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DIODE LASERS FOR FREQUENCY STANDARDS AND PRECISION SPECTROSCOPY*

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Abstract

As they apply to frequency standards and precision spectroscopy the characteristics and technology of tunable diode lasers are briefly reviewed. It is now possible to use nonlinear optical techniques and high quality diode lasers to extend the useful wavelength coverage of semiconductor lasers into the UV, the IR and even millimeter-wave spectral regions. Progress in developing an all diode-laser system for cooling, trapping and precision spectroscopy of calcium is discussed. New measurements indicated that two-stage optical cooling of calcium may be feasible; this should improve the accuracy of the 657 nm optical wavelength/frequency reference.

Introduction

Diode lasers based on the III-V semiconductor materials are very attractive sources of coherent radiation; they are simple to use, compact, highly efficient (~30 % electrical to optical power conversion), reliable and low cost. In addition they have other beneficial attributes such as room-temperature operation, tunability and high-speed modulation capabilities. Single spatial-mode lasers are available in the red and near infrared regions with power levels that range from 10 to 200 mW . At a few special wavelengths high-power tapered-amplifiers and MOPAs (master oscillator power amplifiers) are now available with power levels approaching 1 watt. Most precision spectroscopy does not require high-power lasers, but the high-power devices greatly simplify the nonlinear mixing that is required to reach other spectral regions. Some of the characteristics of commercially available diode lasers are given in table 1.

There are many compelling reasons to develop diode laser systems for applications in precision spectroscopy and frequency standards. For long-term operation of standards and transportable (non-laboratory) instruments we need practical, robust, efficient, tunable, optical sources with high spectral-purity. For applications that require a tunable source, diode lasers may be the only practical solution. The influence of diode lasers on frequency and length standards is apparent in the research programs at all of the major national standards laboratories. For example, efforts are now underway to develop optical and microwave frequency references using diode lasers with a number of neutral atoms and molecules including: Cs, Rb, Rb 2-photon, Sr, Ba, Ca, I_2, C_2H_2, HCN, and CH_4. Significant work is also progressing to develop diode laser systems for trapped-ion frequency standards based on Hg^+, Ba^+, Sr^+,Ca^+, Yb^+, etc.

Now that there are a number of improved frequency/wavelength references in the visible and infrared, there is a real need to expand the capabilities and simplify the methods that are used to synthesize and measure optical frequencies. Impressive results of past optical frequency measurements were achieved using large, complex, multi-laser frequency multiplication chains. With diode lasers and nonlinear optical techniques these systems can be simplified.

Unfortunately, diode lasers also have well known problems such as: discontinuous and limited tuning range, limited power at most wavelengths, and lack of availability at many wavelengths. Some of these problems can be solved with electronic and optical control systems. The parameters in Table 1 are for solitary single-mode lasers without external control.

TABLE OF SEMICONDUCTOR LASER PARAMETERS

Semiconductor	$(Al_xGa_{1-x})_yIn_{1-y}P$	$Al_xGa_{1-x}As$	$Ga_xIn_{1-x}P_yAs_{1-y}$	MOPA
Wavelength	635-670 nm	750-850 nm	1.3 - 1.5 μm	850, 980 nm
Output power (mW)	3-30	5-200	3-100	500 - 1000
farfield divergence FWHM (degrees)	8 × 40	11 × 33	30 × 35	0.3 x 35
Wavcguide mode dimensions, μm	4 x 1	3 × 1	1.25 × 1	1 x 100
Astigmatism	~10 μm	1 to 5 μm	1 to 5 μm	~500 μm
Threshold current	30 - 90 mA	20-60 mA	20 - 50 mA	~0.5 A
Operating Current	50 - 120 mA	50 - 200 mA	40 - 120 mA	~2.5 A
$I_2 = I_1 e^{(T2-T1)/To}$	$T_o \approx 100$ K	$T_o \approx 150$ K	$T_o \approx 60$ K	
slope efficiency, (mW/mA)	0.5 - 0.7	0.7	0.2	1
Refractive index	3.1 - 3.5	3.3 - 3.6	3.2 - 3.5	3.3 -3.6
Freq. vs. Inject. current	~5 GHz/mA	~3 GHz/mA	~ 1 GHz/mA	
Freq. vs. temp. large scale small scale	~0.2 nm/K ~30 GHz/K	~0.25 nm/K ~30 GHz/K	~0.3 nm/K ~ 10 GHz/K	
gain bandwidth	20 nm	30 nm	50 nm	20 nm
typical linewidth	200 MHz	5 - 20 MHz	100 MHz	
alpha factor -- α		3 to 6	4 to 8	

Table 1. Typical Characteristics of semiconductor diode lasers. (Table is from Fox et al[1]).

The causes of frequency fluctuations in diode lasers include: current and temperature instabilities, optical feedback, spontaneous emission, and aging effects. For spectroscopic applications the most challenging parameters are the change in wavelength with temperature and injection current. The fast-linewidth of a solitary laser is typically about 20 MHz, and in order to optimally use this potential resolution we need to have a precision in tuning that is slightly better than the linewidth, say 10 MHz. This means we require a temperature stability of about 300 microkelvin, and current stability of about 3 microamps (out of a DC current of about 100 mA, or equivalently $\Delta I/I=3x10-5$). These results are certainly possible, but they are also non-trivial. Obviously, for high resolution applications care must be taken with the precision and stability of the control systems that are used.

Diode laser spectral characteristics

If for the moment, we ignore the fact that these diodes are lasers, and consider them just as tunable oscillators their characteristics don't seem so unusual. Without external optical or electronic feedback the linewidth of a typical diode laser is about 20 MHz, the oscillation frequency is about 3 $x10^{14}$ Hz, and the tuning range is about 10^{13} Hz. In relative terms, this is an oscillator with a center frequency in the visible, with a fractional spectral width of about 10^{-7}, and a tuning range of about 5% of the center frequency. The absolute numbers are large, but the relative numbers are not so different from other tunable semiconductor oscillators.

For applications in the area of frequency and length standards the diode laser's spectral characteristics are of paramount importance. A significant amount of research and development effort has already gone into understanding and controlling these properties. Good reviews of the spectral characteristics of diode lasers as they apply to scientific applications can be found in a number of recent publications.[1,2,3] The details of the spectral characteristics and the dynamics of diode lasers are actually quite complex: there is the fundamental role of spontaneous emission, the cross coupling of amplitude and phase fluctuations, as-well-as a very high sensitivity of the lasers to optical feedback. Typically, for single-mode lasers the amplitude noise is relatively low and under the right conditions can be near the shot-noise limit. On the other hand, when compared with other types of tunable lasers, the frequency noise on diode lasers is relatively large and spectrally broadband.

It is now common practice to use optical and/or electronic feedback to narrow the spectral width of diode lasers. When using optical feedback to control the spectral characteristics there are essentially two stable operating regimes of feedback power. A diode laser with optical feedback can be stable with a level of feedback that is low, or high, compared with the laser's internal facet reflection. We typically use extended-cavity grating-tuned lasers (ECDL) in the strong feedback regime because this configuration usually provides reliable tuning, single-mode operation and narrow linewidths (fast-linewidth ~50 kHz).[4] In this case the wavelength is controlled by the grating, and the tuning with temperature and injection current are typically reduced by a factor of about 100. Unfortunately, the extended cavity lasers are larger, more complicated and more susceptible to mechanical disturbances. An ECDL built in an enclosed box in a laboratory environment will show increased frequency noise at Fourier frequencies less than about 100 kHz. This low frequency noise usually has strong components at the various mechanical and acoustical resonances of the ECDL system.

Extending Wavelength Coverage

Semiconductor lasers can be used in conjunction with nonlinear optical mixing techniques to generate coherent, tunable radiation throughout the electromagnetic spectrum, from the ultraviolet to the microwave region. That is not to imply that all the interesting wavelengths are accessible in a practical system; rather, it now seems feasible (at least in principle) to reach almost any wavelength between 210 nm and 18 μm using diode laser sources. For example, second-harmonic-generation and sum-frequency-mixing can be used with commercial diode lasers to cover the spectral region between 500 nm and 315 nm. Cascading two of these systems in series can extend the coverage into the ultraviolet, as has now been demonstrated in a couple of recent experiments.[5,6] Likewise, difference frequency generation (DFG) can be used to cover the infrared region. In principle, visible and near-visible diode lasers and DFG in $AgGaS_2$ and $AgGaSe_2$ can cover the spectral region from 2 to 18 μm. We are presently using this technology in the 3 μm region. These systems are now being demonstrated for use in a variety of applications.[7] Even lower frequencies are now accessible using special, low-temperature-grown GaAs photomixers (developed by E. Brown et al.[8]) to generate tunable mm-wave radiation as the difference-frequency between two laser sources. Tunable radiation in the frequency range between 40 GHz and 3.7 THz has now been demonstrated. Recent results in our lab and others have shown that these photomixers also work with diode laser sources.

Calcium wavelength/frequency reference

At NIST we have been developing diode laser systems for high resolution spectroscopy and laser cooling of calcium atoms.[9] Similar efforts are underway at other laboratories.[10,11] Ca is of interest as a wavelength/frequency reference, and as a realization of the meter, because of its narrow (400 Hz natural lifetime limited linewidth) 657 nm optical transition in the red.[12] As can be seen from the energy level diagram (Fig. 1) calcium is also a very good match for use with commercial semiconductor lasers. Because of the availability of good quality of diode lasers in the red a high performance, transportable, transfer-standard of wavelength/frequency could be constructed using traditional atomic beam or cell methods.

For the highest accuracy cold atoms are required. As demonstrated by others[13,14,15] calcium can be cooled and trapped using the strong 423 nm line. We have now developed a frequency-doubled, tunable diode laser for this purpose. A grating-tuned extended-cavity diode laser injection locks a 150 mW single-mode laser which is then frequency-doubled using $KNbO_3$ in a resonant ring cavity. This method produces as much as 45 mW of useful output power at 423 nm which has been used for 1-dimensional, transverse cooling of a calcium atomic beam. We have observed 10 kHz wide Ramsey fringes on the 657 nm transition with this system. To improve the resolution, and more importantly, the accuracy of this 657 nm wavelength reference, 3-dimensional cooling is now required.

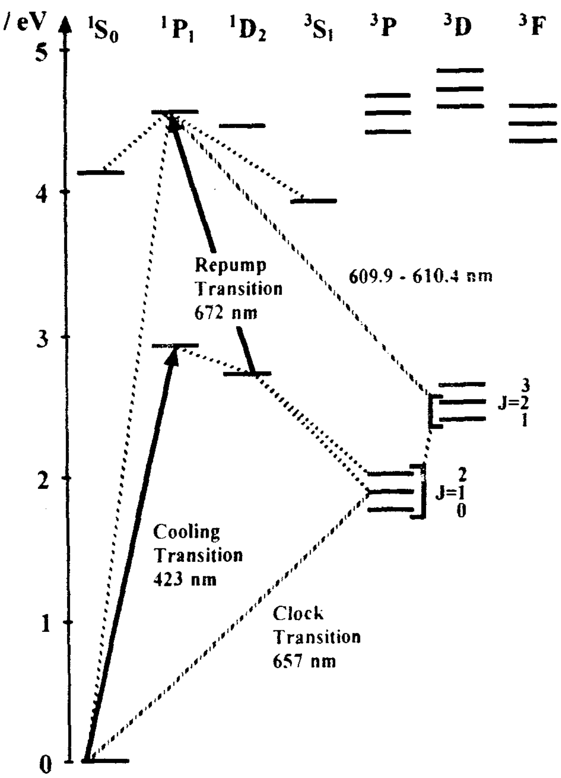

Figure. 1 Calcium energy level diagram showing the narrow 657 nm reference line, the 423 nm cooling/trapping transition and the proposed repumping transition at 672 nm.

It is known that it may be possible to enhance the storage time of the Ca magneto-optic trap by using a laser (at 672 nm) to repump atoms out of the $^1D_2$(4s3d) state before they are lost out of the laser cooling cycle in the trap.[15] Questions and unresolved discrepancies still remain about the efficiency of this method, the trap lifetime and atomic branching ratios. These issues need to be resolved to determine whether this repumping scheme (or other schemes) could be effective. In particular, the transition-rates out of, and lifetime of the $^1P_1$(4s5p) state (upper state of the 672 nm transition) are not in good agreement. We have used our transverse-cooled Ca beam to begin to resolve the discrepancies in previous experimental results, and to explore the possibility of using the 672 nm light for repumping. The 609 nm transition is an intercombination line which is a potential loss channel from the trapping and cooling cycle. We have now measured the ratio of the 672 nm decay rate to the 609 nm decay rate. Preliminary results indicate that the ratio of decay rates ($\Gamma_{672}/\Gamma_{609}$) is about 100. This means that the 609 nm transition is not a dominant loss of population out of the $^1P_1$(4s5p) state, and thus does not preclude the use of the 672 nm line for repumping. However, this measurement does not resolve the discrepancy that remains with the lifetime of the $^1P_1$(4s5p) state. Since it is possible to cycle numerous photons on the repumping transition it may even be possible to use this transition as a 2nd cooling stage. A high-power tunable 672 nm diode laser is now being developed to explore these possibilities.

References

1. R.W. Fox, A.S. Zibrov, and L. Hollberg, Semiconductor Diode Lasers, in Methods in Experimental Physics, vol. Atomic, Molecular and Optical Physics, to be published Academic Press (1995).

2. M. Ohtsu, *Highly Coherent Semiconductor Lasers*, Artech House, Norwood MA, 1992.

3. H. Telle, Stabilization and Modulation Schemes of Laser Diodes for Applied Spectroscopy, *Spectrochimica Acta Rev.*, vol. 15, no. 5, 301-327, 1993.

4. C. Weiman and L. Hollberg, Using Diode Lasers for Atomic Physics, Rev. Sci. Instrum., 62, 1-20, 1991.

5. C. Zimmerman, V. Vuletic, A. Hemmerich, and T.W. Hänsch, All solid state laser source for tunable blue and ultraviolet radiation, Appl. Phys. Lett. 66, 2318-2320 (1995).

6. Lew Goldberg et al. CLEO/QELS '95, proceed. postdeadline papers, Opt. Soc. Am. Boston, (1995).

7. U. Simon, S. Waltman, I. Loa, F.K. Tittel, and L. Hollberg, External Cavity Difference-Frequency Source in the Mid-Infrared based on $AgGaS_2$ and Diode Lasers, J. Opt. Soc. Am. B, 12, 323-327 (1994).

8. E.R. Brown, F.W. Smith and K.A. McIntosh, Coherent millimeter-wave generation by heterodyne conversion in low-temperature-grown GaAs photoconductors, J. Appl. Phys. 73, 1480 (1993).

9. 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, Appl. Phys. B, 59, 327-331 (1994).

10. A. Celikov, F. Riehle, V.L. Velichansky and J. Helmcke, High-resolution spectroscopy in a Ca atomic beam, Opt. Comm., 107, 54-60 (1994).

11. T. Kurosu, J. Ishikawa, N. Ito, and R.W. Fox, High-resolution diode laser spectrometer for the Ca $^1S_0$-$^3P_1$ Transition, proceed. *Laser Frequency Stabilization and Noise Reduction,* SPIE, vol. 2378, 236-244 (1995).

12. R.L. Barger, J.C. Bergquist, T.C. English, and D.J. Glaze, Resolution of the photon recoil structure of the 6573-Å calcium line in an atomic beam with optical Ramsey fringes, Appl. Phys. Lett., 34, 850-852 (1979).

13. N. Beverini, F. Giammanco, E. Maccioni, F. Strumia, and G. Vissani, Measurement of the calcium $^1P_1$-$^1D_2$ transition rate in a laser-cooled atomic beam, J. Opt. Soc. Am. B6, 2188-2193 (1989).

14. Th. Kisters, K. Zeiske, F. Riehle and J. Helmcke, High-resolution spectroscopy with laser-cooled and trapped calcium atoms, Appl. Phys. B, 59, 89-98 (1994).

15. T. Kurosu and F. Shimizu, Laser cooling and trapping of Alkaline earth atoms, Jpn. J. Appl. Phys., 31, 908-912 (1992).