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A modified commercial Ti:sapphire laser with 4 kHz rms linewidth

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Abstract

We have modified a commercial Ti:sapphire laser to allow optical phase stabilization to an extremely stable semiconductor laser, which in turn is locked to a Doppler-free resonance in a cesium vapor cell. For time scales from 10 μs up to several hours the combined system has a rms linewidth of 4 kHz with respect to the cesium resonance. The system allows the resolution of extremely narrow resonances in a cloud of trapped atoms.

Ti:sapphire ring lasers have become increasingly useful tools in high-resolution spectroscopy. They are widely tunable, offer power levels of several watts, and can readily be obtained commercially. Although the passive stability of Ti:sapphire systems is much better than that of dye lasers it is still limited by their high level of (mostly) technical noise caused by cavity length fluctuations at various time scales. Some commercial models (such as the Coherent Model 899/21 we are using) incorporate a reference cavity, and the laser is locked to the side of a fringe of that auxiliary cavity. The error signal is fed to a piezo-mounted mirror ("tweeter") and a galvo-driven Brewster plate ("woofer") inside the laser resonator. The maximum servo bandwidth of a few kHz keeps the laser frequency stabilized to within better than 1 MHz with respect to the reference cavity. It turns out, however, that due to acoustic noise acting upon the reference cavity this line is broadened to several MHz ("slow linewidth") with respect to an absolute standard.

Some experiments require light sources with much smaller bandwidth, both on a fast and on a slow time scale. In a spectroscopic application it is also very important to be able to precisely control the frequency offset of the laser source with respect to some frequency reference (e.g., the line center of the resonance under study). We have solved both problems with the help of an intracavity electrooptic modulator as a fast servo element. This allows to phase-lock the laser to a stable reference laser with a heterodyne phase-locked loop [1]. There are other possibilities to tackle both problems individually whose advantages and disadvantages will be discussed later.

Our experimental setup consists of a stable narrowband diode laser ("master") in one laboratory whose output is transferred to the Ti:sapphire laser in another laboratory via an optical fiber (Fig. 1). On a fast photodiode the beat note between the two laser sources is generated and its frequency and phase are compared to that of a stable electronic reference oscillator. Their phase difference is used to control the Ti:sapphire laser frequency and phase. In the following paragraphs the individual components are discussed in more detail.

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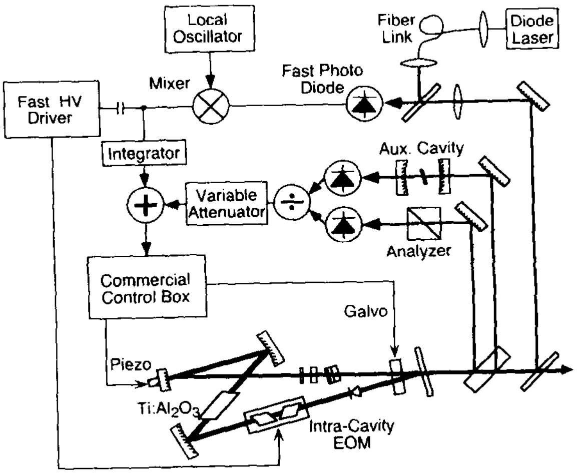

Fig. 1. Experimental setup showing the stable diode laser, the Ti:sapphire laser, and their optical and electrical interconnections.

The master laser (Fig. 2) is a nominal 50 mW single-mode diode laser at 852 nm wavelength (STC LT50A-03U). Its drive current is controlled within an rms current noise of less than 500 nA in 100 kHz bandwidth, and its temperature within 0.3 mK in 5 kHz bandwidth. A thin glass substrate at a variable distance in front of the laser chip facet allows the selection of a specific longitudinal laser mode [2]. The fast linewidth is drastically reduced by resonant feedback from an external confocal cavity of finesse 70 in a setup analogous to that of Refs. [2–5]. The cavity is operated in a V-shaped configuration. One of the output beams that is of transmission-like character provides the feedback when the laser is in resonance with the cavity. One other output beam is of reflection-like character and can be used for a Hänsch-Couillaud locking scheme [6]. The whole setup is placed inside an actively temperature stabilized box with styrofoam insulation.

Outside the box the laser passes a 60 dB Faraday isolator [7] to prevent feedback from the following optics, and about 10% of its output power are split off towards a polarization spectroscopy setup. The rest of the power is sent into a fiber coupler, and an optical fiber transports this radiation to the Ti:sapphire laser. There about 8 mW of diode laser radiation are available under typical operating conditions.

To derive a steep error signal for frequency stabilization without having to modulate the laser frequency we have employed a standard polarization spectroscopy setup [8] (Fig. 2). A quarter-wave plate transforms the linearly polarized laser light into a circularly polarized pump beam that traverses a cesium vapor cell in the opposite direction of the linearly polarized probe beam. With an analyzer a change in polarization direction of the probe beam due to the presence of the pump beam can be detected. An instrumentation amplifier generates the difference of the photocurrents from the two photo diodes which can be used as an error signal for a servo loop because it has a steep dispersive shape, centered on the $(6^2S_{1/2}, F=4) \rightarrow (6^2P_{3/2}, F'=5)$ transition of the cesium D_2 line. The DC part of the error signal is electronically integrated and used to control the length of the feedback cavity via the cavity piezo, and the AC component controls the gate of a field-effect transistor that shunts the diode laser junction and thus provides a fast control with an overall bandwidth of 100 kHz. Drifts of the laser current are negligible so that no DC feedback path for the current is needed.

Due to the dynamics of the optical pumping processes in polarization spectroscopy the error signal can

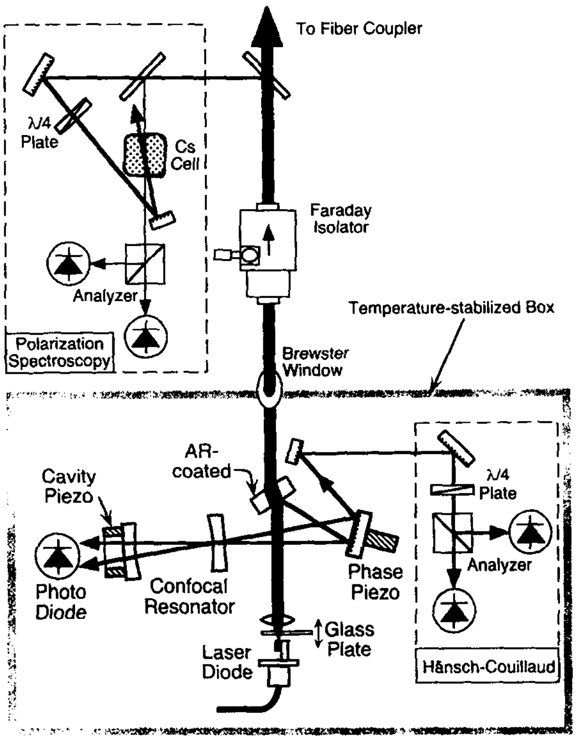

Fig. 2. More detailed view of the optical setup of the stable diode laser. To the right is the optional Hänsch-Couillaud stabilization setup, to the left the polarization spectroscopy.

only reflect changes in the laser frequency that are slower than a few times the lifetime of the upper level of the cesium D_2 transition of about 30 ns. As a result, the steepness of the dispersive error signal is reduced for servo frequencies above 1 MHz. This is no practical limitation, however, since the optical feedback mechanism takes care of the high-frequency fluctuations, and the servo loop only has to deal with the slower acoustic vibrations, and a 100 kHz servo bandwidth is plenty for that purpose.

A critical parameter for the stability of the optical feedback mechanism is the length of the feedback path. It can be adjusted with the piezo-mounted mirror (Fig. 2) which in principle can be controlled with a Hänsch-Couillaud locking scheme [6]. In our setup, however, it turns out that thermal drifts are all but eliminated by the active temperature stabilization of the whole laser setup, and the acoustic noise is taken care of by the polarization spectroscopy servo loop. Therefore the Hänsch-Couillaud scheme is not used at the moment. Instead, the piezo voltage is derived from a stable voltage source and set by hand when the laser is switched on.

Special care was taken to avoid ground loops and shield the setup from 50 Hz line frequency interference. This is especially important for the polarization spectroscopy [8] where the cesium cell had to be placed inside a μ-metal shielding in order to reduce Faraday rotation that caused a broadening of the absolute rms linewidth on a 100 ms time scale to 100 kHz.

The thermally stabilized box, the isolator, the polarization spectroscopy, and the fiber coupler are all mounted on the same thick aluminum plate resting on soft foam rubber to reduce acoustic vibrations. The system fits into a volume of $70 \times 35 \times 25$ cm^3.

The rms linewidth of the laser system was measured by demodulation of the frequency fluctuations with two independent steep frequency-to-amplitude converters: an etalon transmission fringe and a cesium resonance line. With an electrical bandwidth of 100 kHz the output signal of the converters was captured on a storage oscilloscope and transferred to a computer for rms value calculation. The signal from the etalon transmission was extremely sensitive to variations in the angle of incidence on the etalon and thus very susceptible to acoustic noise. Merely touching the mirror holders that were used to couple the light into the etalon caused wild excursions of the transmission signal. When the electronic servo loops were gradually tightened the measured rms linewidth decreased until at a level of about 80 kHz rms linewidth a plateau was reached and no further reduction in the measured rms value could be achieved. At the same time, we monitored the signal of our absolute frequency standard, the $F=4' \rightarrow F'=5$ transition in the magnetically shielded cesium polarization spectroscopy setup. The rms linewidth value derived from the cesium line initially corresponded to the rms linewidth measured with the etalon but continued to decrease for ever tighter servo loops below the 80 kHz down to 4 kHz at the optimum servo parameter settings. Since beam pointing stability was much less critical for the polarization spectroscopy setup we conclude that acoustic vibrations of the setup dominate the transmission changes seen behind the etalon if the laser rms linewidth is below 80 kHz.

We also looked at the discriminator signal with a Fast Fourier Transform spectrum analyzer. Most of the remaining 4 kHz rms linewidth is still due to residual 50 Hz line frequency interference. At Fourier frequencies above 60 kHz the noise spectral density is flat and corresponds to about 1 kHz linewidth assuming purely white noise. The laser remains locked for many hours. Since all the error signals for the various servo loops are derived without having to modulate the laser frequency this laser system constitutes an extremely monochromatic radiation source in the vicinity of the cesium D_2 resonance.

Our main application of this stable laser is its use as a frequency reference for a commercial Ti:sapphire laser (Coherent model 899/21). The Ti:sapphire laser resonator is a ring resonator in bow-tie configuration with several servo elements for frequency stabilization and scanning. All these elements are controlled by servo electronics supplied and well-documented by the manufacturer. In addition, we inserted an electrooptic modulator (EOM, Gsänger model PM25-IR) into the laser resonator to provide enough servo bandwidth for phase locking. The EOM consists of two KD*P crystals in a compensation arrangement and thus does not change the overall beam path inside the resonator.

The setup for phase locking is as follows (Fig. 1). A small portion of the Ti:sapphire light is directed towards a fast photo diode where it is superposed with the light from the master diode laser coming out of the fiber. The radio-frequency beat note between the two laser sources is compared to the output of a stable

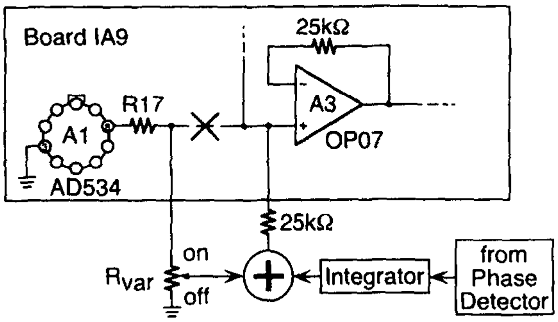

Fig. 3. Sketch of the modifications to the commercial Ti:sapphire servo system.

programmable radio frequency source (local oscillator) with an analog mixer, and the mixer output provides the error signal for the phase-lock of the Ti:sapphire laser to the master diode laser. The high-frequency part of the error signal is fed to the intracavity EOM for fast control whereas the low-frequency part is electronically integrated and added to the error signal derived from the auxiliary reference cavity (Fig. 1). This addition can be carried out with only slight modifications to the commercial servo electronics. Pin 3 of IC A1 on board 1A9 (an Analog Devices AD534) was originally connected to ground, this connection was scratched open and the integrated low-frequency error signal was connected to pin 3.

It turns out that the auxiliary cavity is not needed when the laser is phase-locked. In fact, the loop is much less sensitive to acoustic disturbances when the error signal component from the auxiliary cavity is ignored. Decoupling of the commercial auxiliary cavity lock was accomplished with the circuitry sketched in Fig. 3. The wiper of R_{var} is initially in the "on" position until all servo loops are closed and locked. Then it is gradually moved to the "off" position. In this way the Ti:sapphire laser remains phase-locked for hours before one of the servo elements reaches its maximum excursion and requires manual adjustment.

Fig. 4 shows the phase-locked radio frequency beat note between the master diode laser and the Ti:sapphire laser. 99% of the optical power are concentrated in the carrier. So to a good approximation the Ti:sapphire laser has the same spectrum and the same linewidth as the master diode laser.

A conventional technique for laser stabilization at a comparable level requires much more effort, both experimentally and financially. A standard technique is the stabilization of a ring laser to a fringe of a high-finesse cavity [9,10] with the help of an intracavity EOM. However, an additional good-quality external EOM with very low spurious amplitude modulation is needed to modulate the laser frequency with a radio frequency to derive a steep error signal from the cavity. The design of a reference resonator with drift rates and resonance widths in the kHz regime is a major experimental challenge which can be met only with (nominal) fixed-frequency cavities. To allow tunability of the laser and eliminate drift effects one needs an AOM to shift the laser frequency which in practice limits the continuous tuning range to a few 100 MHz at best. On the other hand, the master-slave phase-locking technique is limited in tuning range only by the bandwidth of the photo diode and the mixer which can easily be

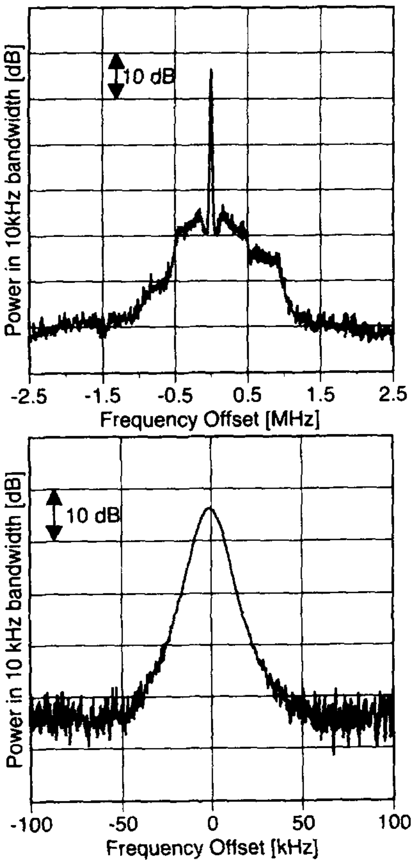

Fig. 4. Phase-locked radio frequency beat note between the stable diode laser and the Ti:sapphire laser. 99% of the optical power are contained in the carrier.

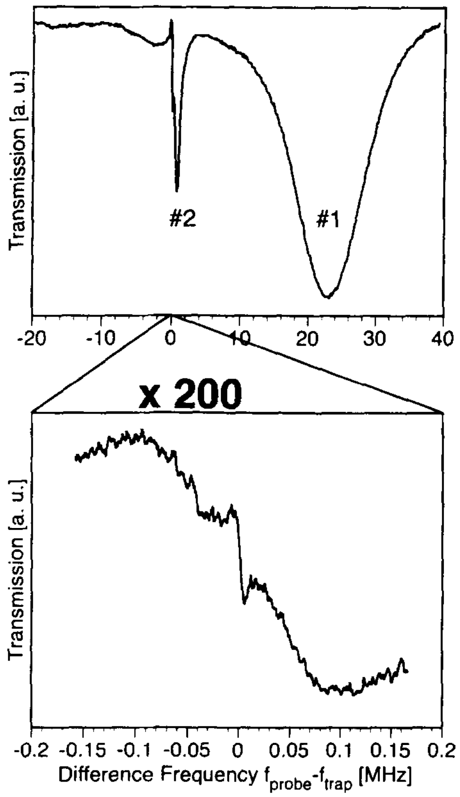

Fig. 5. Transmission spectra of a weak probe laser beam through a cloud of cold cesium atoms. The sharp dispersive resonance in the bottom spectrum has a width of only 12 kHz and is clearly resolved using the phase-locking technique.

several GHz. A major advantage of our phase-locking technique is that we can lock a second slave laser to the master laser at minimum cost (a suitable photo diode and a mixer).

To illustrate the usefulness of the phase-locking technique we discuss two experiments with laser cooled cesium atoms where the trap light was provided by the phase-stabilized Ti:sapphire laser. In the first experiment the transmission of a weak probe laser beam through a cloud of cold atoms localized in potential wells created by the trapping light fields (frequency f_{trap}) was recorded. The probe laser, a second diode laser, was phase-locked to the same master laser and its frequency f_{probe} was controlled with a variable frequency offset provided by a voltage-controlled oscillator. In Fig. 5 a wide-span transmission spectrum is plotted where besides the usual $F=4 \to F'=5$ absorption line (peak #1) a dispersive feature centered around the frequency of the Ti:sapphire laser can be seen (peak #2). A more detailed view reveals another sharp dispersive structure with a width of only 12 kHz which is only resolved using the phase-locking technique for both the trapping and the probe laser. A detailed discussion of these spectra is beyond the scope of this publication. Similar spectra have been obtained, e. g., in Ref. [11], using a different technique.

The Ti:sapphire laser was also used to trap individual cesium atoms in a special magnetooptic trap [12] where each additional atom in the trap caused a step in the fluorescence intensity. Long uninterrupted data runs of several hours provide excellent statistics of capture and loss events in such a single-atom trap [13].

Acknowledgements

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