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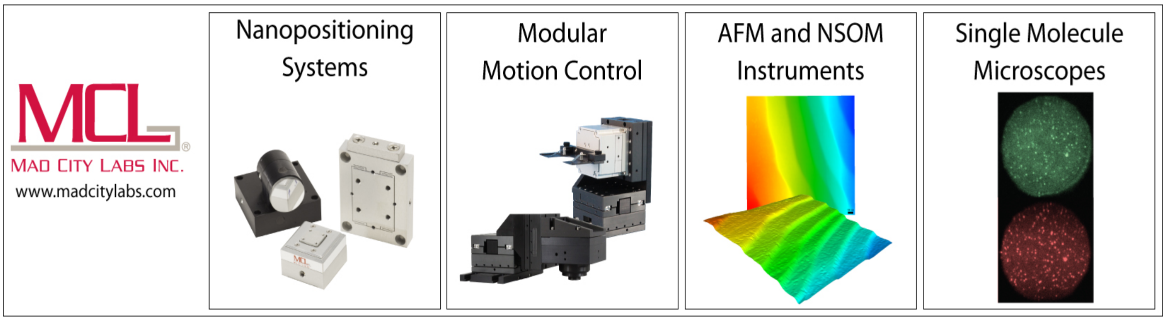

High accuracy digital temperature control for a laser diode

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A digital servo-loop was implemented to control the temperature of a laser diode. By using a conditionally stable loop we obtained a temperature stability of about ± 20 μK over periods of hours. © *1995 American Institute of Physics.*

I. INTRODUCTION

There are several applications of laser diodes in which their frequency tunability over a wide range of frequencies, from infrared to visible light, is fundamental. For example, they are used in atomic and molecular spectroscopy,[1,2] or as pump sources for high power solid-state lasers.[3,4] The frequency tuning is possible thanks to the sensitivity of the emission frequency to both the diode input current and the temperature. Stable operation of the laser is fundamental for all these applications and then great effort is directed[5] to the development of stable current drivers and suitable temperature control loops to reduce the frequency drift to a tolerable level; the typical frequency change rate is 30–40 GHz/K. For temperature control, analog servo-loops generally use a proportional-integrative-derivative (PID) network as a reaction filter; temperature stability to within 1 mK over periods of hours have been reported.[3] In this paper we describe a high accuracy digital servo-loop for the temperature control of a laser diode. The use of a digital system considerably simplifies the implementation of the reaction filter, and allows the realization of networks more complex than the usual PID. By realizing a conditionally stable loop we obtained a temperature stability of ± 20 μK over a period of 6250 s (1 h 44 min), which can easily be extended.

II. EXPERIMENTAL APPARATUS

The laser diode (Sharp LD024MD) is inserted in a copper plate which is mounted on a Peltier cooler (PT); on the same plate we mounted a miniature negative temperature coefficient thermistor (NTC). The electronic control circuit can be divided in two parts: an analog portion which is typical for similar applications[5] and a digital part used for implementing the loop filter. The NTC is inserted in one arm of a Wheatstone bridge; the reference voltage (7 V) is provided by a high stability generator (LM399). The bridge is balanced for a given temperature that is the working point of the system; this temperature can be regulated with a potentiometer inserted in another arm of the bridge. Figure 1 shows the electronic scheme of the apparatus. The signal of the bridge is amplified by an INA101 Burr–Brown instrumentational amplifier (IA). The bridge, the generator, and the IA are all mounted in a shielded box close to the diode itself. The output, i.e., the error signal for the temperature control, is sent to the digital system which provides the correction signal. The digital signal processor, based on a VME bus, is composed of a 16-bit analog-to-digital converter, a CPU 68030, and a 16-bit digital-to-analog converter; the digital filtering is performed using a bilinear transformation algorithm.[6] The correction is applied to a complementary symmetry push–pull current driver that drives the PT.

The bridge output voltage provides a measure of the temperature deviation of the NTC, and hence of the laser diode, with respect to the working temperature.

Aside from the NTC two further temperature sensors (Analog Devices AD590JK) are used. The first, mounted on the same copper plate used for the diode laser, is used for measuring the working temperature and for system calibration; the second one measures the room temperature.

III. DIGITAL SERVO-LOOP

To stabilize the temperature of the laser diode it is necessary to design a proper feedback system. The choice of the loop filter is very important since it determines the stability and the performances of the servomechanism.[7] Generally in analog systems a PID filter is used. This provides both a high

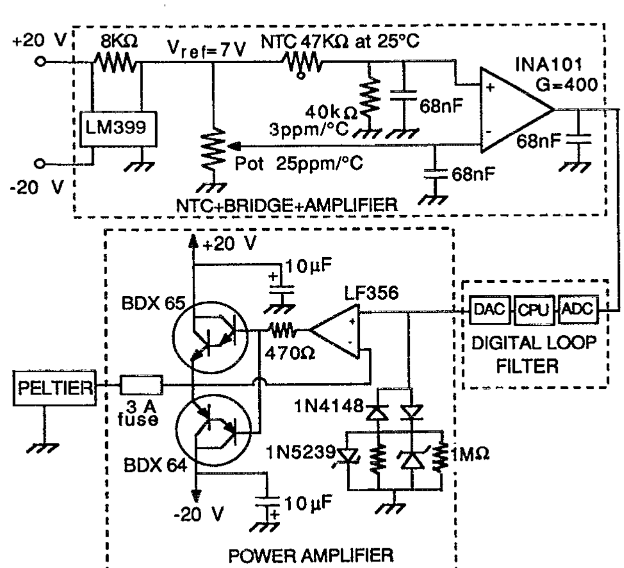

FIG. 1. Electronic scheme of the temperature controller.

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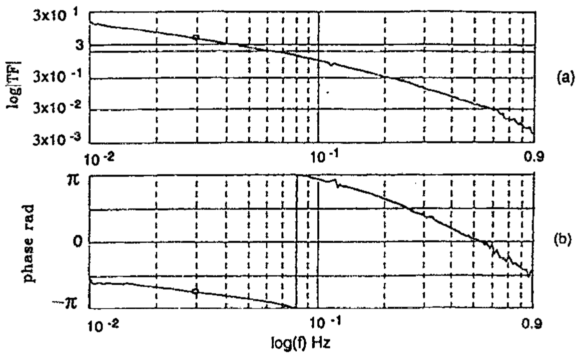

FIG. 2. Measured system transfer function; (a) gain and (b) phase.

gain at low frequencies, where the temperature fluctuations are large, and a compensation of the phase delay introduced by the thermal inertial of the system, mainly due to the Peltier cooler and the mounting copper plate. This also permits a larger correction bandwidth. For a well compensated system, the open-loop transfer function (OL), i.e., the product of the loop filter and the system transfer function, is, for frequency below the unity gain, close to that of a simple integrator with very low cutoff frequency and high dc gain. In principle more complex loop filters with several poles and zeroes can be used in order to obtain a larger gain and speed but this requires a much more complicated circuital implementation.[8] Furthermore, since such a loop can only be conditionally stable, it is very important to set with extreme accuracy the parameters of the filter, i.e., the cutoff frequency, of poles and zeros. For these reasons the analogic implementation of very complex filters presents problems difficult to overcome.

The problem can be solved using digital filters.[4] In this case it is possible to implement any number of poles and zeros, and the only limitation, for real time systems, is the time necessary for the mathematical operations that produce the filtering, which can limit the maximum usable sampling frequency. This is generally not a problem for very low-frequency applications like temperature controls.

The actual loop filter should be designed according to the system transfer function (TF), that is, the product of temperature sensor (V/K), current driver (A/V), Peltier cooler (K/A), and laser mounting transfer functions. For our system the measured TF is reported in Fig. 2. In the design of

TABLE I. Parameters of the synthesized temperature controller transfer function.

dc gain Pole number	53.5 Pole frequency (Hz)
1	$2.0e^{-3}$
2	0.043
3	0.36
4	0.9
5	0.9
6	1.2
7	1.6

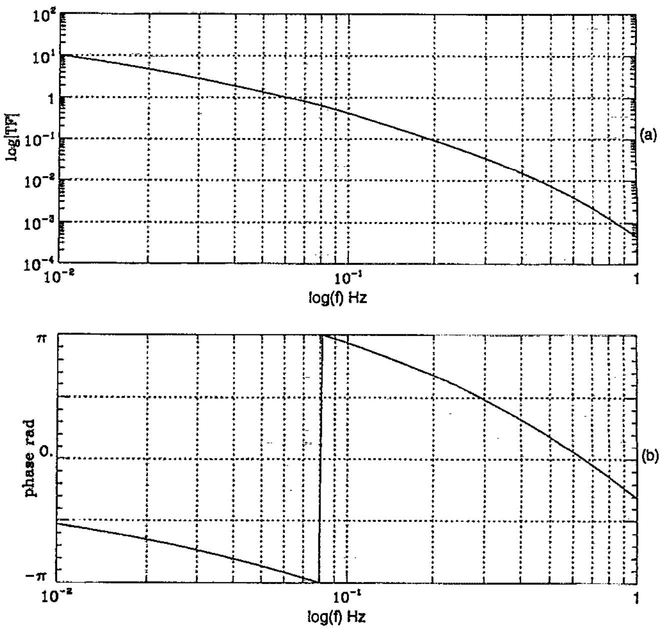

FIG. 3. System transfer function synthesized with the parameters reported in Table I; (a) gain and (b) phase.

the servo-loop this TF was approximated with a seven pole low-pass filter. The filter parameters are reported in Table I, and the synthesized TF is shown in Fig. 3.

For our feedback we designed a loop filter with four poles and four zeros, whose values are reported in Table II. In Fig. 4 we report the Bode diagram of the filter, compared with that of a PID filter which gives the same phase margin (about 45°) and in Fig. 5 we report the calculated OL transfer function for the implemented servo-loop, again compared with the one obtained with the PID. The unity (0 dB) gain is at about 50 mHz, and is limited by the thermal inertia of the laser diode copper mounting.

The two loops are almost equivalent above 10 mHz, but at low frequencies our filter gives a gain much higher than the PID. The gain is about 87 dB at 1 mHz and 148 dB at 100 μHz; the PID gives 57 and 78 dB, respectively. With such a filter a sinusoidal temperature variation at 1 mHz of 1 K should be reduced to less than 10 μK.

IV. RESULTS

We implemented the designed filter on our digital system (sampling frequency 500 Hz) and used it for the temperature control of the laser diode. The measured OL transfer function is reported in Fig. 6. It is very close to the theoretical prediction (Fig. 5). From the plot we can deduce a gain margin

TABLE II. Parameters of the digital loop filter.

No.	dc gain Pole freq. (Hz)	$4.64\ e^{11}$ Zero freq. (Hz)
1	$1.0e^{-6}$	0.01
2	$1.0e^{-6}$	0.01
3	$1.0e^{-6}$	0.01
4	1.0	0.1

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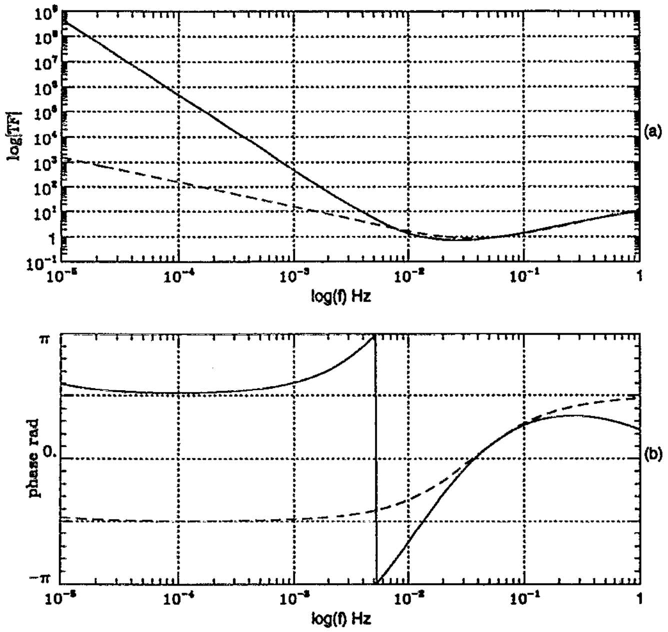

FIG. 4. Bode diagram of the loop filter of Table II (solid line), compared with that of a PID filter (dashed line) which gives the same phase margin (about 45°); (a) gain and (b) phase.

of about 10 dB, and a phase margin of 46°. The servo-loop is stable when the unity gain falls in the frequency interval 17.5 mHz$<f<$133.7 mHz.

In Fig. 7 it shows the residual laser temperature fluctuation as measured at the output of the transducer bridge, compared with the contemporary room-temperature drift, over a period of 6250 s. The room temperature changed by about 733 mK (with constant rate), while the low-frequency drift of the laser temperature was less than 10 μK, with a reduction of more than 100 dB at 80 μHz. The larger contribution to the residual temperature fluctuation is given by higher frequency noise, outside the loop bandwidth (50 mK); this noise could be reduced with a more compact mounting of the laser diode on the Peltier cooler, which should provide a faster system response. The overall temperature fluctuation is about ± 20 μK, and corresponds to a frequency jitter of ± 800 kHz.

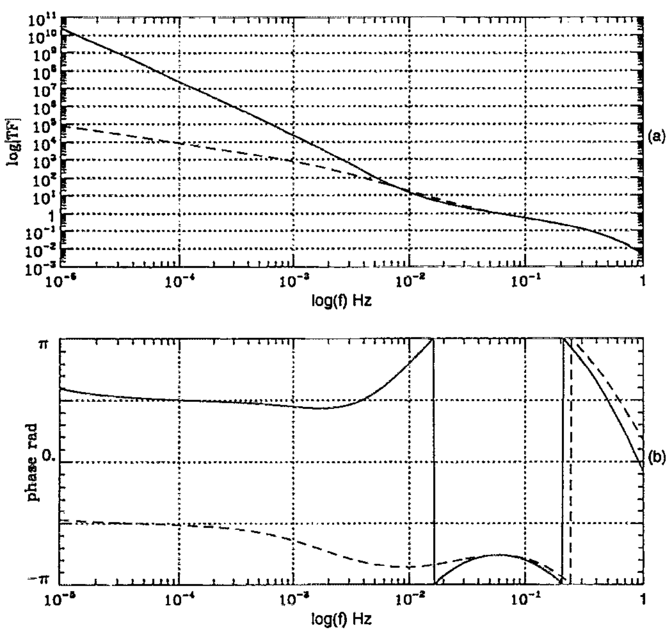

FIG. 5. Calculated OL transfer function for the implemented servo-loop (solid line), compared with the one obtained with the PID (dashed line); (a) gain and (b) phase.

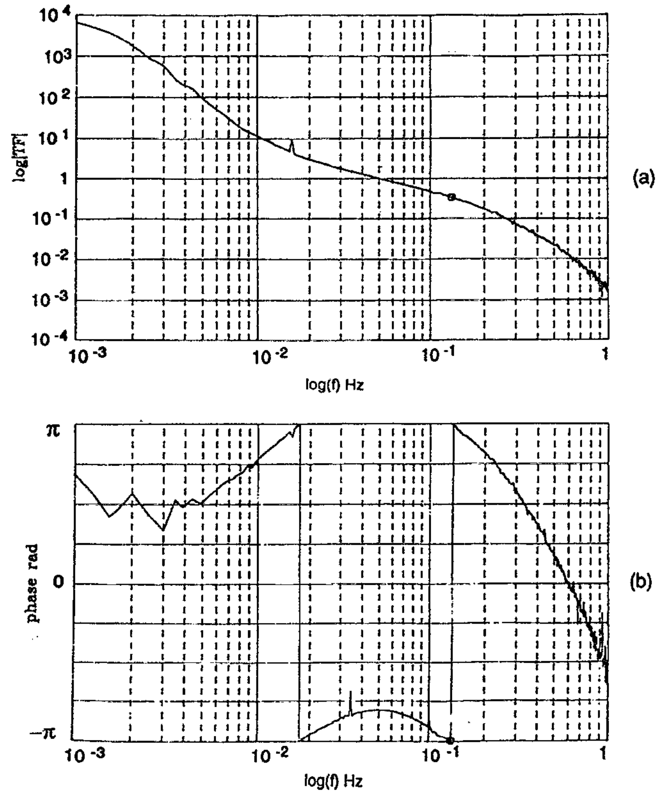

FIG. 6. Measured OL transfer function for the implemented servo-loop; (a) gain and (b) phase.

V. SYSTEM CALIBRATION

A delicate point is the calibration of the system. The calibration is obtained by changing the NTC temperature a known amount, and measuring the corresponding IA output

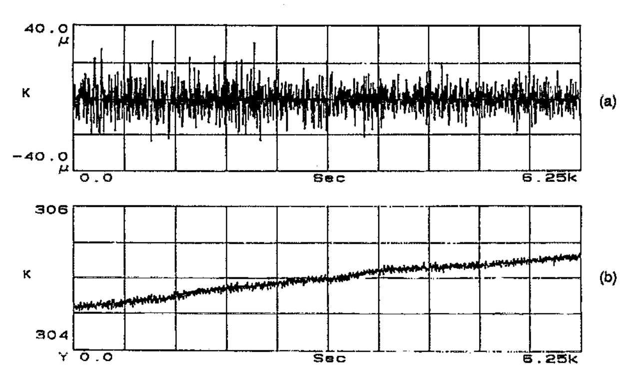

FIG. 7. Residual (closed loop) laser temperature fluctuation as measured at the output of the transducer bridge (a), compared with the contemporary room temperature drift (b), over a period of 6250 s.

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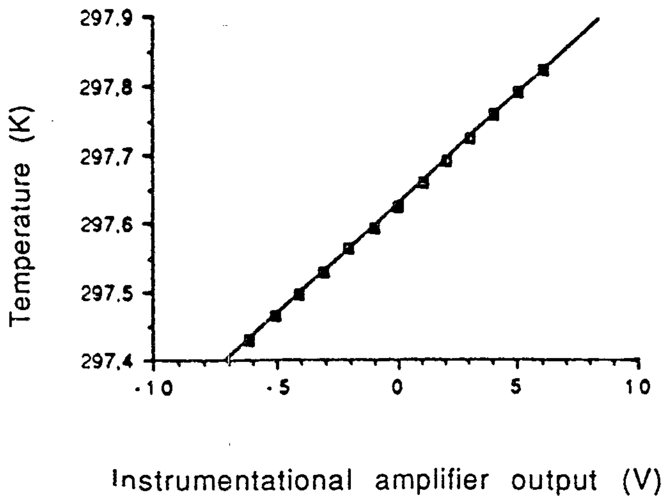

FIG. 8. System calibration curve: laser temperature (K) vs IA closed-loop output (V).

V_{out}. The measurement was performed in closed loop, because, with the loop open, the room thermal drift would saturate the IA very soon. We added a dc voltage V_{dc} to V_{out}; the effect of the feedback is to reduce to zero the error signal $V_e = V_{out} + V_{dc}$; the result is that the PT changes the laser diode mounting temperature in order to get $V_{out} = -V_{dc}$. The corresponding absolute temperature was measured with the AD590JK mounted on the same copper plate. The calibration curve is shown in Fig. 8. The best fit of the data gives $\partial V/\partial T = 31.1 \pm 0.7$ (V/K); this agrees fairly well with the NTC characteristics and the amplifier gain ($A = 400$).

VI. DISCUSSION

We realized a temperature control system capable of reducing the temperature fluctuations of a laser diode to less than ± 20 μK; this is not an ultimate limit at all, since the performance of the FB can be improved, basically with a more compact mounting of the diode on the Peltier cooler.

It is worth noting that the quantity that is actually controlled is not the temperature but the error signal, and then the bridge output. To be sure that the laser temperature fluctuation is really reduced to the expected level, it is necessary to consider the effect of the temperature drift of the bridge components and of the amplifier.

A temperature stability of $\Delta T = 10$ μK requires that the bridge output changes less than $\Delta V = \Delta T(\partial V/\partial T)/A = 1.e^{-5} \times 31.7/400 = 0.75$ μV, being $A = 400$ the IA gain. For the bridge we used resistors with a temperature coefficient of about 3 ppm/K; the corresponding bridge output drift is about 5 μV/K. The IA gain has a low-temperature coefficient (22 ppm/K) which gives a negligible effect: the main sources of error are the variations of the input bias current I_B (that is, 0.2 nA/K) and of the input offset current I_{off} (0.5 nA/K); they produce an amplifier input voltage drift of 13.5 μV/K. The overall input voltage drift is then about 18.5 μV/K. Then the amplifier temperature should change less than 40 mK. In our experiment the room temperature changed by about 733 mK; we estimate that the corresponding laser temperature drift induced by the drift of the components is less than 180 μK.

We can conclude that our system is able to reduce the laser temperature fluctuations to less than ± 20 μK, with the condition that the transducer bridge (excluding the NTC, of course) and the instrumentational amplifier are thermostabilized to less than 40 mK, which is easy to obtain with a commercial temperature controller.

According to a typical rate of 40 GHz/K, we expect that the corresponding thermal drift of the laser emission frequency is less than ± 800 kHz.

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