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Affection of optical phase-locked loop on the coherence properties improving of laser

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A R T I C L E I N F O

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A B S T R A C T

In order to achieve the coherent combination of independent lasers by using optical phase-locked loop (OPLL), the working mechanism of OPLL is analyzed. By calculating the autocorrelation function and the cross-correlation function of lasers, the performance of phase-locking system has been analyzed while a non-ideal laser is employed as the reference laser. The results prove that the coherence of an ordinary laser can be improved obviously by using an OPLL. Furthermore, some main parameters of the phase-locking system have been discussed in detail to provide a theoretical basis for the design of the OPLL system. The results show that if the linewidth of an ordinary laser is 2 MHz, to meet the requirement of efficient coherent beam combining, the time constant of OPLL should be less than 10 ns and the linewidth of reference laser ought to be less than 20 kHz.

1. Introduction

Coherent combining is an effective way to obtain high power laser with good beam quality and spectral purity [1–4]. Strictly, in coherent beam combining system, the same frequency and constant phase difference of unit beams are the essential conditions. Therefore, the optical parameters such as phase, amplitude and polarization should be controlled precisely when we design a system [2]. To get an stable phase relationship between unit beams is always the most difficult link in the system. In order to solve this problem, some technologies such as common resonant cavity [5], evanescent wave coupling, self-organizing [4], injection locking [1] and active feedback mechanism [6,7], have been developed. However, these technologies are mainly employed to stabilize the phase relationship by means of the synchronous output of the laser during the stimulated oscillation. So the scale of coherent combining array is limited and the actual output power is difficult to further improve.

Combined with an electronic feedback control system, the optical phase-locked loop technique is used to control the phase of each laser and achieve efficient coherent combination [8–11] by its excellent performance on phase noise suppressing [12–14]. At present, the controlling effect of OPLL on laser phase has been proved in theory when an ideal laser is used as reference laser [15]. But in reality, the ideal laser without any noise is non-existent. It is necessary to establish an analytical theory to analyze the phase-locking effect of OPLL when an actual laser is used as the reference. In this paper, based on the statistical properties of laser phase noise, the work mechanism of OPLL is introduced. The autocorrelation function and the cross-correlation function of lasers with or without the treatment of OPLL are calculated. The phase-locked performance with a non-ideal laser reference has been analyzed. And the optimal time constant and reference laser's linewidth of an OPLL are confirmed by theoretical analysis and numerical calculation.

2. The structure and working principle of OPLL

As shown in Fig. 1, OPLL is the key part of a coherent combining system. Its main function is to achieve the phase modulation of the ordinary laser as required. So the phase relationship among the output beams becomes stable. One OPLL system is mainly composed of a reference laser, an ordinary laser, a mixer, a phase discriminator (PD), a signal processing system (SPS) and a phase modulator (PM). The SPS is used to detect the signal from PD, which is composed of an amplifier and a loop filter.

In principle, the OPLL system can be represented by a linear system, as shown in Fig. 2 [15]. The input signal is $\Delta\phi(t)$, which is the phase difference between the ordinary laser $U_1$and the reference laser U_c. The output signal is $\phi_{out}(t)$, which is the phase difference between the output laser $U_o$and the reference laser U_c. The transfer function of the system is $H(s) = 1/(Ts + 1)$, where T is the time constant which is determined by the performance of OPLL system.

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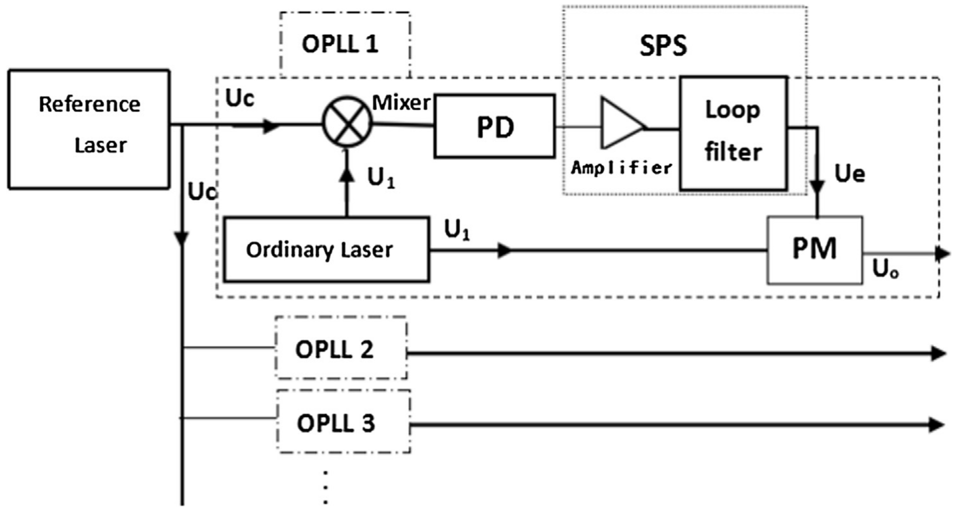

Fig. 1. Schematic diagram of the basic structure of coherent combining.

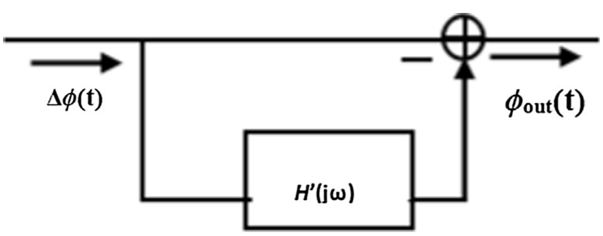

Fig. 2. The principle block diagram of OPLL system.

Then the impulse-response function of the inertial components can be expressed as $h(t) = 1/\mathrm{T}\cdot\exp(-t/\mathrm{T})$. The total point diffusion function of the system is $\delta(t) - h(t)$, where $\delta(t)$ is the unit-impulse function.

The topic under study in this paper is phase-locking, so in the following discussion we will focus on the phase. The complex amplitude of a laser with phase noise can be expressed as $U = \exp[j(\omega t + \phi(t))]$, where ω is frequency of laser, $\phi(t)$ is a Wiener random process [12]. We can describe the reference laser and the ordinary laser as $U_c = \exp[j(\omega_0 t + \phi_c(t))]$ and $U_1 = \exp[j(\omega_1 t + \phi_1(t))]$ respectively. The output signal of the OPLL system is $\phi_{out}(t) = [\beta t + \phi_1(t) - \phi_c(t)] * [\delta(t) - h(t)]$, where $\beta = (\omega_1 - \omega_0)$, '*' indicates convolution operation. So the complex amplitude of the phase-locked laser is $U_o = \exp[j(\omega_0 t + \phi_c(t) + \phi_{out}(t))]$.

3. Phase-locking characteristics

3.1. The improvement of ordinary laser's coherence

The coherence of a laser can be described by its autocorrelation function. The closer the value of autocorrelation function is to 1, the better the coherence of the laser is [15].We discuss the autocorrelation functions of U_1 and U_c firstly. The autocorrelation function of these two lasers can be written as

$$\begin{cases} R_{U_1}(s) = \exp[-\sigma_1{}^2|t_1 - t_2|/2] = \exp[-\sigma_1{}^2|s|/2] \\ R_{U_c}(s) = \exp[-\sigma_c{}^2|t_1 - t_2|/2] = \exp[-\sigma_c{}^2|s|/2] \end{cases} \quad (1)$$

where s is the time interval, $\sigma_1{}^2 = \Delta\omega_1$ and $\sigma_c{}^2 = \Delta\omega_c$ are two constants which actually correspond to the linewidths of these two lasers [16]. We assume the time interval is positive number ($s > 0$) to facilitate analysis. After the OPLL system, the phase of U_1 has been locked. Then, the expectation of U_o's autocorrelation function can be deduced as

$$\begin{aligned} E[\mathrm{R}_{U_o}(s)] &= E[< U_o(t)\cdot U_o{}^*(t+s) >] \\ &= \exp[-j\omega_0 s]\cdot\exp[-\tfrac{\sigma_c^2 s + (\sigma_1{}^2 + \sigma_c^2)\mathrm{T}(1-e^{-s/\mathrm{T}})}{2}] \end{aligned} \quad (2)$$

where $\mathrm{R}_{U_o}(s)$is the autocorrelation function of the phase-locked laser U_o, $< f(t) >= \lim_{T_0\to\infty}\frac{1}{T_0}\cdot\int_0^{T_0} f(t)dt$ represents a mean value taken over a period of time and T_0 is the integration time.

In Eq. (2), we can see that the value of $E[\mathrm{R}_{U_o}(s)]$ varies with $\sigma_c{}^2$ and T. So it is necessary to analyze the effect of these two parameters on phase-locking process in detail. We assume the linewidths of the ordinary laser and reference laser are 2 MHz and 20 kHz respectively (ie.$\sigma_1{}^2 = 2\,\mathrm{MHz}$, $\sigma_c{}^2 = 20\,\mathrm{kHz}$). $E[\mathrm{R}_{U_o}(s)]$drops dramatically with an increase in time constant T, as shownd in Fig. 3. For example, if we take $\mathrm{T} = 1\times10^{-8}$ s and $\mathrm{T} = 1\times10^{-6}$ s, the values of $E[\mathrm{R}_{U_o}(s)]$ are 0.9051 and 0.336 respectively when $s = 1\times10^{-5}$ s. Therefore, to make the phase-locked laser have high level coherence, T should be controlled in a small range. Fig. 3(a) shows that if we set T = 10 ns, both the values of $E[\mathrm{R}_{U_o}(s)]$ and $E[\mathrm{R}_{U_c}(s)]$ are over 0.9051 when s is less 10 μs. It can be considered to achieve a better effect of phase-locking.

To quantify the effect of phase-locking, we defined a ratio coefficient M. If M = 1, the coherence of the phase-locked laser is the same as that of the reference laser. Thus means the phase of phase-locked laser keeps consistent with that of the reference laser.

$$\mathrm{M} = \frac{E[\mathrm{R}_{U_o}(s)]}{E[\mathrm{R}_{U_c}(s)]} = \exp\left[-\frac{(\sigma_1{}^2 + \sigma_c^2)\mathrm{T}(1-e^{-s/\mathrm{T}})}{2}\right] \quad (3)$$

As shown in Fig. 4, when T = 10 ns, M will eventually be a stable value 0.9802, which means a better effect of phase-locking has achieved.

Now we focus on the effect of $\sigma_c{}^2$on $E[\mathrm{R}_{U_o}(s)]$. Defining $\sigma_1{}^2 = \mathrm{n}\sigma_c{}^2$, which means the linewidth of the ordinary laser is **n** times the reference laser's linewidth. And the variation of $E[\mathrm{R}_{U_o}(s)]$ with n can be obtained by Eq. (2). When $\sigma_1{}^2 = 2\mathrm{MHz}$, T = 10 ns, the results are shown in Fig. 5.

Fig. 5 shows that with the increase of n, the decrease rate of $E[\mathrm{R}_{U_o}(s)]$ slows down. When time interval is 8 μs and n is 100, the value of $E[\mathrm{R}_{U_o}(s)]$ is 0.9381.