A Portable Iodine Stabilized Helium-Neon Laser

HOWARD P. LAYER

Abstract—A newly designed iodine stabilized helium-neon (He-Ne) laser is described which is stable to $3 \times 10^{-13}$ (1000-s sample time) but which exhibits an intensity dependent shift of about 8 kHz/W-cm$^2$. Closer agreement between dissimilar lasers is attained when the internal power densities are approximately equal.

INTRODUCTION

The general acceptance by the standards community of the intracavity iodine stabilized helium-neon (He-Ne) laser operating at 633 nm as the de facto standard of length, and the demand by the metrological and scientific communities for a length reference whose stability exceeds that of currently available commercial lasers, prompted the National Bureau of Standards (NBS) to develop a portable stabilized laser system. The primary purpose of this effort was to promote the use of the iodine stabilized laser in applications remote from the laser laboratory by technicians or scientists who have neither the resources nor the time to develop their own instruments. This system was designed to be compact and lightweight and therefore easily transportable. The controls were designed to facilitate operation by people who have not had prior laser experience. In consequence of this, performance compromises were made relative to systems which are used as standards in national laboratories.

THE SYSTEM

The stabilized laser system consists of two units as shown in Fig. 1—the laser head and the electronic controller—the latter being completely contained in a commercial oscilloscope mainframe. Printed on the faces of the plug-in modules are the instructions for operation and the BIPM [1] vacuum wavelengths for the seven central iodine (127) hyperfine components coincident with the (He-Ne) gain curve. A drawing of the laser head is shown in Fig. 2; it is of standard configuration using four INVAR rods to separate the mirrors and secure the optical elements. The cavity length is 30 cm and is formed by a flat total reflector, which is placed at the absorption end of the cavity, and a 60-cm radius of curvature spherical output coupler which has a transmittance of 0.07. The laser tube is approximately 20 cm long, has a 1-mm bore diameter, and is filled with an 11:1 mixture of He$^4$ and natural neon at a total pressure of 3.5 torr. Both the laser tube and the absorption cell are mounted in collets for ease of alignment and maintenance.

The iodine cell is mounted in a finned housing which is the heat sink for the thermoelectric cooler which maintains the iodine at a prescribed pressure. The contrast of the peaks due to the saturated absorption of the iodine relative to the laser intensity is approximately 0.15 percent. The tilt plates, to which the mirrors are attached, are kinematically mounted and can be removed and replaced without requiring realignment. Five flexible multiconductor shielded cables connect the laser head to the servo plug-in modules in the oscilloscope mainframe. The laser tube is powered by a high-efficiency current feedback switching power supply; and, while the laser tube is normally operated in saturation, some 20-kHz and 60-Hz feedthrough can be observed on the laser light. All of the servo circuits use the mainframe power supplies which were designed to power the manufacturers own plug-in modules.

The servosystem block diagram is shown in Fig. 3 and is similar in many respects to previously published designs, although some important details are significantly different. The signal channel uses a fixed-frequency 8-pole filter to isolate the desired third harmonic signal from the first and second harmonic signals which are present on the detected light signal. The third harmonic reference signal is produced by an analog...
polynomial function generator utilizing two analog multiplier integrated circuits and a summing amplifier (\( \sin 2\theta = 3 \sin \theta - 4 \sin^3 \theta \)). Since the phase shifter operates at the fundamental frequency, the reference phase can be shifted by over \( 2\pi \) radians by using a single variable resistor.

An analog variable transconductance 4-quadrant multiplier is used as the phase-sensitive detector. By using an analog phase detector and a sinusoidal reference wave, two advantages accrue compared to a square-wave reference or switching phase detector. The system responds only to signals whose frequency is equal to the reference frequency, thus rendering the servosystem immune from spurious harmonic signals. In addition, the rectified output has a much lower harmonic content as it contains only the sum and difference products of the signal and the reference wave and not harmonics of the reference wave.

The dc output offset of the phase detector can be nulled, and devices are selected whose output offset voltages are stable to within a few tenths of a millivolt in the laboratory environment. The high-voltage driver has an output swing of 400 V which is sufficient to change the cavity length by approximately two orders.

The servo was mathematically modeled and the gain and bandwidth adjusted to provide optimum performance. The signal 8-pole bandpass filter characteristics are shown in Fig. 4 illustrating the steep-sided flat top response. The modulation is at 2.5 kHz and the third harmonic is at 7.5 kHz. Since the effect of the feedback control is to servo the third harmonic to zero, the first, second, and fourth harmonics dominate the spectrum. These signals, if unattenuated, would saturate succeeding amplifiers and overload the phase detector. By amplifying and filtering this signal, the second and fourth harmonics are reduced to at least 30 dB below the third harmonic error signal. The dynamic voltage range of the signal bandpass filter exceeds 70 dB.

The complete open-loop response is shown in Fig. 5. The Bode stability criterion requires that the open-loop gain rolloff with frequency be less than 12 dB/octave when the gain is unity or that the gain be less than unity when the phase shift is \( \pi \). The servo is unconditionally stable for the response shown when operated at the specified gain. Two integrators are used to achieve a rolloff of 12 dB/octave at low frequencies and of 6 dB/octave near the unity-gain frequency. The main integrator has a rolloff of 6 dB/octave over its entire operating range while the second integrator rolls off at 6 dB/octave only below its cutoff frequency. Above its cutoff frequency, it has unity gain.

The rolloff above the unity-gain frequency is caused by the combination of the integrator and the steep sides of the signal bandpass filter. The unity-gain frequency is about 300 Hz and the open-loop low-frequency gain at 0.01 Hz is 160 dB. The integrator output spectrum, shown in Fig. 6 shows \(-110\)-dBV
(3 μV) residual third-harmonic feedthrough which is further reduced by 20 dB by the limited bandpass of the output driver. The 15-kHz sum signal, being twice the reference frequency, does not produce an error in the servosystem but could be reduced by using a wider bandwidth operational amplifier for the main integrator.

**OPERATION**

The front panel of the electronic control displays the information necessary to identify, select, and lock the desired hyperfine component. The conventional designation of the components [2] is displayed on the left plug-in panel and the corresponding vacuum wavelengths on the center panel. Brief operating instructions are printed on the right plug-in panel.

In the sweep mode, which is used in preparation for acquisition and lock, the third derivative spectrum is displayed on the screen of the bistable storage oscilloscope which is used to house the plug-in modules, as shown in Fig. 7. This is a real-time display and enables the operator to identify and select a hyperfine transition using a representation of the spectrum which is printed on the front panel as a guide. The signal-to-noise ratio of the system can be estimated from the trace of one component as shown in Fig. 8. The sweep time is 1 s and the time constant of the low-pass filter is 0.01 s, the modulation width (peak-to-peak) is 5.5 MHz, the iodine temperature is 18°C, and the power output is approximately 100 μW.

**PERFORMANCE**

The frequency stability of the NBS portable laser system is displayed by the σ(τ) [4] plot for time intervals between 10−9 and 109 s as is shown in Fig. 9. Two identical laser systems operating on adjacent components were used. The measurements were made on a vibration isolated table upon which the electronics package was also placed. The room temperature was controlled to ±2°C. The 1000-s fractional frequency deviation is about 3.5 × 10−13, and the break point has not yet been observed. The resettable nature of the system, however, possesses a systematic power-dependent offset in addition to the offsets produced by modulation width and iodine pressure [3]. This offset, shown in Fig. 10, was taken on two components d and g for which the operating frequency shift with output power had the same algebraic sign. It is not due to either the electronic servosystem, simultaneous 3390-nm radiation, or off-axis modes but is a physical effect produced in the laser cavity by a mechanism not well understood at this time. While the servo electronics system has been excluded as a cause of this error, harmonic generation by a nonlinear PZT mirror driver has, as yet, not. An explanation for this performance is being sought.

**CONCLUSION**

A truly portable iodine stabilized He-Ne laser system has been described whose operation by technicians, who have little laser experience, has been facilitated by simplified controls. The servosystem exhibits excellent stability, and the frequency of the lock points is predictable if the operating parameters are known. For accuracy limit which does not exceed 5 parts in 1010, no further calibration is necessary. Several of these in-
Frequency Stabilization of Ar$^+$ Lasers at 582 THz Using Expanded Beams in External $^{127}$I$_2$ Cells

FRANK SPIEWEEK

Abstract—The I$_2$ stabilized Ar$^+$ laser is now an internationally accepted frequency or wavelength standard having the wavelength $\lambda_{13} = 514.673$ 467 nm. Using an improved stabilization scheme the intrinsic frequency uncertainty is now less than $10^{-11}$ $\nu$. A Fabry–Perot prestabilization circuit reduces the effective laser linewidth from 2 MHz to 70 kHz. Therefore, the iodine cell can be operated at a lower I$_2$ vapor pressure of 1 Pa yielding narrower I$_2$ reference signals. In order to avoid power shifts, the power density inside the iodine cell was reduced to 0.3 mW/mm$^2$ by expanding the beam diameter. The resulting improved signal-to-noise ratio also allowed to measure the frequency separation of 13 isolated $^{127}$I$_2$ hyperfine components of the P(13) 43–0 absorption line with an uncertainty of less than 1 kHz.

I. INTRODUCTION

The coincidence of the strong Ar$^+$ laser line at 582 THz and the strong $^{127}$I$_2$ absorption of the P(13) 43–0 line is attractive for realizing an optical frequency or wavelength standard of low uncertainty [1]–[3].

Due to the absorption from the zeroth vibrational level with a low rotational quantum number ($J = 13$), strong saturated absorption signals are obtained even at a relatively low iodine vapor pressure of 1 Pa. Thus the pressure shift of the stabilized laser frequency can be kept very small. In order to reduce power shifts, which become important at these low pressures [4], a low power should be used. The corresponding weakening of the saturated absorption signal can then be avoided by using a large number of absorbers, i.e., by expanding the beam diameter, also lowering the transit time broadening of the iodine reference line.

Manuscript received June 28, 1980.

The author is with the Physikalisch-Technische Bundesanstalt, D-3300 Braunschweig, Federal Republic of Germany.

[4] The Allan variance for two identical oscillators is

$$\sigma(\nu) = \sqrt{\frac{1}{\nu(N-1)} \sum_{i=1}^{N-1} (\nu_i - \nu)^2}$$

where $\nu$ is the oscillator frequency.

II. PRINCIPLE

The principle of the laser frequency stabilization system is given in Fig. 1. A commercial single-frequency argon ion laser is used, fitted with two piezoelectric drives, one of them used for modulating the laser frequency and the other one for the control of the cavity length. The laser beam diameter is expanded fivefold by a Galilean telescope. Part of the beam passes a high-finesse confocal Fabry–Perot resonator (Tropel, model 216), another part is used for the stabilization to the line center of an appropriate I$_2$ reference line. The short-term stabilization loop having a unity gain frequency of about 2 kHz holds the laser frequency at the side of a Fabry–Perot transition maximum by means of the usual differencing technique.