Design of concentric ring bi-detectors to obtain directly the curve of frequency discrimination

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A novel concentric-ring shaped Si-photocell bi-detector, to detect the frequency-discrimination curve, is suggested and details of the design procedure are given. The design is based on the shrinkage and expansion of the interference fringe of a confocal Fabry-Perot cavity when either the cavity length is scanned or the light frequency modulated. It has been successfully used in frequency-stabilized pulsed Nd:YAG laser systems and gives a frequency-stability of better than 1 MHz.

KEYWORDS: concentric-ring bi-detector, frequency-discrimination curve, fringes

Introduction

A frequency-stabilization system using a Fabry-Perot (F-P) confocal cavity as the reference cavity has been extensively used in laser techniques because of its wide frequency tuning range.

The amplitude–frequency characteristics of the Fabry-Perot cavity are used to obtain error signals. Generally, this is achieved in two ways. The first method is the modulation, synchronous demodulation detection method[1]. However, the bandwidth of the system is narrow and the falling side of the frequency-discrimination curve is narrower still. An accidental frequency jump can easily cause the laser to become out of lock. The other method is to lock the laser frequency to one side of a transmission fringe of the F-P cavity by means of the usual differencing servo-technique[2]. Short-term stability can be improved. However, a shift of the light axis and/or a variation of light intensity may cause frequency instability.

In recent years, attention has turned to the phase–frequency characteristics of a Fabry-Perot cavity. The error signal at the ends, far away from resonance, remains strong enough to permit re-locking even after larger accidental frequency jumps. In addition, it also offers a larger signal-to-noise ratio.

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In its early stage, a dispersive frequency-stabilized system is achieved by placing a piece of polarizer in the Fabry-Perot cavity[3]. However, a polarizer in the cavity will degrade the finesse of the cavity, and this system also needs a larger number of optical elements. Drever *et al.* gave another method[4] of obtaining the frequency error signal from the reflected light of a Fabry-Perot cavity—the method of checking the RF phase-modulated sideband with an optical heterodyne method—and built a high precision, low noise laser frequency stabilization system. However, this system is very complicated.

We have designed a simple frequency-stabilization system. It uses a Fabry-Perot cavity as a reference cavity but uses a parallel bi-detector as shown in Fig.1.

The system detects the difference in the transmitted light from a Fabry-Perot cavity and gives the error signal without the light being modulated. It also gives a good result, of less than 1 MHz, for a cw Nd:YAG

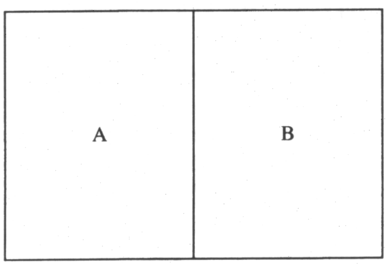

Fig. 1 Diagram of parallel bi-detector

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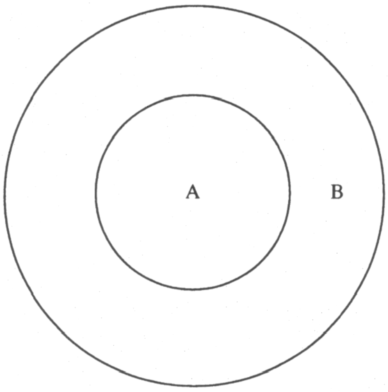

Fig. 2 Diagram of concentric bi-detector

laser[5]. However, a detailed analysis shows that it does not work at the central interference spot, where the dispersion is largest. Thus, we suggested and designed a concentric-ring shaped bi-detector. This works well in the frequency stabilization of a pulsed Nd:YAG laser.

Design principle

The interference ring fringe of a confocal Fabry-Perot cavity will shrink or expand when either the cavity length or the light frequency is changed. Thus, if a concentric-ring shaped bi-detector is placed at the centre of the interference fringe, with its axis coincident with the cavity axis, we can obtain the error signal directly by the voltage difference of the bi-detector.

The diagram of the detector is shown in Fig. 2. It consists of a round detector A and a ring detector B. The two detectors are connected in series in an inverted order. Therefore, the output of the bi-detector will be

$$U_{ab} = U_a - U_b \qquad (1)$$

In normal conditions (the laser working at the to-be-stabilized frequency), the photo-voltages of A and B will balance and the bi-detector gives a null output. However, if the laser varies from its normal frequency, the balance changes and an error signal will be given, with different signs (+ or −) for different changes (an increase or decrease) if the light is modulated or the cavity length is scanned. We will obtain the frequency discrimination curve directly.

Interference pattern of a Fabry-Perot confocal cavity

As is well-known, when a laser beam of wavelength λ is incident on a confocal Fabry-Perot cavity, the intensity distribution function of the interference fringes is

$$I(\rho, \lambda) = I_0 / \left\{ (1-R)^2 + 4R[\sin(\varphi/2)]^2 \right\} \qquad (2)$$

here R is the reflectance of cavity mirrors, $\varphi = 2\pi\Delta/\lambda$ and Δ are the differences of the phase and optical paths between successive interfering beams. A simple geometric-optics calculation gives

$$\Delta = 4r + \rho^4/r^3 \qquad (3)$$

where r is the radius of curvature of cavity mirrors and ρ is the distance from any point on the focal plane to the optical axis of the cavity. When $\varphi = 2m\pi$ or $\Delta = m\lambda$, where m is a positive integer, we obtain the interference maximum of the integral order m with the radius

$$\rho_m = \left[(m\lambda - 4r)r^3\right]^{1/4} \qquad (4)$$

The radial dispersion is

$$\frac{d\rho}{d\lambda} = (mr^3/4)\left[(m\lambda - 4r)r^3\right]^{-3/4} \qquad (5)$$

In the case of $m\lambda = 4r$ we have $\rho_m = 0$ (see (4)), the mth order interference maximum appears on the optical axis and the maximum of the radial dispersion also appears here (see (5)).

Design of concentric ring bi-detector

The round detector A and ring detector B are made of the same material and have the same quantum efficiencies. The crucial point of the design is the choice of ρ_A and ρ_B, which must meet the following requirements.

(i) When the laser is working at the correct frequency (Fabry-Perot cavity resonance), it gives a null output.
(ii) When the Fabry-Perot cavity is out-of-resonance, it should give an error signal as large as possible.

While the first requirement can be exactly expressed by

$$\int_0^{\rho_A} I(\rho, \lambda_0) 2\pi\rho \, d\rho = \int_{\rho_A}^{\rho_B} I(\rho, \lambda_0) 2\pi\rho \, d\rho \qquad (6)$$

the second requirement does tolerate some arbitrariness. A reasonable choice is that we choose both ρ_A and ρ_B to lie inside the central range, as shown in Fig. 3.

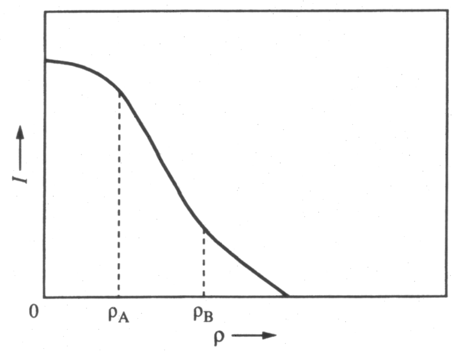

Fig. 3 The intensity distribution scheme of the central interference fringe

The value of ρ_B can be determined by direct observation. Yet we make a numerical estimation by calculating $\rho_{1/2}$, the radius at which the light intensity is just half that at the centre under resonance, that is

$$I(\rho_{1/2B}) = 1/2 I_{max} = \frac{I_0}{2(1-R)^2}$$

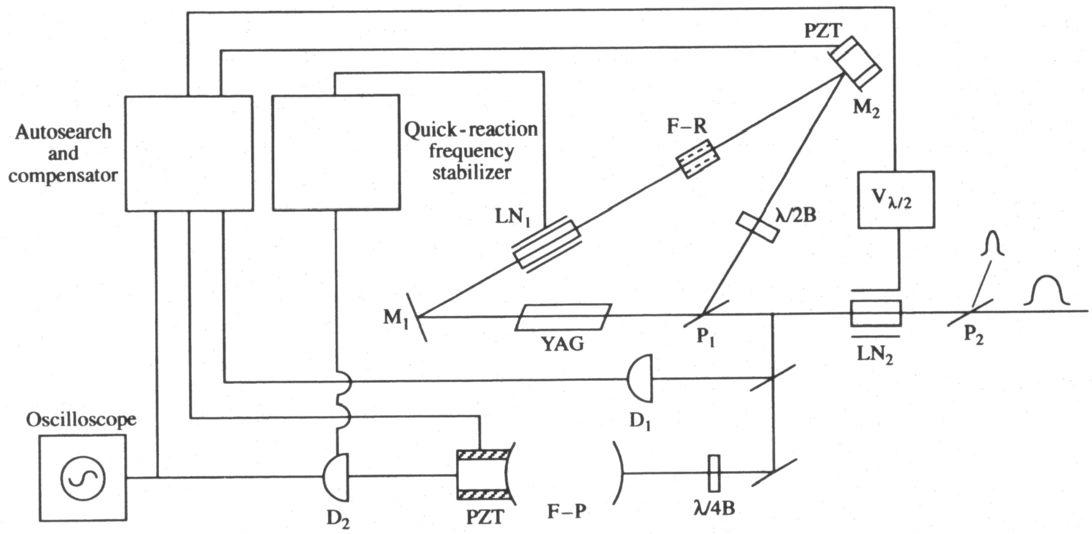

Fig 4 Layout of the pulsed frequency-stabilized laser

i.e.

$$\frac{I_0}{(1-R)^2 + 4R\{\sin[\varphi(\rho_{1/2})]\}^2} = \frac{I_0}{2(1-R)^2} \tag{7}$$

Expanding the function $\sin(\varphi/2)$ around its maximum into a Taylor's series and taking the fourth-order approximation

$$\sin(\varphi/2) = \sin\frac{2\pi}{\lambda}\left(4r + \frac{\rho_{1/2}^4}{r^3}\right) = \sin\frac{2\pi_{1/2}^4}{\lambda r^3} \approx \frac{2\pi\rho_{1/2}^4}{\lambda r^3} \tag{8}$$

we readily obtain that

$$\rho_{1/2} = \left[\frac{(1-R)\lambda r^3}{2\pi\sqrt{R}}\right]^{1/4} \tag{9}$$

In our experimental system $r = 102$ mm, $R = 99\%$ and $\lambda = 1.064$ μm, thus $\rho_{1/2} = 1.16$ mm.

The laser light has a definite linewidth and a detailed analysis shows that this linewidth can be subdivided into two kinds according to their origin: one is the intrinsic linewidth of the light that is very narrow (single frequency); the other is caused by the frequency drift of the laser oscillation. As the bi-detector has a rapid response, the linewidth has little effect in the design procedure and is thus neglected.

In practice, we take $\rho_B = 2.0$ mm, and ρ_A is determined by (6) through numerical integration to give $\rho_A = 0.94$ mm ≈ 1.0 mm. The fine adjustment of the balance between U_A and U_B is achieved by adjusting the matching (loading) resistors of detectors A and B.

Application

For a frequency locked pulsed Nd:YAG laser, we designed a frequency-control system consisting of a confocal Fabry-Perot cavity, a concentric bi-detector, an autosearch compensator and a quick-reaction frequency controller. Using this system we have obtained an output of the frequency-stabilized pulsed laser light at 1.064 μm with a pulse width of 0.7 ms, a peak power of more than 100 W, and frequency-stability of less than 1 MHz (see Ref. 6).

Figure 4 is the layout of the pulsed frequency-stabilized laser set, in which the concentric bi-detector (D_2) is placed at the centre of the transmitted interference pattern of the confocal Fabry-Perot cavity. The error signal received by D_2 is amplified and fed back to the electro-optic crystal LN_1, which is placed in the laser cavity, to result in the change of its refractivity. The quick response of the electro-optic crystal to the error signal can immediately compensate for the shift of laser wavelength by changing the optical path of the laser cavity.

Figure 5 shows the transmission curve of the confocal cavity recorded by detector A when the Fabry-Perot cavity length is scanned by applying a periodic sawtooth voltage on the PZT that holds one mirror of the cavity. In our experimental system $r = L = 102$ mm, the spectral range is $\Delta\nu = C/2L = 735$ MHz. According to the experimental data used, one obtains a 1 ms time interval corresponding to a frequency width of 1200 MHz. Figure 6 is the curve of the frequency-discrimination obtained under the same conditions as Fig. 5. The width and amplitude of the peak-to-peak

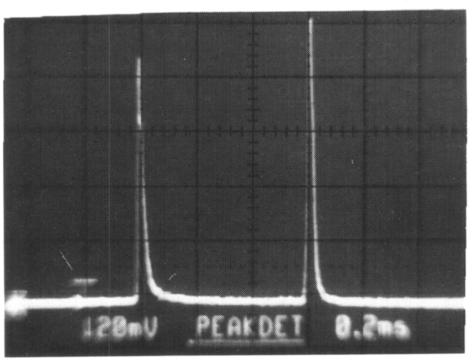

Fig. 5 Transmission curve of the confocal cavity

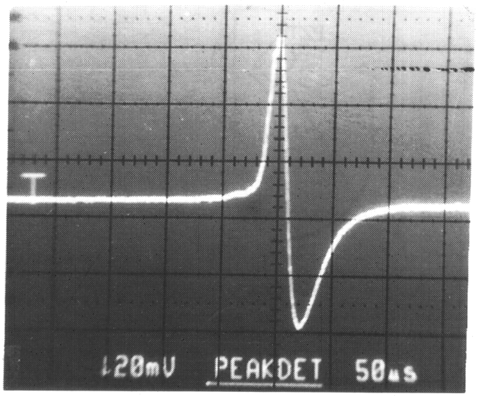

Fig. 6 Curve of the frequency discriminator

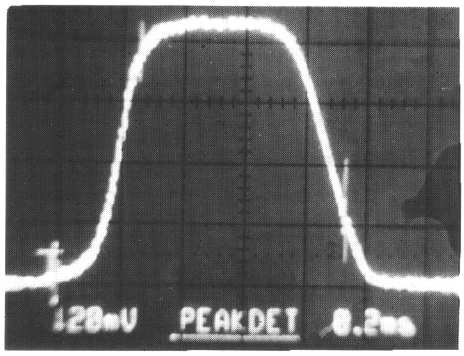

Fig. 7 Transmission curve of a confocal cavity with frequency lock-in

signal are 24 MHz and 108 mV; therefore, the electric signal of 1 mV corresponds to a frequency shift of 0.22 MHz.

Figure 7 shows the transmission curve of a Fabry-Perot confocal cavity after the laser frequency is locked in. The frequency stability is less than 1 MHz. The pulse width, output energy and output power of the laser are 0.7 ms, 90 mJ and 130 W respectively[6].

Conclusions

The curve of frequency-discrimination can be directly obtained with the concentric bi-detector. The simple frequency-control system has a high sensitivity and a quick response speed. In addition, as the laser is locked to the centre of a cavity resonance, this bi-detector can also be used in the frequency locking of a OPO cavity.

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