be done in our own labs. Though an on going effort, we now have diode laser systems under quite good control; to the point that they can (in most cases) be applied directly as a precision research tool. Along this line we have developed advanced in-house capabilities for optical coating of semiconductor lasers. This allows us to put high quality coatings on the laser's facets which greatly improves their performance as tunable single frequency sources. With optical and electronic feedback the resulting performance characteristics are; a short-term linewidth of about 500 Hz, with a residual frequency jitter of the reference cavity of less than 5 kHz. Present enhancements to this now include an electronically phase-locked frequency-offset laser that can be scanned with RF synthesizer precision, and an improve reference cavity.

Second harmonic generation of diode lasers - precision blue light source

Because many of the important atomic and molecular transitions of interest are in the blue region of the optical spectrum we have pushed the technology of diode laser frequency doubling. This is of particular immediate interest for the calcium program because we require 423 nm light for laser cooling. Dr. C. Weimer, a postdoc, in our group has developed a diode laser frequency doubling system that gives reliable state-of-the-art performance (starting with 150 mW at 846 nm we produce more than 40 mW of single frequency single spatial mode light at 423 nm. This has now been applied to a number of experiments including 1-D laser

cooling of calcium in the atomic beam system.

Diode laser difference-frequency generation of tunable IR

A new optical difference frequency system was developed in collaboration with Dr. U. Simon and Dr. F. Tittel (of Rice Univ). Nonlinear optical crystals are used to generate tunable infrared radiation (in the 3 μm region) from the difference frequency between two near IR lasers (in our case a diode laser and a diode pumped Yag laser). This technology provides a precisely tunable high resolution laser source and opens a whole new frontier in the important IR spectral region. Up to now, no good tunable lasers sources existed in this region. This system will have a number of important applications, but in particular for optical frequency measurements it provides the all important bridge between the visible and the IR. This work was supported in part by this AFOSR grant.

Ultra-high-speed optical detectors and mixing

A project was pursued on developing the high speed detectors that are necessary for optical frequency measurements this was also supported in part through this AFOSR grant. We have demonstrated the ability to detect beat-notes between lasers in the 0.8 micron spectral region up to difference frequencies as high as 700 GHz. This system is now being used as part of the measurement chain in Hall's lab for the first actual optical frequency measurement of the iodine stabilized doubled Yag laser (see below).

Multi-photon spectroscopy of cold trapped atoms

We have made progress on high resolution spectroscopy of laser-cooled neutral atoms, one experiment on sodium (Hall's lab) and one experiment on cesium (Hollberg's lab). Cascade two-photon transitions with laser cooled and trapped Cs atoms have been detected and analyzed. The observed two-photon lineshape gives us new detailed information about the interaction of cold trapped atoms and multiple laser fields. Linewidths on the two-photon cascade are observed to be less than the natural linewidth of the cooling transition. Spectra also provide information about atom trap dynamics.

Frequency measurement of I, stabilized frequency-doubled Yag laser at 532 nm.

The diode-laser-pumped Nd:YAG laser (after frequency-doubling) can be tuned to some 6 strong absorption lines in molecular Iodine. Two independent laser systems are stabilized to the 532 nm Iodine resonances using our (patented) "modulation transfer" spectroscopic technique. Very strong resonances of nearly ideal symmetry are obtained, which leads to a stability unprecedented for any visible laser: $\sigma_y(\tau) \sim 60 \text{ Hz}$ at 0.1 sec ($1 \cdot 10^{-13}$), improving below $4 \cdot 10^{-14}$ for $T > 10$ sec. The reproducibility is $\sim 300 \text{ Hz}$. These first results with the doubled-Nd 532 nm green are some 40-fold better than those obtained with the 633 nm Iodine-stabilized HeNe laser, and that is after 24 years development work in countless national standards labs! We have built a reliable apparatus using nonlinear crystals LiNbO₃ and LiIO₃, respectively to double 1.06 μm , and add the resulting green and ir frequencies, obtaining at present 1/4 mW of the 355 nm output. A delicious "target of opportunity" has recently come into view based on the excellent performance of this locking system, coupled with a new measurement of 15 kHz accuracy reported recently by Nez, Clairon, Biraben, Felder et. al. of the frequency of the 778 nm two-photon lines in atomic Rb. Remarkably, it turns out that these frequencies satisfy the equation:

$$2 * f(633 \text{ nm}) = f(532 \text{ nm}) + f(778 \text{ nm}), \text{ to within } 1200 \text{ GHz!}$$

For simplicity, we have made our measurements first relative to the Rb D2 line at 780 nm, since the beat frequency is then "only" 263 GHz. The frequency of this Rb transition is known to 160 kHz from wavelength measurements at NPL. For the nonlinear optical system, we use doubling of the 633 nm laser with a temperature-tuned phase-matched RDP crystal in a "build-up" resonator, and frequency-summing the ir and green single-pass in an angle-tuned sample of the same material. The observed heterodyne beat S/N >20 dB in a 300 kHz bandwidth is more than adequate for the phase-tracking circuits we fabricated. The 263 GHz interval has been measured with a "conventional" Schottky diode, driven at 43 GHz by a phase-locked klystron microwave source. The resulting 1 GHz beat has sufficient S/N for direct counting, but for safety we use a tracking oscillator here as well. The measured frequency of the Iodine molecular reference line (R(56) 32-0 a10 component) is found to be 563 260 223.480 MHz \pm 170 kHz.

We helped organize two meetings on frequency stabilized laser sources

1) SPIE conference in Nov. 1992 proceedings now out (vol. 1837) contain many useful papers on frequency stabilized lasers and precision measurements. This proceedings contains 3 papers from our research efforts; i) general summary by J.L. Hall, ii) diode laser frequency stabilization and calcium spectroscopy by Fox et al., iii) high speed detectors for laser difference frequency measurements by Waltman et al.

2) Organized two sessions on stabilized lasers and precision spectroscopy as part of the annual meeting of the Optical Society of America, Toronto 1993.

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Publications

- 1) L. Hollberg, R. Fox, N. Mackie, A.S. Zibrov, V.L. Velichansky, R. Ellingsen, and H.G. Robinson, Diode Lasers and Spectroscopic Applications, Proc. of Tenth Int'l Conf. on Laser Spectroscopy (TENICOLS), Ed. M. Ducloy, E. Giacobino and G. Camy, Font-Rommeu, France, June 17-21, 1991, 347-352.
- 2) R.W. Fox, S.L. Gilbert, L. Hollberg, J.H. Marquardt and H.G. Robinson, Optical Probing of Cold Trapped Atoms, *Optics Lett*, 18, 1456, (1993).
- 3) R.W. Fox, C. Weimer, L. Hollberg, and G.C. Turk, The Diode Laser as a Spectroscopic Tool, *Spectrochimica Acta Reviews*, 15, 291, 1993.
- 4) K. G. Libbrecht and J. L. Hall, "A low-noise high-speed diode laser current controller," *subm. to Rev. Sci. Instr.*, March 1993
- 5) H.-R. Xia, J. I. Cirac, S. Swartz, B. Kohler, D. S. Elliott, J. L. Hall, and P. Zoller, "Phase-shifts and Intensity Dependence in Frequency Modulation Spectroscopy," *subm. to Opt. Lett.*
- 6) R.W. Fox, H.G. Robinson, A.S. Zibrov, N. Mackie, J. Marquardt, J. Magyar, and L. Hollberg, High-Sensitivity Spectroscopy with Diode Lasers, *Proceed. SPIE*, 1837, 360 (1992).
- 7) S. Waltman, A. Romanovsky, J. Wells, R.W. Fox, and L. Hollberg, Precise Optical Frequency References and Difference Frequency Measurements with Diode Lasers, *Proceed. SPIE*, 1837, 386 (1992).
- 8) R. Fox, G. Turk, N. Mackie, T. Zibrova, S. Waltman, M.P. Sassi, J. Marquardt, A.S. Zibrov, C. Weimer, and L. Hollberg, Diode Lasers and Metrology, in *Solid State Lasers: New Developments and Applications*, Proc. Nato Advanced Study Institute, Elba Italy, Plenum (1993).
- 9) J.L.Hall and M. Zhu, "An Introduction to Phase-stable optical sources," in *International School of Physics Enrico Fermi, 1991: Laser Manipulation of Atoms and Ions* (E. Arimondo, W. D. Phillips, and F. Strumia, Eds., 1992) pp. 671-702.
- 10) J. L. Hall, 'Frequency-stabilized Lasers - a parochial review,' (Keynote Address) in *Frequency-Stabilized Lasers and their Applications*, *SPIE* 1837, 2-15 (1993).
- 11) J. L. Hall, "Frequency stabilized lasers -- a driving force for new spectroscopies," in *International School of Physics Enrico Fermi, 1992 : Frontiers in Laser Spectroscopy* (T. Hansch and M. Inguscio, Eds., in press).
- 12) L. D'Evelyn, L. Hollberg and Z.B. Popovic, A CPW Phase-Locked Loop for Diode-Laser Stabilization, *IEEE MTT-S Symposium Digest*, 1994.

- 13) R. Ellingsen, A.S. Zibrov, R.W. Fox, V.L. Velichansky, C. Weimer, G.M. Tino, and L. Hollberg, High-Resolution Diode Laser Spectroscopy of Calcium, to be published special issue Applied Physics B (1994).
- 14) C. Weimer, J.H. Marquardt, A.S. Zibrov, and L. Hollberg, Diode Laser Systems for Precision Spectroscopy, to be published Proceedings of CSOISS Meeting, Ukrainian Phys. J. (1994).
- 15) D.A. Van Baak and L. Hollberg, A Proposed Sum-and-Difference Method for Optical Frequency Measurement in the Near Infrared, to be published Opt. Lett. (1994).
- 16) A. Dax, J.S. Wells, L. Hollberg, A.G. Maki, and W. Urban, Sub-Doppler Frequency Measurements on OCS at 87 THz (3.4 μm) with the CO Overtone Laser, to be published J. Mol. Spect. (1994).
- 17) U. Simon, S. Waltman, I. Loa, F.K. Tittel, and L. Hollberg, External Cavity Difference-Frequency Source in the Mid-Infrared based on AgGaS₂ and Diode Lasers, submitted to J. Opt. Soc. Am. B (1994).
- 18) P. Jungner, S. Swartz, M. Eickhoff, J. Ye, J.L. Hall and S. Waltman, Absolute frequency measurement of molecular Iodine transitions near 532 nm, to be published IEEE I.M. (1994).