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Instrumentation for the stable operation of laser diodes

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We have developed a constant current supply and a temperature control circuit that can be used for frequency-stable operation of laser diodes. These instruments can stabilize laser diode injection current and temperature to better than $\pm 1 \mu\text{A}$ and $\pm 0.3 \text{ mK}$, respectively, over time periods exceeding 1 h. We have excited the $\text{Li}(2S \leftrightarrow 2P)$ transition with a red-light-emitting laser diode and find that our instrumentation stabilizes the laser frequency to within $\pm 10 \text{ MHz}$ over a period exceeding 1 h.

I. INTRODUCTION

Laser diodes have become an important tool in many commercial and research applications. These lasers are useful for wide-band communications, data storage and retrieval, as pump sources for other laser systems, and for atomic and molecular spectroscopy. Recently, diode lasers have been utilized in laser cooling experiments. In addition, they have been proposed for use in plasma diagnostics and for optical pumping in atomic time and frequency standards. Laser diodes possess several properties that make them useful for these and other applications. First, devices can be obtained which emit in the red, near-infrared, or mid-infrared regions of the spectrum. Second, they are broadly frequency tunable, capable of rapid modulation, easy to use, and inexpensive. Frequency tuning of these lasers is possible due to the inherent sensitivity of their frequency to both temperature and injection current. For example, tuning coefficients for indium gallium aluminum phosphide visible laser diodes ($\sim 670 \text{ nm}$) are approximately $30 \text{ GHz}/^\circ\text{C}$ and $7 \text{ GHz}/\text{mA}$. For frequency-stable output, this sensitivity must be addressed.

For stable operation of laser diodes it is necessary that both injection current and laser temperature are controlled. Current stabilization is typically obtained by comparison of a reference voltage to the voltage drop produced by the current through a "sense" resistor which is in series with the load. Through careful choice of circuit components and/or control of the circuit environment, current drift may be reduced to $1 \mu\text{A}/\text{h}$ or better.^{1,2} Temperature controllers commonly employ a temperature sensor in a resistance bridge in a feedback loop which regulates the power given to a heating/cooling element. Bridge-feedback loop designs using either a constant or alternating reference voltage yield stabilities of better than $\pm 100 \mu\text{K}$ (Refs. 3 and 4) or $\pm 15 \mu\text{K}$,^{5,6} respectively.

In this paper, we describe an ultrastable current supply and a single-stage temperature controller that can be used to produce a tunable, frequency-stable output from any type of laser diode (and, of course, may be useful for other constant current and temperature applications). Compared to earlier designs, our instrumentation is relatively simple and inexpensive to construct and, we believe, performs better than commercially available devices. We have used this instrumentation with a laser diode to excite the $2S \leftrightarrow 2P$ transition of atomic lithium at 671 nm . The laser frequency was dem-

onstrated to be stable to $\pm 10 \text{ MHz}$ over periods exceeding 1 h.

II. CURRENT DRIVER

The current driver regulates the laser current by comparing a set voltage with a feedback voltage proportional to the laser current. Consideration must be given to possible drifts of these voltages since the current stability results directly from them. To achieve the laser frequency stability that we desired, we set a design goal for current fluctuations of less than $1 \mu\text{A}$ at an operating current of 100 mA . Therefore, voltage fluctuations must be limited to less than 10 ppm .

The drifts in the set and feedback voltages result from changes in the ambient temperature of the relevant circuit components (see Fig. 1). The critical components include a voltage reference and the resistors and amplifiers that determine the set and feedback voltage gains. Each of these components should have a low-temperature coefficient ("tempco") in order to minimize their drift. In our design, a LM299A precision voltage reference is used since it has a negligible drift of $0.5 \text{ ppm}/^\circ\text{C}$. For the critical resistances, we used metal film resistors with tempcos of $50 \text{ ppm}/^\circ\text{C}$ (resistors with tempcos of only $2 \text{ ppm}/^\circ\text{C}$ are also available⁷ and will be incorporated in the future). Also, we used OP-77E operational amplifiers and a AMP-01E precision instrumentation amplifier for their acceptably low offset voltage and gain drifts.

The current driver delivers up to 150 mA of current. The main sections of the current driver are the control voltage inputs, the feedback loop, and the current/power display. The desired laser current is selected via the coarse, fine, and sweep voltages that are added to produce the set voltage. The difference between the set and feedback voltages controls the gate of a field-effect transistor (FET) which regulates the current flowing in series through the laser diode and a precision $10\text{-}\Omega$ resistor. The feedback voltage is supplied by the instrumentation amplifier which measures the voltage across the $10\text{-}\Omega$ resistor. The coarse and fine voltage inputs utilize the stability of the temperature-compensated voltage reference while the sweep input stability depends on the external source. Automotive-type lead-acid batteries are used to supply power to the circuit in order to minimize line noise. The current monitor displays a voltage proportional to the

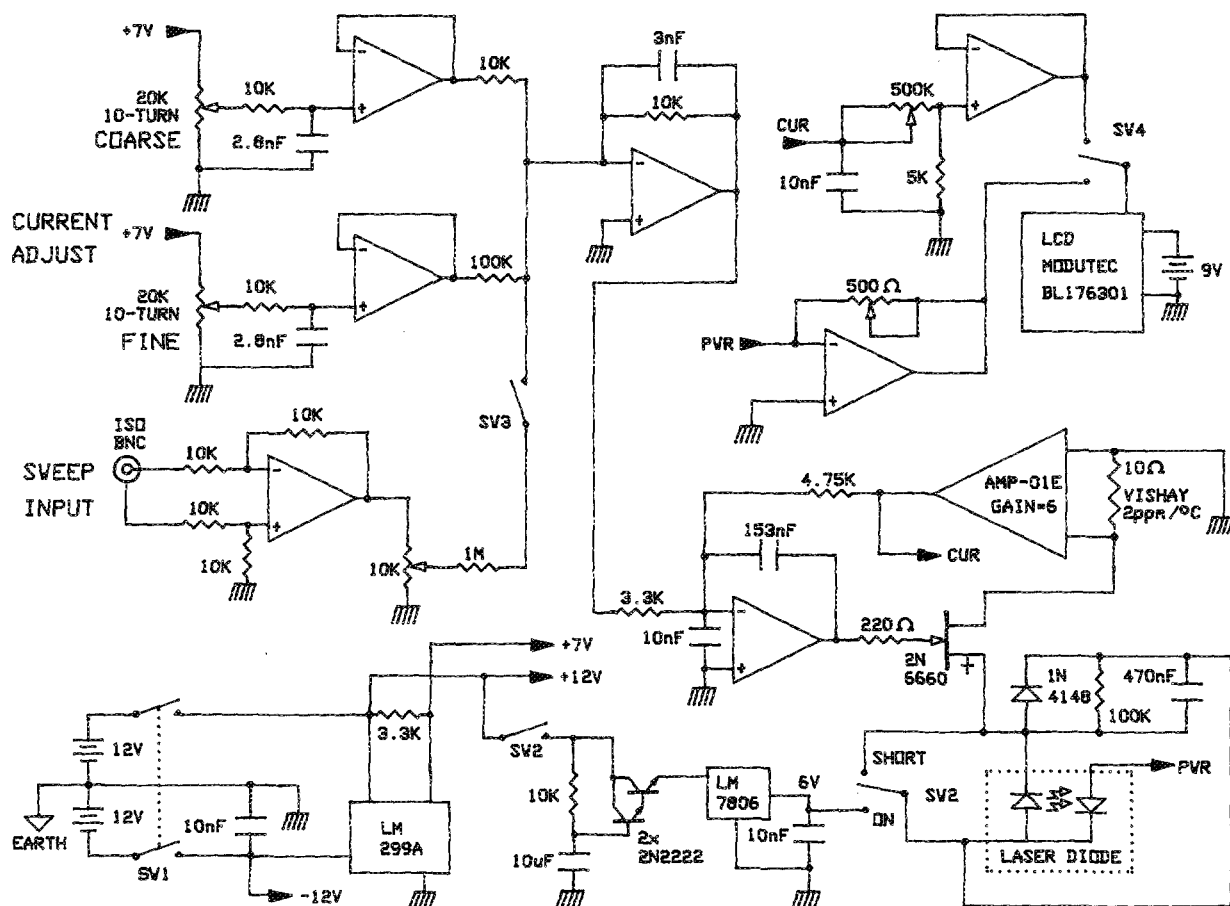


FIG. 1. Schematic of current driver which can supply 0–150 mA of current, stable to $\pm 1 \mu\text{A}$ over periods exceeding 1 h. Current is set by potentiometers and an external scan input. All operational amplifiers are OP-77E.

instrumentation amplifier output. The laser diode output power may be displayed by monitoring the current of the laser's built-in photodiode.

Laser diodes are easily destroyed by voltage spikes and transients. Therefore, our current driver incorporates several features to minimize the likelihood of damaging a laser diode. A switch which simultaneously shuts off the laser diode voltage and shorts the laser anode to cathode must be closed while the circuit power is being turned on or off. Also, it is important to reduce the current controls to zero before unshorting the diode. The two transistors in a Darlington configuration and the $10\text{-}\mu\text{F}$ capacitor slow the turn-on of the laser voltage. A reverse biased diode and a capacitor in parallel to the laser help protect against reverse surges and fast start-up currents. The batteries eliminate power supply noise as well as line transients. Finally, we maintain absolutely dependable connections to the laser diode and to the power supply to prevent any interruption of the current.

Figure 2 shows the stability of the current driver. An HP 3457A multimeter was used to measure the voltage produced by the current through a $10\text{-}\Omega$ load resistor. Variations in this voltage were used to calculate a current drift of $\sim 1 \mu\text{A}/\text{h}$. Additionally, short-term current noise was monitored with an oscilloscope and was found to be $\sim 1 \mu\text{A}$ peak to peak.

III. TEMPERATURE STABILIZATION

The temperature controller is designed both to set the laser operating temperature and to detect the laser temperature fluctuations and correct for them. A thermistor, which forms one arm of a resistance bridge, is placed near the laser

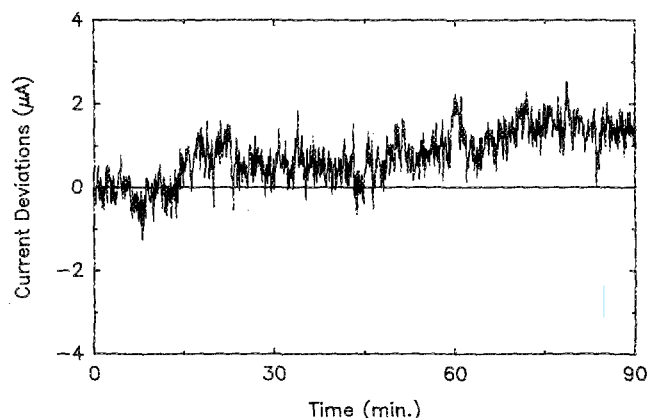


FIG. 2. Current driver stability was measured using a precision $10\text{-}\Omega$ load and an HP 3457A multimeter. Current stability was measured to be better than $\pm 0.5 \mu\text{A}$ for time periods of thirty seconds and $\pm 1 \mu\text{A}$ for periods exceeding 1 h.

and is used to detect the laser temperature changes. When the thermistor resistance changes, a voltage difference appears across the bridge which is amplified by an instrumentation amplifier. The smallest detectable temperature fluctuation is limited by the input characteristics of the amplifier and by the changes in the other bridge resistances due to ambient temperature drifts.

For the bridge configuration located at the top left of Fig. 3, the differential error signal ΔV at the amplifier inputs due to a thermistor temperature change ΔT is given by

$$\Delta V = V_{\text{ref}} C_T \Delta T R_T R / (R + R_T)^2, \quad (1)$$

where C_T is the thermistor's tempco, V_{ref} is the voltage of the stable reference source (7 V), and R and R_T are the fixed resistor (125 k Ω) and thermistor resistances, respectively. To achieve our desired laser stability, our design goal was to detect and respond to a ΔT as small as 0.1 mK. This ΔT corresponds to an error signal ΔV_{min} of 7 μ V for the component values shown in Fig. 3. All other sources of voltage drift at the amplifier inputs must necessarily be less than 7 μ V.

The bridge resistors must satisfy certain requirements in order not to produce drift voltages larger than ΔV_{min} . The voltage change at the amplifier inputs due to a change in R caused by an ambient temperature drift ΔT_A is given by

$$\Delta V_A = V_{\text{ref}} C_R \Delta T_A R_T R / (R + R_T)^2, \quad (2)$$

where C_R is the tempco of the fixed resistor. For $\Delta V_{\text{min}} > \Delta V_A$, C_R must satisfy $C_R < C_T \Delta T / \Delta T_A$. Assuming ambient drifts of 2 $^{\circ}$ C, C_R must be 2 ppm/ $^{\circ}$ C or less for our component values. If the tempco of the set point potentiometer is uniform along the length of the potentiometer, ambient drifts will not affect the set point voltage. We checked this uniformity by monitoring the variations in the set point voltage over a range of potentiometer settings and temperatures. These voltage variations were small compared to ΔV_{min} .

Consideration must also be given to the input characteristics of the instrumentation amplifier. The amplifier must be sensitive to small differences between its input voltages. Consequently, the common mode rejection (CMR) of the amplifier must satisfy

$$\begin{aligned} \text{CMR (dB)} &> -20 \log_{10} (\Delta V_{\text{min}} / V) \\ &= -20 \log_{10} [R_T C_T \Delta T / (R + R_T)]. \quad (3) \end{aligned}$$

We need a CMR > 114 dB which is satisfied by the AMP-01E. Also, the drifts due to ΔT_A in the amplifier input offset voltage V_{OS} , bias current I_B , and bias offset current I_{BOS} must be sufficiently small. The V_{OS} tempco of the AMP-01E

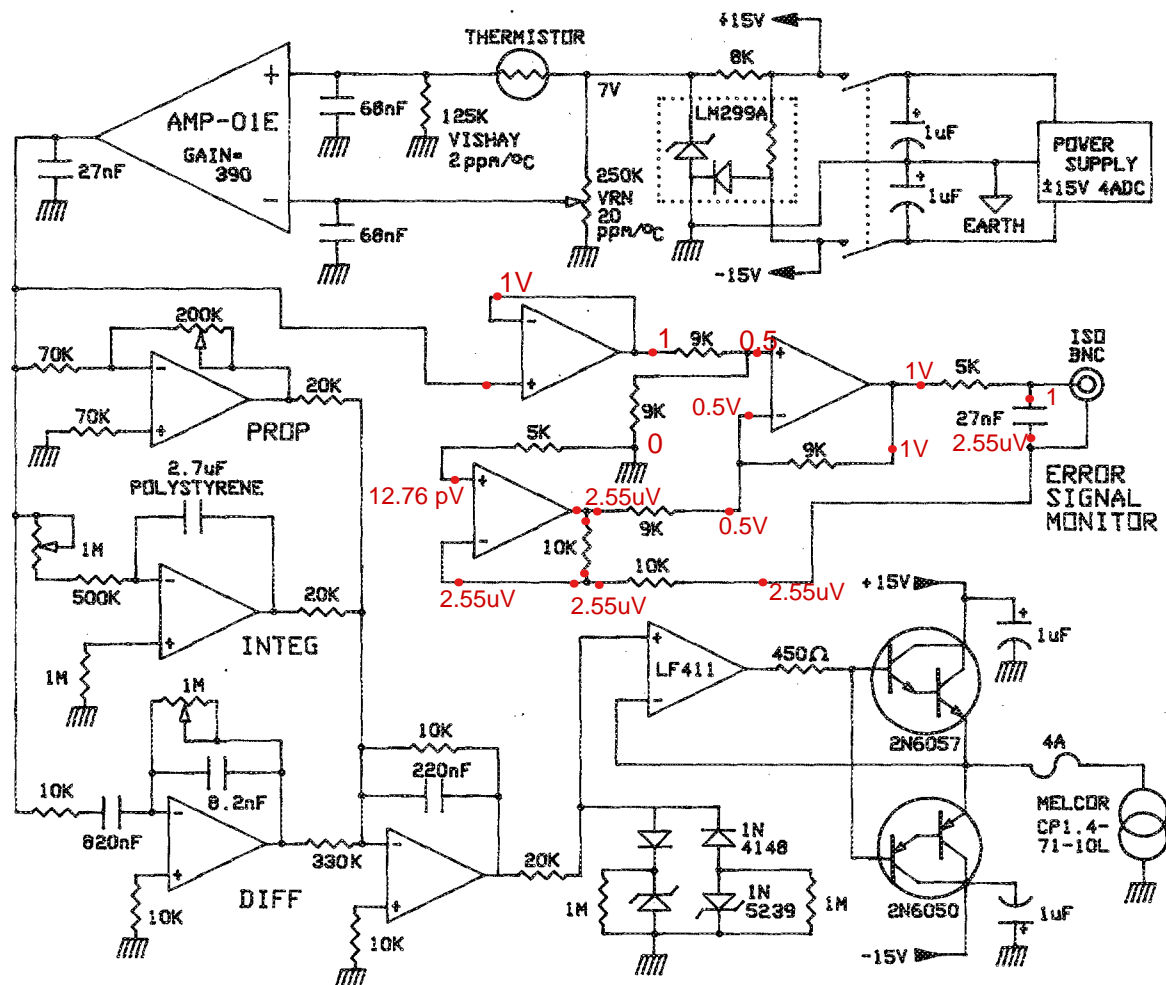


FIG. 3. Schematic of temperature controller which can stabilize temperature to better than ± 0.3 mK over periods exceeding 1 h. The thermistor's nominal resistance is selected to be 125 k Ω at the working temperature. The error signal monitor is used to measure the stability without introducing ground loops (the 9-k Ω resistors are matched to better than 0.05%). All operational amplifiers, except as noted, are LM11.

is only $0.3 \mu\text{V}/^\circ\text{C}$. If R_S is the maximum resistance of the bridge potentiometer ($250 \text{ K}\Omega$), I_B produces an offset at the differential inputs which is given by

$$V_B = I_B(R + R_T - R_S)\max(R, R_T)/(R + R_T), \quad (4)$$

where \max means the larger of R or R_T . The drift in V_B , ΔV_B , may result from changes in R , R_S , or I_B . Because of the low tempcos selected for R and R_S , the resulting ΔV_B due to resistance changes is much smaller than ΔV_{\min} . However, the drift in I_B may cause an unacceptably large ΔV_B unless R_T is selected to minimize $R + R_T - R_S$ at the operating temperature. For the components we used, R_T may take values between 25 and $250 \text{ k}\Omega$ with ΔV_B remaining less than ΔV_{\min} . Finally, the voltage drift due to a change in I_{BOS} must satisfy

$$\Delta V_{\text{BOS}} = \frac{\partial I_{\text{BOS}}}{\partial T} \Delta T_A \max(R, R_T) < \Delta V_{\min}. \quad (5)$$

For our components, $R \approx R_T$, and for ΔT_A of 2°C this effect produces a maximum offset of $\sim 1 \mu\text{V}$.

The principal parts of the **temperature controller**, in addition to the **resistance bridge**, are the error signal gain stages and the **Peltier thermoelectric heat pump** (see Fig. 3). The desired temperature is selected via the set point **potentiometer**. The amplifier gain and the thermistor's tempco determine that the amplifier output corresponds to a 30 mV/mK error signal. This signal is fed to the **integrating, proportional, and differential gain stages**, which in combination affect the voltage applied to the heat pump. The integrator output settles to a level that balances the resistance bridge while continuing to compensate for slow temperature drifts ($RC \approx 3 \text{ s}$). The near-unity gain proportional stage helps to damp out feedback oscillations and the low-gain differential stage is provided to respond to any high-frequency signal. The gain and time constants of these stages were selected for our particular laser mount configuration and do require adjustment for different thermistor positions and laser mounts. **Zener diodes** clamp the heat pump voltage preventing it from drawing excessive current. For our system, we observe an error signal which is typically $\pm 3 \text{ mV}$ peak to peak, which corresponds to a temperature stability of about $\pm 0.1 \text{ mK}$. Temperature fluctuations at the **laser diode** itself are likely to be somewhat greater than this due to the imperfect thermal contact between the **laser diode and the thermistor**.

The mechanical mounting of the laser diode must be considered carefully in order to achieve good thermal stability. The laser diode is mounted on a $5\text{-cm-square} \times 0.8\text{-cm-thick}$ copper plate which is attached to the 3.6-cm-square heat pump. The heat pump is squeezed between the copper plate and a $10 \text{ cm} \times 17 \text{ cm}$ finned heat sink using nylon screws. The copper plate and heat pump extend into a hole in a large aluminum block which bolts to the heat sink, thereby isolating the laser diode from room air currents. We emphasize that the thermistor must be mounted as close to the laser chip as possible in order to achieve maximum temperature stability. In our first attempt, the thermistor (Fenwal, Standard Bead) was coated with thermal grease and placed in a small hole in the copper block about 1 cm from the laser chip. From laser frequency drift measurements, we calculated a temperature stability of $\sim 1 \text{ mK}$ over periods of 1 h . In

our latest, more stable design we glued the **thermistor** into a small hole which was drilled through the laser diode case and into the internal heat sink of the device. We believe that the temperature stability of our configuration is limited by the remaining distance between the laser and the thermistor and not by the **controller circuit**.

IV. FREQUENCY STABILITY

A laser frequency stability of $\pm 10 \text{ MHz}$ was determined using the current and temperature stabilized laser diode (Toshiba TOLD 9211) to excite lithium atoms in a thermal atomic beam. To produce the correct wavelength, the laser diode was cooled to 18°C . The laser frequency was scanned, by ramping the injection current, near the $2S \leftrightarrow 2P$ resonance frequency to obtain the fluorescence signal shown in Fig. 4. The two peaks correspond to transitions from the two ground-state hyperfine sublevels to the excited state (hyperfine splitting is 803 MHz). The larger peak corresponds to the $F=2$ sublevel and the smaller peak to the $F=1$ sublevel. To measure the long-term frequency stability, the laser frequency was set to the side of the $F=2$ resonance and the resulting fluorescence was monitored over a period of one hour. Variations in this signal may result from the combined drift of the laser frequency, due to laser injection current and/or temperature fluctuations, and drift in the atom flux out of the oven. For a conservative estimate of frequency and temperature stability we assume that these signal variations are largely due to frequency fluctuations resulting from temperature drifts. With this assumption, frequency stability may be derived from the fluctuations in the fluorescence signal using the slope of the resonance at this frequency. This measurement implies a laser temperature stability of better than $\pm 0.3 \text{ mK}$ over a period of 1 h . Because of oven and current drift, however, the actual frequency and temperature stability may be somewhat better than

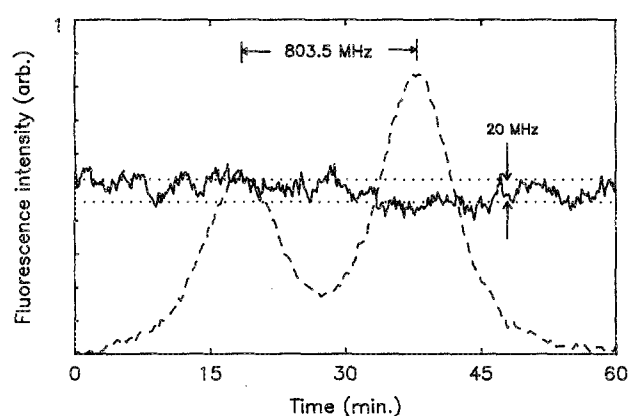


FIG. 4. Laser diode frequency stability was determined from the excitation of lithium atoms in a thermal beam. The dashed curve corresponds to the intensity of the fluorescence signal as the laser diode frequency was scanned over the $2S \leftrightarrow 2P$ resonance. The two peaks correspond to transitions from the $F=1$ and $F=2$ ground-state hyperfine sublevels. The solid curve was obtained by setting the laser frequency to the side of the $F=2$ resonance (the larger peak) while monitoring the fluorescence for a period of 1 h . The laser stability of $\pm 10 \text{ MHz}$ was derived from the slope of the resonance at this frequency.

these conservative estimates.

In addition to sensitivity to current and temperature, laser diode performance is also affected by optical feedback. Stray back reflections from optical elements can result in frequency instability that is difficult to diagnose. These reflections should be minimized and/or kept constant by means of appropriately coated, carefully oriented and securely mounted optics. However, feedback from a frequency dispersive device such as a grating or etalon can be used to significantly narrow the laser linewidth. By using a tuned Fabry-Perot interferometer feedback method,⁸ we have reduced the 150-MHz free-running linewidth of a TOLD 9211 laser diode to a value less than our measurement resolution of 10 MHz.

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