Inexpensive diode laser microwave modulation for atom trapping

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We describe a simple modification to a grating-stabilized diode laser intended for use in neutral atom cooling and trapping. Modulation of the laser diode's driving current at microwave frequencies induces sidebands in the laser's spectrum that eliminate the need for a second laser in a trapping apparatus, yielding a considerable savings in effort and cost. A detailed description of the process for selection and assembly of microwave components is given. In an appendix we list the hardware used, with vendor and pricing information. © *1995 American Association of Physics Teachers.*

Laser cooling and trapping of neutral atoms is a young and rapidly growing area of atomic physics research.[1] Previous papers in this journal have provided detailed instructions for building grating-stabilized diode lasers to trap atoms[2] and an inexpensive trapping apparatus[3] with the goal of incorporating this exciting technique into undergraduate laboratories. This paper describes a modest modification to the trapping laser that eliminates the need for a second laser, significantly simplifying the hardware and reducing the cost of atom trapping. Myatt, Newbury, and Wieman[4] demonstrated a simple circuit for modulation of a diode laser's injection current at microwave frequencies in order to induce sidebands in the laser's spectrum, and showed that the sideband production is enhanced if the free spectral range of the laser cavity is close to the modulation frequency. One of these sidebands is used to provide light previously supplied by a second laser. They demonstrated this technique for ^{87}Rb trapping using a frequency synthesizer as their microwave source; in this paper, we describe a simpler, less expensive source of microwave modulation power for a ^{85}Rb trap, and also, at somewhat greater expense, for ^{87}Rb as well.

The magneto-optical trap (MOT) for alkali atoms usually requires laser light at two frequencies. This can be understood with reference to Fig. 1, a hyperfine energy level diagram for the $5^2S_{1/2}$ and $5^2P_{3/2}$ states of ^{85}Rb. The most common technique is to trap and cool with light detuned a few linewidths from the $F=3 \rightarrow F'=4$ resonance. A principal reason for choosing this transition is that an atom in the $F'=4$ excited state is only allowed to decay back to the $F=3$ ground state, where it is immediately available for reexcitation. The need for a second laser arises because infrequent Raman scattering puts the atoms in the $F=2$ level. Without a mechanism for removing atoms from $F=2$, the trap would cease to function. Thus a second laser is needed to remove atoms from the $F=2$ state by exciting the $F=2 \rightarrow F'=2$ or 3 transition; from $F'=2$ or 3, the atoms can decay back to $F=3$, where they will be trapped once again. This laser is commonly referred to as the "hyperfine pumping" laser, as it pumps atoms from $F=2$ to $F=3$.

In this work we provide the needed hyperfine pumping light by generating sidebands on the main trapping laser. When modulating the injection current to a laser diode, one obtains both amplitude modulation (AM) and frequency modulation (FM) of the laser light. It is probable under our conditions that FM dominates, but with either AM or FM, one result is that sidebands are generated above and below the main carrier frequency at the frequency of modulation. (For further discussion of amplitude- and frequency-modulation, see, for example, Elmore and Heald.[5])

Light to excite $F=2 \rightarrow F'=3$ is approximately 2.9 GHz higher in frequency than trapping light tuned to $F=3 \rightarrow F'=4$. Therefore to generate a sideband for hyperfine pumping, one modulates the current to the trapping laser diode at 2.9 GHz. (The corresponding frequency for ^{87}Rb is 6.6 GHz. Throughout this paper we refer to ^{85}Rb, but we have trapped ^{87}Rb also using the same method.) Microwave

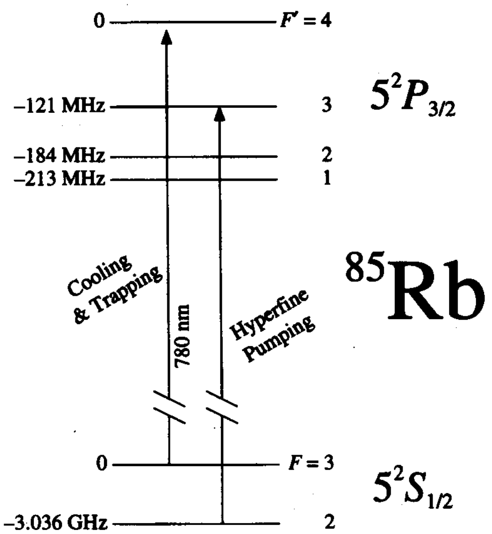

Fig. 1. Hyperfine structure of the $5^2S_{1/2}$ and $5^2P_{3/2}$ states of ^{85}Rb. The carrier frequency of the laser provides the cooling and trapping light, while a sideband frequency gives the light for hyperfine pumping.

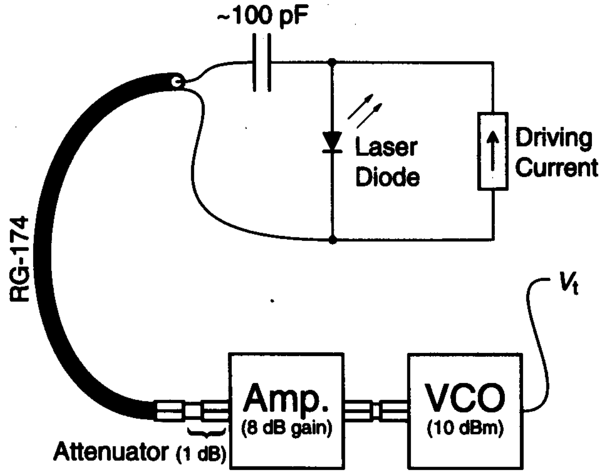

Fig. 2. Schematic of the circuit for modulating a diode laser at microwave frequencies. The driving current is supplied from a standard diode laser current source. V_t is the DC tuning voltage for the VCO. The amount of microwave power required by a particular laser may vary, as discussed in the text. Part numbers of the microwave components are given in the Appendix.

circuit design, in general, requires greater sophistication than the design of circuits at the lower frequencies more common in laboratory instrumentation. One must start to regard wires and cables as waveguides, for example, and poorly chosen components will be very lossy. However, one of the points of Myatt *et al.*,[4] which we reiterate, is that one can avoid the effort of optimal microwave design and still achieve good results. We present here a description of what has proved successful in our work. In the appendix we list the specific hardware used, with vendor information.

One of the problems of microwave circuit design is impedance mismatching. Reflections from connections between sections of circuits with different impedances result in inefficient transmission of power, and too much power reflected back into the output of a component may even prevent it from operating properly, so it is usually important to minimize the differences in impedance in a circuit. Before the point where we finally couple the microwave power into the laser diode (treated later in this paper), we minimize impedance mismatching by use of standard microwave hardware—specifically, we adopt the 50 ohm SMA-type connector. Oscillators and amplifiers are commonly available with SMA-connectorized outputs and inputs. In our particular case, we use a voltage controlled oscillator (VCO) that comes in a TO-8 package which is not itself connectorized, but TO-8 packages are easily plugged into commercially available test fixtures that provide SMA connectors. RG-174 coaxial cable (50 ohm) can be purchased with SMA connectors already attached, or they can be attached in the lab. Though lossy at high frequencies, RG-174 performs adequately for our application and has the important advantage that it is more flexible than most of the alternatives; this means that it will transmit vibrations less, which is crucial for laser stability.

In choosing oscillators and amplifiers, we do not concern ourselves with specifications such as harmonics, noise figure, gain flatness, and the like. We simply choose an oscillator–amplifier combination that provides enough power, tunable over the frequency range of interest. We typically use 14–17 dBm of power. [Microwave power is commonly expressed in dBm, which is defined so that 0 dBm = 1 mW when driving a 50 ohm load. Gain is expressed in decibels (dB).] The oscillator will have a specification for power output and the amplifier will have specifications for gain and maximum power output, which for our purposes is the value usually expressed as "power output at 1 dB compression." If the power output of the oscillator plus the amplifier's gain exceeds the maximum power output of the amplifier, then an attenuator (which comes as a pass-through SMA component) should be placed between the two components in addition to the SMA barrel connector needed to join them. Also, it is desirable to place an attenuator at the output of the amplifier to serve as an impedance buffer between the amplifier and the load, which in our case is not the ideal 50 ohms. Even with the attenuation loss, we observe better results with a 1 dB attenuator in this role than without.

Figure 2 is a schematic of the circuit. The laser we modified is a Sharp LT025MD0 laser diode with grating feedback.[2] When driven with 120 mA of current, over 20 mW of usable light is coupled out of the laser. The oscillator and amplifier should be placed as close to the laser box as possible in order to minimize the length of coaxial cable needed. We couple our microwaves into the laser by soldering the coaxial cable to a capacitor that is soldered to the current lead for the laser. (It is best to solder the leads and capacitor to a socket for the laser diode, rather than directly to the diode package, in order to minimize the risk of damaging the diode via excessive heating, static discharge, etc.) The value of the capacitor is not critical. We have tried various types of capacitors ranging from 3.3 to 100 pF, whose capacitive impedances at 2.9 GHz range from 17 to 0.5 ohms. The efficiency of power coupling into the diode varies by perhaps a factor of 2, but probably depends on factors such as capacitor design as much as the labeled capacitance. The total power-supply current drawn by our oscillator and amplifier (at 15 V) is less than 200 mA. It is prudent to attach the oscillator and amplifier to a heat sink; their cases may have tapped holes that facilitate this. The tuning voltage for the VCO is typically in the 0–15 Volt range, with negligible current draw.

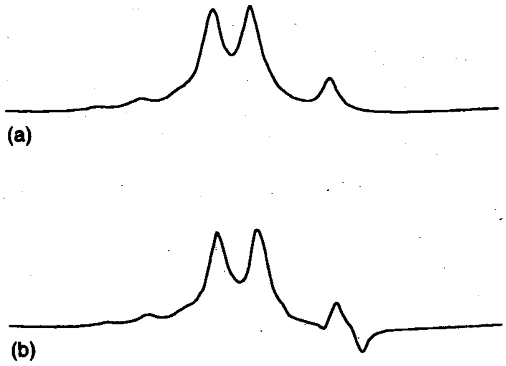

Fig. 3. Saturated absorption spectra of the ^{85}Rb $5^2P_{3/2}$ levels ($F=3 \rightarrow F'=2,3,4$) without sidebands on the laser (a), and with sidebands at 2.9 GHz (b). The modification of the spectrum by the sideband is easily observed to change with the tuning of the sideband.

If one has an appropriate microwave counter or optical spectrum analyzer at one's disposal, the task of tuning the oscillator to the correct frequency for hyperfine pumping is straightforward. Fortunately, no such sophisticated instrumentation is needed. The frequency band over which hyperfine pumping can be effected is broad: greater than ~100 MHz, corresponding to over ~1.5 V range in tuning voltage for our particular VCO. If all other requirements for atom trapping are in place (e.g., if atoms have been trapped before in the apparatus, but with a dedicated hyperfine pumping laser), the carrier frequency can be locked to the trapping transition and the microwave frequency swept by hand until a trap is observed. Even if one does not have the capability to trap atoms, the proper microwave tuning can be observed by an enhancement in the fluorescence of a Rb vapor through which the laser beam passes with carrier tuned to $F=3 \rightarrow F'=4$. Furthermore, one may observe the presence of the sideband with the laser's Doppler-free saturated absorption spectrometer:[2] the presence of the sideband that excites the $F=2 \rightarrow F'=1,2,3$ transitions modifies the saturated absorption spectrum of the carrier frequency (tuned to $F=3 \rightarrow F'=2,3,4$), as shown in Fig. 3.

As emphasized by Myatt *et al.*,[4] we observe particularly enhanced production of sidebands when the microwave frequency matches the free spectral range (FSR) of our laser cavity, as defined by the back facet of the laser diode and the external diffraction grating. In contrast to their work, our laser's FSR is several hundred MHz from the hyperfine pumping frequency and thus we do not benefit from this sideband enhancement. In the frequency range of hyperfine pumping, we observe sidebands (with an optical spectrum analyzer) of approximately 3% of the power of our carrier frequency with ~17 dBm power out of our oscillator amplifier, compared to 25% or more when the sideband frequency is close to the FSR. In general, the power spectrum of the sidebands (at fixed microwave power) is a nontrivial function of factors such as the laser cavity FSR and circuit resonances. At some microwave frequencies (fortunately, not where we need light), we observe vanishingly small sidebands. Our success in trapping atoms with two retrofitted lasers suggests that it probably is not vital that one use a laser with a precisely chosen FSR, but if a new laser is to be built, it would be prudent to build it with the hyperfine-pumping-matched FSR, or even with a variable FSR for more flexibility. If the FSR sideband enhancement were great enough, one might forgo the amplifier if the oscillator alone provided enough power to generate sufficient sideband power for trapping. For applications other than atom trapping where one wishes to maximize sideband power, one should certainly match the laser's FSR to the modulation frequency.

If one can control the power output of the oscillator amplifier (for example, through a variety of attenuators), it is desirable to study the number of atoms as a function of microwave power, as in Fig. 2 of Myatt *et al.*[4] As the power in the sideband increases from zero the number of atoms trapped will increase due to more complete hyperfine pumping, but beyond a point the total number of atoms may decrease as the sideband steals excess power from the carrier frequency. In our apparatus we do not reach this power regime where the number of atoms decreases, but we do observe a leveling-off in the number of atoms vs power. From our observations and those of Myatt *et al.*, typically this occurs when the sideband power is ~1%–3% of the carrier power.

In addition to eliminating the cost and complication of a second laser, the microwave-modulation sideband approach to hyperfine pumping has additional advantages. For example, by changing the tuning voltage to the VCO, the hyperfine pumping can be switched on and off electronically, providing a convenient method for rapidly turning the trap on and off. An interesting possible undergraduate experiment would be to measure the rate of Raman scattering when the hyperfine pumping is switched off. Also, as Myatt *et al.*[4] observe, other applications, such as various Raman processes, require light separated by microwave frequencies for which modulated diode lasers are excellent sources.

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APPENDIX: COMPONENTS USED FOR MICROWAVE MODULATION OF DIODE LASER

We list here the components used in our apparatus, their vendors, and approximate prices. No endorsement is implied; we have not researched the market thoroughly and have no reason to believe that products from other manufacturers will not work as well or better as the ones we have used. Buyers' guides such as the one from Physics Today are good sources of vendor lists. Microwave Product Digest is a trade journal for microwave hardware.

A. Voltage Controlled Oscillator: VTO-8240 (2.4–3.7 GHz @ 10 dBm; $129) mounted in a TF-801 test fixture ($192). For ^{87}Rb, VTO-8650 (6.5–8.6 GHz @ 10 dBm; $313). Avantek, 3175 Bowers Ave., Santa Clara, CA 95054-3292, (800)-AVANTEK. Avantek is distributed by Penstock, among others (see item D).

Another source for SMA-connectorized test fixtures for TO-8 packages ($175) is Vari-L, 11101 E. 51st Ave., Denver, CO 80239, (303) 371-1560.

B. Amplifier: AC3579C ("C" stands for "connectorized;" 0.01–3.5 GHz; gain 8.3 dB; max. power 22 dBm; $298). Cougar Components, 2225-K Martin Ave., Santa Clara, CA 95050, (408) 492-1400.

For ^{85}Rb or ^{87}Rb, AFS4-02000800-20P-MP (2–8 GHz; gain 22 dB; max. power 20 dBm; $750). Miteq Inc., 100 Davids Dr., Hauppauge. NY 11788, (516) 436-7400.

C. Attenuators: FP-18/[attenuation value in dB] (DC to 18 GHz; $61 each). Trilithic, 9202 East 33rd St., Indianapolis, IN 46236, (800) 344-2412.

D. SMA connectors of various types (~$10–$20 each). M/A-COM Omni Spectra "Microwave Coaxial Connectors" catalog, distributed by Penstock, 520 Mercury Dr., Sunnyvale, CA 94086, (800)-PENSTOC. Penstock will also sell cables with connectors attached.

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[2] K. B. MacAdam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode laser system with grating feedback and a saturated absorption spectrometer for Cs and Rb," Am. J. Phys. **60**, 1098–1111 (1992).

[3] C. Wieman, G. Flowers, and S. Gilbert, "Inexpensive laser cooling and trapping experiment for undergraduate laboratories," Am. J. Phys. **63** (4), 317–330 (1995).

[4] C. J. Myatt, N. R. Newbury, and C. E. Wieman, "Simplified atom trap by using direct microwave modulation of a diode laser," Opt. Lett. **18**, 649–651 (1993).

[5] W. C. Elmore and M. A. Heald, *Physics of Waves* (Dover, New York, 1969), pp. 426–431.