Improving frequency stability of laser by means of temperature-controlled Fabry-Perot cavity

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The frequency stability of an all-solid-state Nd:YVO$_4$ laser is significantly improved by means of a specially designed Fabry-Perot (F-P) interferometer used for the frequency standard in the frequency-stabilizing system. The temperature of the F-P cavity is accurately controlled by a set of thermoelectric cooler (TEC) modules attached on the body of the cavity and the electronic feedback circuit. We find that the long-term unidirectional frequency shift of the output laser, resulting from the slow increase of the cavity length under the effect of the temperature integration on the cavity body, is essentially eliminated. The frequency stability of the output laser with the power of 530 mW is better than ±200 kHz in 1 minute and ±2.3 MHz in 40 minutes, respectively. The fluctuation of output power is smaller than ±0.5% over one hour.

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Usually a Fabry-Perot (F-P) interferometer is used as a frequency standard in frequency-stabilizing systems of lasers. It has been demonstrated that the quality of the F-P cavity is very important for obtaining better frequency stability. The bodies of F-P cavity have been constructed with invar in most systems for protecting from the effect of the thermal expansion. However, the expansion coefficient of invar is not equal to zero, so the length of the cavity still lengthen slowly which causes the unidirectional shift of the resonant frequency and finally the very pernicious mode-jump of laser occurs during the operating process due to the effect of the temperature integration on the cavity body. In the modern experimental investigation of quantum optics and quantum information, the accuracy of the long-term frequency stability of lasers is required in the range of a few megahertzs[1−4]. Therefore we have to control actively the temperature of the F-P cavity to reduce the influence of the thermal expansion to the minimum. In this paper we present a design for efficiently controlling the temperature of the F-P cavity. When the temperature-controlled F-P cavity is used in the frequency-stabilizing system of a home-made Nd:YVO$_4$ laser[5], the unidirectional frequency shift of the laser is suppressed and the long-term frequency stability of the output laser is significantly improved from ±16.23 MHz at free operating to ±2.3 MHz.

The configuration of the F-P cavity used for a frequency standard in the frequency-stabilizing system should have perfectly long-term mechanical stabilization with an approximately constant cavity length to keep the center of its resonant frequency unchanging. The designed body of the F-P cavity is a tube-shaped invar with low expansion coefficient (1.26×10^{-6}/°C) and the cavity mirrors are fixed on the two sides of the invar tube through a finely adjustable mirror mount. An indium sheet is placed between the cavity mirror and mirror mount. The distortion of the indium sheet under forcing can be utilized for calibrating the F-P cavity to resonate with the injected laser. A piezoelectric transducer (PZT) element is attached on one of the cavity mirror for scanning the length of the cavity. The invar tube is embedded in a sheath made by pure copper for better thermal conductivity. Four pieces of TEC modules connected with a temperature controller are attached on the copper sheath for instantaneously and precisely controlling the temperature of the cavity body by means of an electronic feedback circuit. The sensitivity of the home-made temperature controller is better than 0.3% °C (usually the fluctuation of the room temperature is less than ±1 °C). For keeping a constant temperature other sheath made by bakelite material is covered on the copper sheath and then the covered cavity body is placed in a aluminum box. The configuration of the designed F-P cavity is shown in Fig. 1.

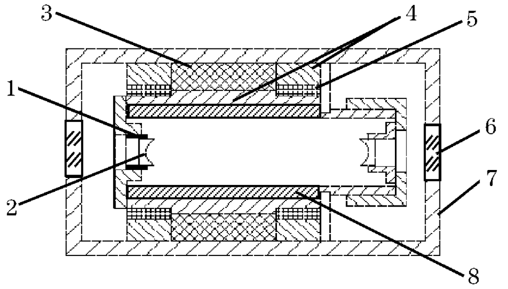

Fig. 1. Schematic configuration of F-P cavity for temperature control. 1: PZT; 2: cavity mirror; 3: bakelite sheath; 4: copper sheath; 5: TEC modules; 6: transparency window; 7: aluminum box; 8: invar tube.

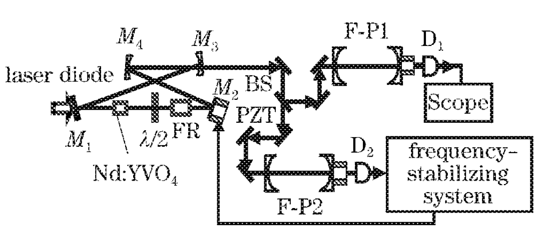

Fig. 2. Experimental setup. $\lambda/2$: half wave plate; M_1, M_2, M_3, M_4: laser cavity mirrors; FR: Faraday rotator; BS: beam splitter; D_1, D_2: detectors.

Figure 2 is a schematic of the experimental system. The laser used in the experiment is a home-made all-solid-state single frequency Nd:YVO$_4$ laser with a ring resonator consisting of four mirrors. A confocal F-P cavity (F-P1) consisting of two concave mirrors with same curvature radius of 102 mm and the free spectral range of 735 MHz is utilized as the mode-monitor of the output laser. The second confocal cavity (F-P2), used for the frequency standard, is the discriminator in the frequency-stabilizing system of laser in which the general method of modulation-synchronous detection is applied[6]. The curvature radii of two cavity mirrors of F-P2 are both 50 mm, the free spectral range and the value of finesse are 1500 MHz and 420, respectively.

The scanning time recorded on the oscilloscope (scope) connected with F-P1 is 7.56 ms in a free spectral range of 735 MHz (shown in the upper curves in each figure from Fig. 3 to 8), so the scale of 1 ms on the oscilloscope corresponds to the frequency drift of 97.2 MHz (see upper photos in Figs. 3–8). The lower photos in Figs. 3–8 show the frequency drifts recorded on the oscilloscope for 1 minute (Figs. 3, 5, and 7) and 40 minutes (Figs. 4, 6, and 8) under three different operating conditions, respectively. The operating condition for Figs. 3 and 4 was the laser free operation with the frequency-stabilizing system turned off, for Figs. 5 and 6 the system was turned on but the temperature of F-P2 was not controlled, and for Figs. 7 and 8 both the frequency-stabilizing system and the temperature controller of F-P2 were turned on and the temperature of the cavity body of F-P2 was controlled at 21 ± 0.003 °C. For above three cases the frequency drifts are ±2.32 MHz, ±220 kHz, and ±200 kHz in 1 minute and ±16.23, ±4.11, and ±2.3 MHz in 40 minutes,

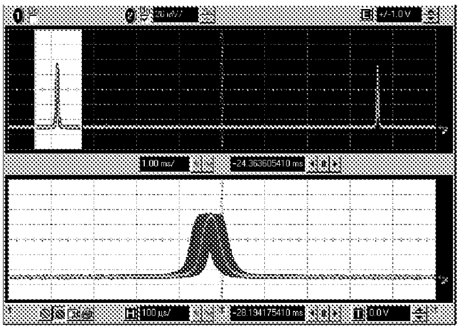

Fig. 3. The frequency fluctuation (±2.32 MHz) in 1 minute under the condition of laser free running.

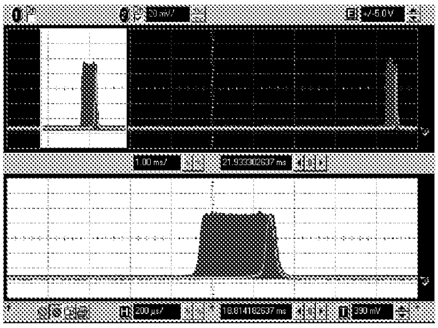

Fig. 4. The frequency fluctuation (±16.23 MHz) in 40 minutes under the condition of laser free running.

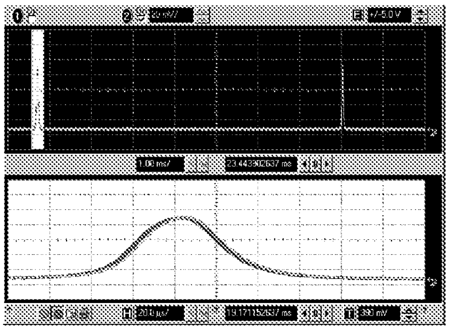

Fig. 5. The frequency fluctuation (±220 kHz) in 1 minute under the condition of laser running with frequency-stabilizing system on but without temperature controlling of F-P2.

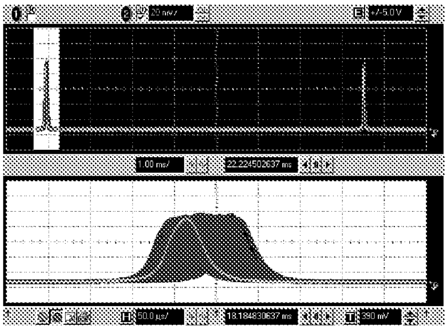

Fig. 6. The frequency fluctuation (±4.11 MHz) in 40 minutes under the condition of laser running with frequency-stabilizing system on but without temperature controlling of F-P2.

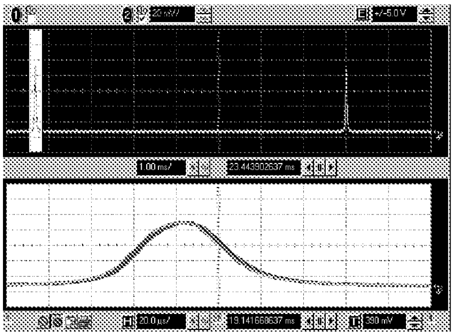

Fig. 7. The frequency fluctuation (±200 kHz) in 1 minute under the condition of laser running with both frequency-stabilizing and temperature controlling of F-P2 systems on.

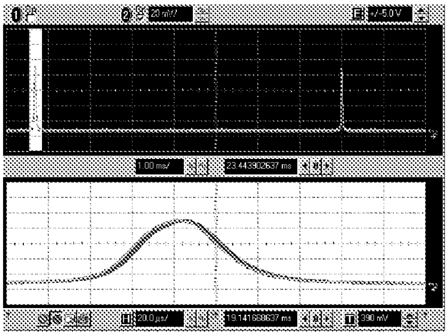

Fig. 8. The frequency fluctuation(±2.3 MHz) in 40 minutes under the condition of laser running with both frequency-stabilizing and temperature controlling of F-P2 systems on.

respectively. The power fluctuation of 530-mW output laser is smaller than ±0.5% in the third case with the frequency-stabilizing and the temperature controlling systems on. Comparing Figs. 4, 6, and 8, we can see, the long-term unidirectional frequency shift is significantly suppressed due to controlling the temperature of F-P2.

By means of accurately controlling the temperature of F-P cavity used in the frequency-stabilizing system of laser, the frequency stability of laser is significantly improved. Especially the long-term unidirectional frequency shift is essentially overcome. The presented design using TEC modules and electronic feedback circuit to control the temperature of the cavity body is sensitive, reliable, and simple. It can be extensively applied in the optical systems whenever the frequency of laser needs to be precisely stabilized.

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