Frequency Stabilization of a High Power Argon Laser

J. P. Hohimer, R. C. Kelly, and F. K. Tittel

A technique for frequency stabilizing a high power, single frequency argon laser is described which offers certain advantages over those that have already been reported. This system is capable of maintaining a relative short term frequency stability of the order of ±2 parts in 10^9 and a long term stability (2 h) of about ±5 parts in 10^9 for the 5145-Å line at a power level of 750 mW. This short and long term stability is achieved by means of a multiple feedback loop composed of an optical cavity discriminator which is stabilized against an iodine vapor absorption line.

Introduction

A feedback scheme is described that has been used effectively to stabilize the frequency of a commercial, high power, single transverse, and axial mode argon laser (CRL model 52B). The advantage of this system as compared to other frequency stabilization methods applicable to high power argon lasers[1] is that it consists of a simple optical and electronic scheme, which does not require modification of the basic commercial system or frequency modulation of the laser itself. This feature of an unmodulated output is a desirable feature for many applications of frequency stabilized lasers. Furthermore, direct monitoring of the relative frequency stability is possible with this method, which eliminates the need for two identical laser systems to determine stability.

Principle of Operation

In a well-designed laser configuration, frequency fluctuations and drift are primarily caused by thermal changes in the laser cavity structure and variations in the refractive index of the laser medium and the air in the resonator.[2,3] The function of the stabilization control system is to sense such changes and to correct the cavity length by means of a piezoelectric translator, thus maintaining a constant effective optical cavity length which in turn means a constant laser frequency within certain error limits, provided the range of the control loop is not exceeded. To achieve both short and long term stability, a double control system is used in which a passive cavity discriminator is employed in a wide bandwidth (fast) control loop to compensate for short term fluctuations, and a molecular line discriminator is used for long term control of the reference cavity.[4] The stability of this scheme cannot be better than the stability of the absorption spectrum, which is mainly influenced by temperature.

A schematic diagram of the complete stabilization system is shown in Fig. 1. The argon laser emits about 1.6 W at 5145 Å for a plasma tube current of 30 A. Single frequency operation is achieved by a temperature stabilized solid intracavity etalon (free spectral range 10 GHz) which suppresses all but a single axial mode. A single mode power in excess of 800 mW is possible provided the etalon orientation and temperature are optimized. The laser mode spectrum is continuously monitored by a spectrum analyzer. Amplitude stabilization capable of light regulation to better than 0.1% rms is part of the commercial system. A small portion of the laser light is coupled to the stabilization loops by means of two beam splitters.

The principle of operation of the primary stabilization loop is similar to the technique described in Refs. 4 and 5 and to a commercially available lock-in stabilizer (Lansing model 80.210). A Spectra model 470-A6 optical spectrum analyzer (free spectral range 8 GHz) serves as a convenient passive reference cavity when located inside a constant temperature enclosure with a thermal stability of better than 0.05°C/h. This corresponds to a long term frequency stability of better than 20 MHz/h in the primary feedback loop. Laser light is incident on the reference cavity whose resonance frequency is adjusted to coincide to the laser frequency. This is done by tuning the reference cavity length with a bias voltage applied to the piezoelectric cavity spacers and thereby changing its cavity length. In addition, the resonant frequency of the reference cavity is modulated at an audio rate (2 kHz) with an amplitude less than the cavity bandwidth (27 MHz). The effect of this on the laser light transmitted by the cavity is monitored with a silicon photodiode. At res-

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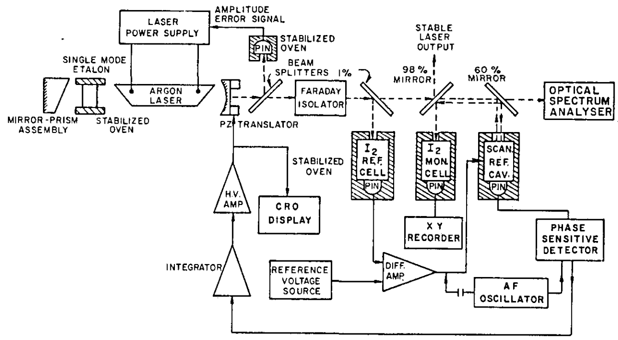

Fig. 1. Schematic diagram of the argon laser frequency stabilization system.

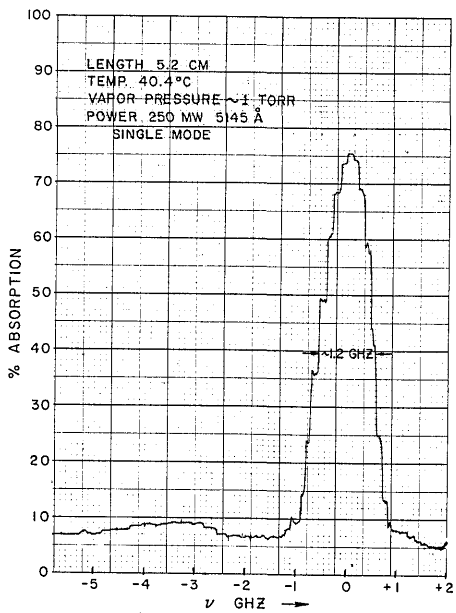

Fig. 2. Absorption characteristic of an $^{127}I_2$ vapor cell in the vicinity of 5145 Å.

onance there will be no signal, since the derivative of the resonator characteristic is zero. When the laser output differs from the center frequency of the reference cavity response, an amplitude modulated signal is detected. The amplitude and phase of this signal reflect the magnitude and sign of the frequency deviation, which can be used to adjust the laser frequency to the reference cavity frequency. This time varying error signal is processed by a commercial phase-sensitive detector (PAR model 124) which is tuned to the cavity modulation frequency and permits easy adjustment of system sensitivity, phase, and time constant. The error output of the phase sensitive detector is integrated (1 sec time constant), amplified, and applied to a piezoelectric translator (Spectra model 590) supporting the laser output reflector. In this manner the loop is completed, and the error signal corrects the length of the laser cavity thereby stabilizing laser frequency with respect to the passive reference cavity.

To improve the frequency performance of this feedback loop with particular emphasis on long term frequency stability the reference cavity is stabilized by means of an additional feedback loop. This loop uses the frequency dependent changes in the absorption of a molecular iodine line[6,7] as its frequency reference to keep the cavity discriminator tuned to a selected point on its absorption spectrum. A part of the laser beam is directed into a 5 cm long and 3 cm in diameter iodine vapor cell which was mounted in a temperature stabilized oven. The Doppler broadened resonance absorption characteristic of two overlapping rotational lines [$R(15)$ and $P(13)$] belonging to the 43-0 vibrational band of the $B^3\Pi_g{}^+ - X^1\Sigma_g{}^+$ electronic transition of $^{127}I_2$ vapor in the region of the 5145°-Å argon laser line is shown in Fig. 2. The discontinuities in the absorption curve are due to the axial mode jumps of the laser cavity ($c/2L \sim 128$ MHz), which were induced by slow temperature scanning of the intracavity etalon.

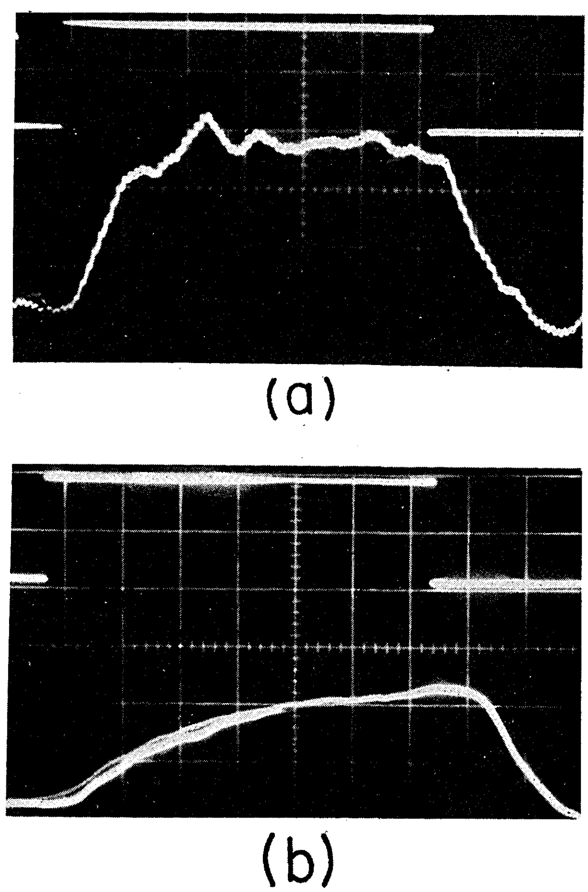

Fig. 3. Step response of stabilization system (a) for primary loop only, (b) for multiple feedback loops. Time scale, 5 msec/div; frequency of input signal, 16 Hz; vertical sensitivity, 2 V/div except for lower trace in (b), when it is 10 V/div.

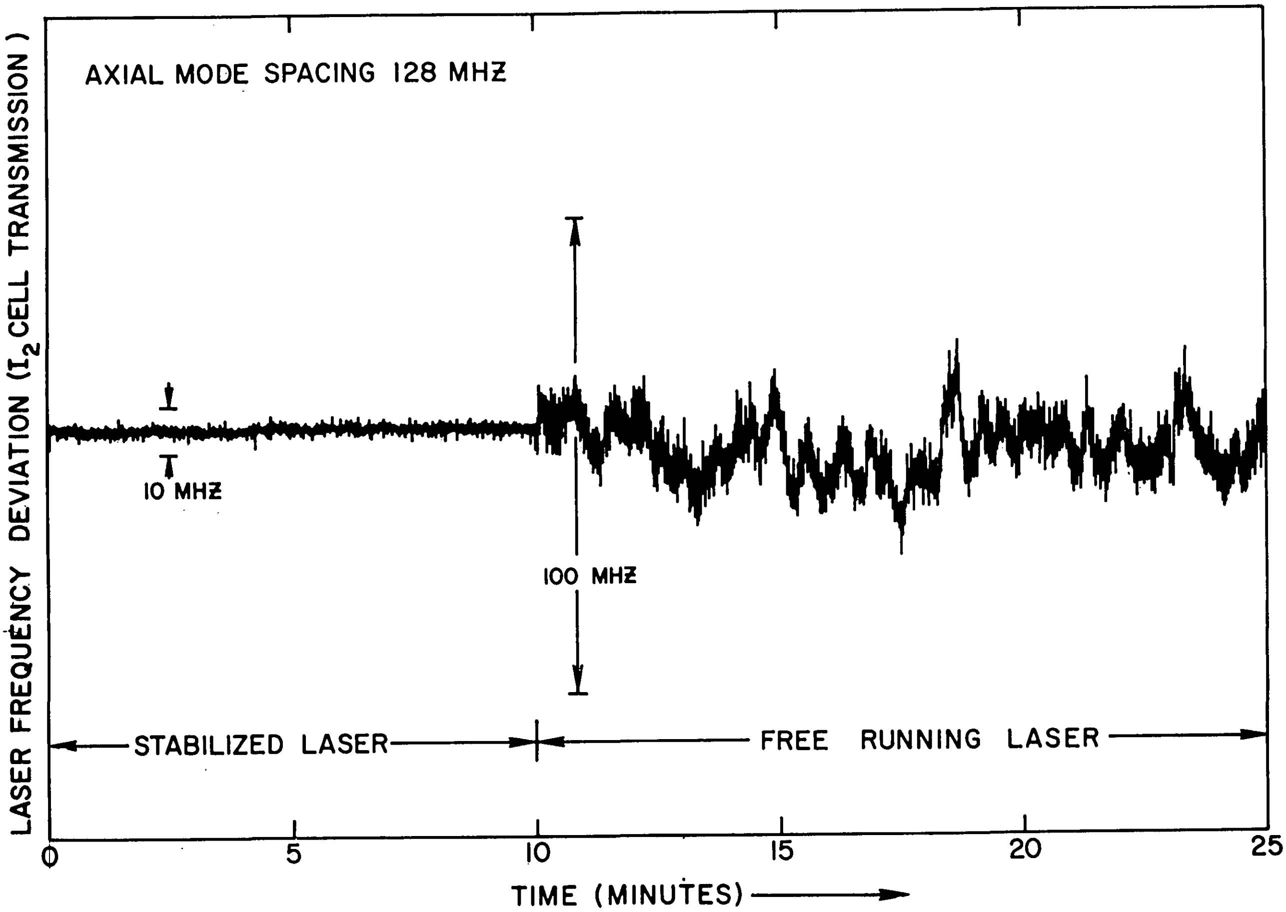

Fig. 4. Time recording of the relative argon laser frequency stability with and without multiple feedback system.

Absorption changes were sensed with a difference amplifier either with respect to a stable voltage source or part of the direct laser beam. The output signal of this amplifier is then used as a bias signal to stabilize the reference cavity frequency.

Optimum performance of the combined optical and electronic loops was achieved by making use of conventional feedback techniques. The voltage gain, time constants, and modulation frequency were adjusted to give satisfactory closed loop stability. Both the loop stability and step input response were examined for the two control loops by injecting a low frequency square wave into the high voltage amplifier and monitoring the output of the phase sensitive detector. Figure 3 shows the step response for the primary and multiple loop system. From Fig. 3(b) it is apparent that in the complete control system short term frequency stability is sacrificed to minimize long term drift with the result that its effective time constant increases. The voltage gain was adjusted to be about 60 dB, which was the maximum value for loop stability. The frequency response of the closed loop was measured, and the system was found to be first order with a break point at 30 Hz. Integration is included in the feedback loop to maintain a fixed voltage bias on the piezoelectric translator so that the steady state error signal can be zero.

Experimental Results and Discussion

The stability performance of the complete system is easily evaluated by monitoring the transmission through an iodine cell. For maximum sensitivity the laser frequency is adjusted to correspond to the half intensity points of the absorption characteristic of the iodine cell by means of the etalon orientation. The frequency stability achieved with the optimized system (after a warmup period of a few hours) for a typical 10 min is compared to the free running argon laser in Fig. 4. The calibration of the frequency scale is checked before and after each measurement. The short term frequency stability is consistently measured to be ± 1 MHz, corresponding to a relative stability of about ± 2 parts in in 10^9 with a recorder response time of $\sim 10^{-1}$ sec. The long term frequency variations and, in particular, drift did not exceed 6 MHz over a 120-min period in a standard laboratory environment. This period was solely limited by the available control voltage of the high voltage dc amplifier (100 V). With a larger voltage range available, considerably longer frequency stabilization periods can be realized since the maximum displacement range of the model 590 translator is about 30 μ, which is equivalent to a frequency correction range of 15 GHz. In the absence of the secondary control loop, slow frequency deviations and drifts occur. The short term stability decreases to ± 5 MHz, and the frequency drift is approximately 6 MHz/min.

The reported frequency stability depended on minimizing all sources of acoustic, mechanical, and thermal fluctuations. The apparatus was mounted on a vibrational isolation table (Lansing model 70-402). The etalon, reference cavity, iodine absorption cell, and the three photodetectors were temperature stabilized to ± 0.05°C/h.

By temperature scanning of the molecular reference discriminator and monitoring the frequency stability with a second temperature stabilized iodine cell, the temperature sensitivity of the molecular iodine discriminator, as used in the manner described in this paper, is measured to be 17 MHz/°C. In terms of the effective temperature stability of the iodine cell ovens this corresponds to a limiting long term frequency stability of $\sim$1 MHz/h. Hence the molecular discriminator offers considerable improvement as compared with the commercial scanning optical cavity discriminator. Further improvement in the long term frequency stability appears possible by using as the molecular discriminant the center of one of the approximately 10-MHz wide hyperfine resonance lines[8] of the inhomogeneously broadened I_2 absorption line shown in Fig. 2. The advantage of this approach in frequency stabilization and reproducibility lies in the fact that the center frequency of the selected iodine resonance line is not strongly temperature dependent. Ezekiel *et al.*[6] estimate that a long term stability of the argon ion laser frequency to a few parts in 10^{13} should be feasible.

Presumably if temperature control of the laser cavity would also be available, lengthy warmup periods could be avoided, and the over-all long term stability of the frequency control system could be improved. The stability was found to be extremely sensitive to vibrations caused by variations in water pressure and flow. In fact, troublesome momentary frequency fluctuations were eliminated by incorporating a simple water regulator in the laser cooling circuit. Variations in the laser frequency due to plasma instabilities were found to be much smaller than thermal or pressure disturbances. The homodyne spectrum of the laser was measured by means of conventional homodyne spectroscopy[9] and from 1 kHz to 1 MHz showed no deviations from the shot noise spectrum of a constant amplitude white light source.

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