Long-term stabilization of the optical fiber phase control using dual PID

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Abstract: We propose an approach of long-term stabilization of optical fiber phase by controlling a piezo-based phase modulator and a Peltier component attached to the fiber via a phase-locked loop (PLL) circuit with dual proportional-integral- derivative (PID) adjustment. With this approach, we can suppress the fast disturbance and slow drifting of optical fiber to satisfy the requirements of optical phase long-term locking. In theory, a mathematical model of an optical fiber phase control system is established. The disturbance term induced by environment influence is considered into the PLL model. The monotonous and continuous changing environment disturbance will cause a steady-state error in this theory model. The experimental results accords well with the theory. The steady-state performance, adjusting time, and overshoot can be improved by using the dual PID control. As a result, the long-term, highly stable and low noise fiber phase locking is realized experimentally.

Keywords: Long-term stabilization, dual PID, phase locking, fiber phase control.

1 Introduction

Optical fiber has aroused great interest among the optical communication applications. It can arbitrarily change the direction of light path for long-distance transmission. Since the outstanding advantages such as wide frequency band, low dissipation, large information capacity and immune to electromagnetic interference, fiber is widely applied in many aspects of industrial and research field.

However, as a transmission medium, fiber is vulnerable to variety of environmental factors including temperature, shape, air pressure and so on. The phase control is becoming increasingly important in an optical fiber system, especially in coherent optical communication [1-3], quantum communication[4-6], time and frequency transfer[7-8], fibre-optic sensing[9-10] and other fields. The long-term locking of fiber phase is one of the key techniques in practice[6,11-12]. The coherent optical communication, as one of the optical fiber application, normally requires long distance transmission of signal in fiber. The signal has already become extremely weak before entering the detector. In order to achieve efficient demodulation, a locked local laser and interference measurement is required[2]. It demands long-term phase locking of fiber. Continuous-variable quantum key distribution (CV-QKD) system, as another optical fiber application, also needs a long-term stable relative phase between the weak signal light and the strong local light [6].

In order to ensure the stability of fiber optic systems, the laboratorial fiber system usually employed a sealed chamber with temperature stabilization to reduce the effect of temperature and airflow[13]. In practical, however, this method can not be adopted. Ref. [14] reported the PLL with PID regulator can improve the performance of optical phase locking and extend the locking time. They introduced an environmental perturbation term at the reference input and proved that the PID regulator can eliminate the influence of environmental change in theory. Nevertheless, for a general optical fiber system, the disturbance of the environment not only exists in the reference input, but also maintains through the transmission line.

In this paper, we introduce the environmental disturbance into the main loop, and establish a disturbance model of the PLL. The steady-state error resulted from disturbance of the environment in PLL has been analyzed, and the steady-state error always exist when the environment monotonously and continuously changes. An optical fiber phase control method using dual PID is presented to achieve the long-term stability of the fiber phase. The simulation results show that this scheme has obvious advantages in the long-term phase stability, settling time, overshoot, steady-state error etc. Also, An experiment is carried out to test the actual effect of dual PID control in CV-QKD.

This paper is organized as follows: Section II establishes the disturbance mathematical model with PID regulator under the influence of environment; Section III proposes an improved PLL with dual PID regulator to improve the steady-state error and realize the long-term stabilization of fiber phase; Section IV verifies the advantages of dual PID control through a long-term fiber phase locking experiments; Section V presents a conclusion.

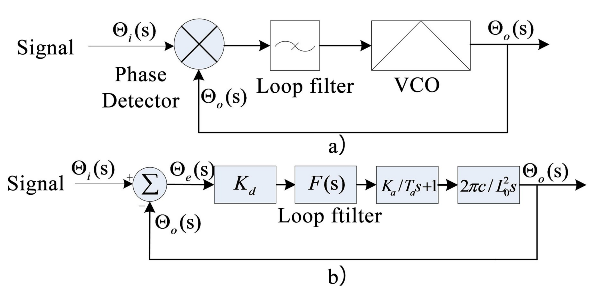

Fig. 1 a) Simplified configuration for the PLL.
b) mathematical blocks of the PLL.
VCO: voltage-controlled oscillator

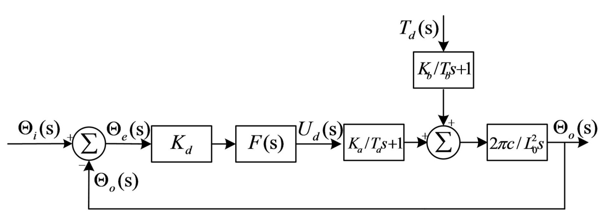

Fig. 2 The disturbance model of the PLL

2 Disturbance model of The PLL

The optical phase-locked loop is shown in Fig. 1a). The PLL consists of three basic blocks: a phase detector, a loop filter and a voltage-controlled oscillator (VCO). In Fig. 1b), all variables are expressed in the complex frequency domain. $\Theta_i(s)$ and $\Theta_o(s)$ are the phase of reference and output signal respectively. $\Theta_e(s)$ is defined as the error signal. Three transfer functions of the system in complex frequency domain can be easily derived[14], which are the open-loop transfer function $H_o(s)$, the close-loop transfer function $H(s)$, and the error transfer function $H_e(s)$ [15].

$$H_o(s) = \frac{\Theta_o(s)}{\Theta_e(s)} = \frac{2\pi c K_d K_a F(s)}{s^2 L_0{}^2 T_a + s L_0{}^2}$$

$$H(s) = \frac{\Theta_o(s)}{\Theta_i(s)} = \frac{2\pi c K_d K_a F(s)}{s^2 L_0{}^2 T_a + s L_0{}^2 + 2\pi c K_d K_a F(s)}$$

$$H_e(s) = \frac{\Theta_e(s)}{\Theta_i(s)} = \frac{s^2 L_0{}^2 T_a + s L_0{}^2}{s^2 L_0{}^2 T_a + s L_0{}^2 + 2\pi c K_d K_a F(s)} \tag{1}$$

where K_d is the phase detector gain, $F(s)$ is the transfer function of loop filter, L_0 is the length of regulation loop, c is light velocity, K_a is called as the regulation gain, T_a is the time-delay parameterand.

Based on the automatic control theory, we established a mathematical model of linear disturbance phase-locked loop, which is used to describe the environment effect on thefiber[15-17], especially the temperature, as shown in Fig. 2.

The temperature effect on the fiber can be treated as a first-order time delay device from its modelinganalysis[15-16]. Therefore, the regulated length of the fiber is written as

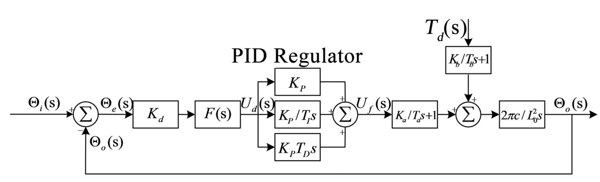

Fig. 3 The disturbance model of the PLL with PID regulator

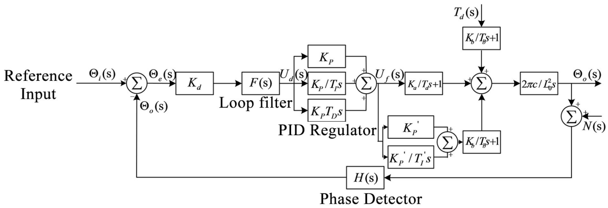

Fig. 4 The disturbance model of the PLL with dual PID regulator

$L^{'}(s) = (K_b/(T_b s+1))T_d(s)$. where K_b is regulation gain, T_b is the time-delay parameter, $T_d(s)$ is the variation of the environment temperature.

The steady error is one of the most important characteristics of the PLL. It represents the consistency between the output signal and the reference input. In order to analyze the steady-state error of the PLL, we need to derive the error function in the disturbance model. Assumingthe referenceinput $\Theta_i(s) = 0$, according to Fig. 2, we can obtain

$$\Theta_o(s)^{'} = \frac{K_b}{T_b s + 1} \cdot \frac{2\pi c(T_a s + 1)}{s^2 L_0^2 T_a + s L_0^2 + 2\pi c K_d K_a F(s)} \cdot T_d(s) \quad (2)$$

Combined with (1), the output signal can be written as

$$\Theta_o(s) = \frac{2\pi c K_d K_a F(s)}{s^2 L_0^2 T_a + s L_0^2 + 2\pi c K_d K_a F(s)} \cdot \Theta_i(s) + \frac{K_b}{T_b s + 1} \cdot \frac{2\pi c(T_a s + 1)}{s^2 L_0^2 T_a + s L_0^2 + 2\pi c K_d K_a F(s)} \cdot T_d(s) \quad (3)$$

The error function can be obtained by type.

$$E(s) = \Theta_i(s) - \Theta_o(s) = \frac{s^2 L_0^2 T_a + s L_0^2}{s^2 L_0^2 T_a + s L_0^2 + 2\pi c K_d K_a F(s)} \cdot \Theta_i(s) - \frac{K_b}{T_b s + 1} \cdot \frac{2\pi c(T_a s + 1)}{s^2 L_0^2 T_a + s L_0^2 + 2\pi c K_d K_a F(s)} \cdot T_d(s) \quad (4)$$

After joining PID ahead-lag adjusting mathematical model as shown in figure 3, the same system error function can be obtained as expression (5).

Mentioned in the literature [14], PID controller can improve the steady-state error of the system, In practice, the environmental disturbance can be treated as ramp signal[17], the Laplace transform for environmental disturbance is

$$\Theta_e(s) = \frac{s^3 L_0^2 T_a T_I + s^2 L_0^2 T_I}{s^3 L_0^2 T_a T_I + s^2(L_0^2 T_I + k T_I T_D) + s T_I k + k} \cdot \Theta_i(s) - \frac{T_d(s) K_b (s^2 T_a T_I + s T_I)(2\pi c T_a s + 2\pi c)}{(T_b s + 1)} \cdot \\ [s^4 L_o^2 T_a^2 T_I + s^3(2L_o^2 T_a^2 T_I - 2\pi c T_a T_I T_D K_a K_d K_P F(s)) + s^2(2\pi c K_1 K_a T_a T_I + L_o^2 T_I - 2\pi c K_a K_d K_P F(s) T_I(T_a + T_D)) \\ + 2\pi c s(K_a - K_a K_d K_P F(s)(T_I + T_a) - 2\pi c K_a K_d K_P F(s)]^{-\frac{1}{2}} \quad (5)$$

$T_d(s) = \frac{\Delta R}{s^2}$, where ΔR is the rate of change of the environmental. The final steady error is given by

$$\theta_{1e}(\infty) = \lim_{s \to 0} s \frac{\Delta R}{s^2} H_2(s) = -\frac{T_I K_b}{K_a K_d F(0) K_P} = \text{constant}$$

So the steady-state error always exists. This is fatal for many systems, such as the quantum communication.

3 Dual control system

In order to solve the above problem, so as to achieve long-term stability of an optical fiber system, a dual PID control scheme is adopted in the fiber system. Fig. 4 describes the mathematical model with dual PID control. Main controller PID1 is designed to suppress high frequency fluctuations in the circuit, which guarantees favorable dynamic characteristics of the system. Meanwhile, the output of the PID1 is used as the input of the slave controller PID2, so as to make sure that the system has good static performance.

Based on the mathematical model, we simulated the transient response of the disturbance system usingsimulink software. The simulation parameters are as follows: K_d is $5/\pi$, τ_1 and τ_2 are both 10^{-3} s, K_P is 1, T_I is 5×10^{-3} s, T_D is 5×10^{-3} s, L_0 is $c/(100 \times 10^6 \text{Hz})$, K_a is 10^{-6}, T_a is 10^{-4} s, K_b is 6.63×10^{-6}, T_b is 10^{-1} s, $K_P^{'}$ is 10, $T_I^{'}$ is 10s.

Fig. 5 shows the evolution of the error signal with the single PID control (solid line) and dual PID control(dashed line) when the environment disturbance is zero, the input signal is a) a step signal, b) a slope signal and c) a acceleration signal respectively. As presented in Fig. 5 a) and b), when the input signal is either a step signal or a slope signal, two kinds of control schemes both have no steady-state error, while the dual PID control has higher response speed and less overshoot than the single PID control. For the acceleration signal input shown as figure 5 c), the single PID control will lead to a steady-state error, while it not exists in the dual PID control model. The error signal fluctuation and overshoot of the single PID model is also bigger than dual PID model.

Fig. 6 further represents the evolution of system transfer functions when the reference input is a constant and disturbance signal $T_d(s)$ is changed. Shown as Fig. 6 a), when the disturbance is a step signal, two kinds of control schemes both have no steady-state error. However, the dual PID control has higher response speed and less overshoot than the single PID control. When the disturbance is a ramp signal, two kinds of control methods both have steady-state error while the steady-state error magnitude of the dual PID control is several orders smaller than the single PID control shown in Fig. 6 b). From Fig. 6 c), it can be seen that the steady-state error of two case both grow continuously when the disturbance is a quadratic signal, while the growth rate of the dual PID control is much smaller than the single PID control. These features cause a prominent advantage at the locking time and dynamic property for the dual PID control scheme.

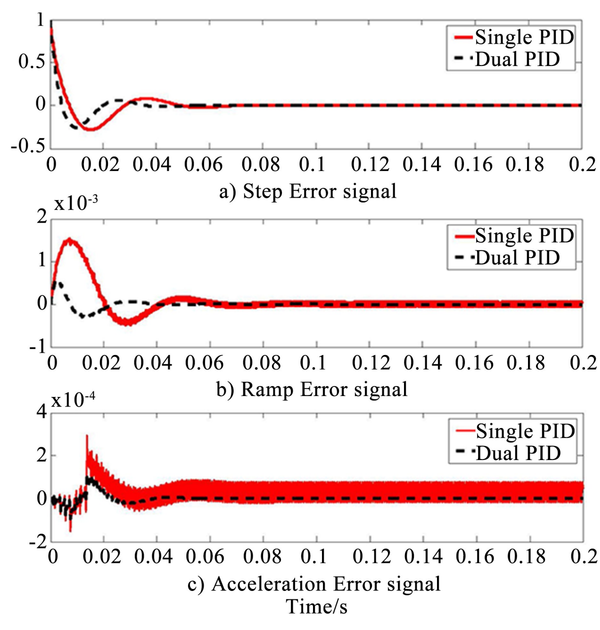

Fig. 5 Transient responses of the phase-locking of two kinds of control scheme on the condition that the input signal is changed at t = 0 with different parameters

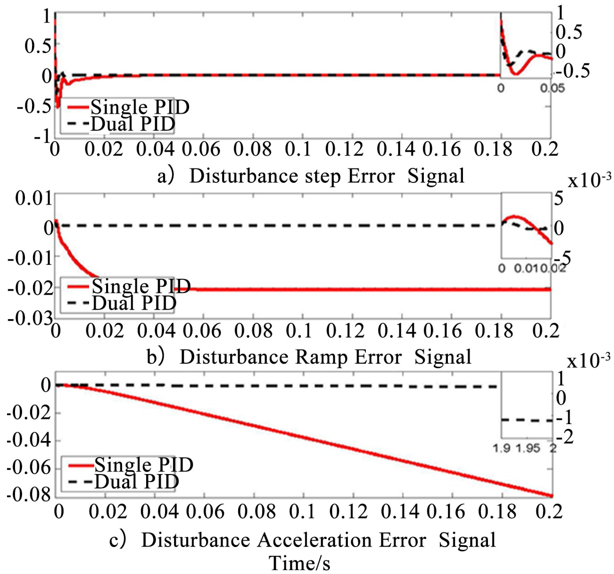

Fig. 6 Transient responses of the phase-locking of two kinds of control scheme on the condition that the disturbance signal is changed at t = 0 with different parameters

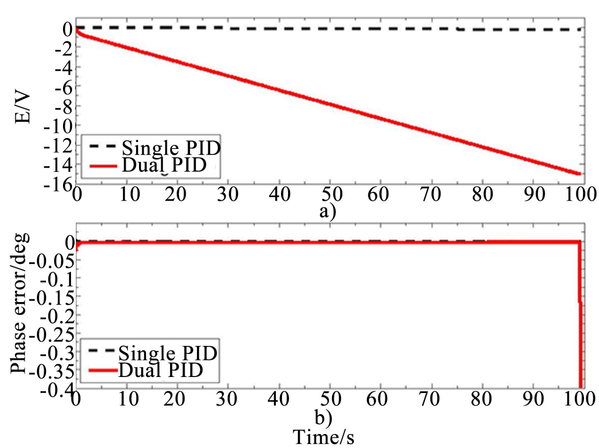

Fig. 7 The evolution of error signal and the PID output driving signal with two kinds of control schemes when the temperature is drifted

In an actual experiment system, the control circuit usually adopts an analog design. With a big disturbance at reference or loop circuit, the system is easy to lose locking. The main reason is that the output of PID circuit reach its maximum value in a short time, which is limited by the control range of performance device. Fig. 7 shows the evolution of error signal and the PID output driving signal with the single PID control (dashed line) and dual PID control (solid line) when the temperature drift of the environment is continuously varied. As presented in Fig. 7 a), a continuous and monotonous signal is added into the system at $t=0s$. It can be seen that for two case, the PID driving signal will drift under the disturbance, while the drift rate of the dual PID is much smaller than that of the single PID, whose driving signal will reach saturationlevel (15 V). In this situation, the performance device (for example piezoelectric transducer) has no more tracking ability, which means the system will get out of locking.

4 Experiment

A CV-QKD experimental system based on all fiber is employed to verify the analysis in Section III. The setup of the experiment is shown in Fig. 8.

In this experiment, the sender adopts both polarization and time division multiplexing for the signal and LO in a telecommunication fiber[6]. The sender separated two orthogonally-polarized beams from the same source as signal and LO pulses. Then the signal is delayed by a 80 m delay fiber to ensure

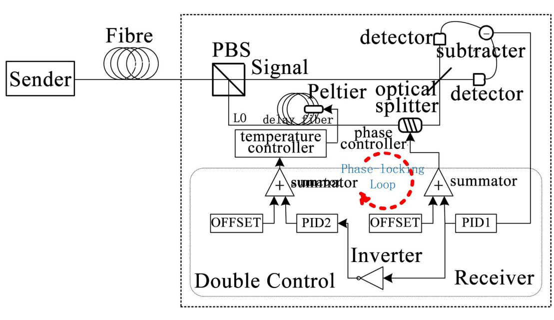

Fig. 8 The setup of the QKD experimental system using PLL With dual control system.

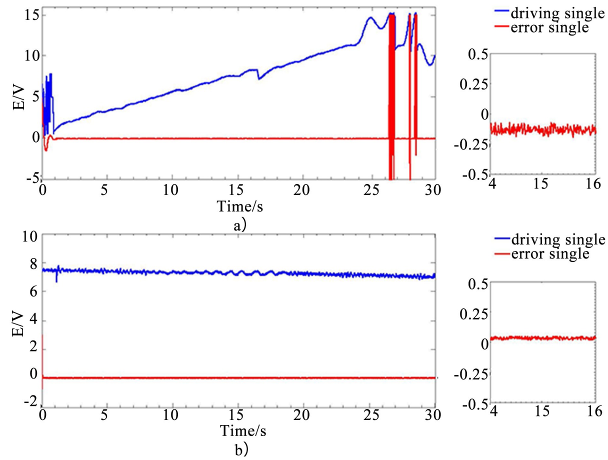

Fig. 9 a) The DC signal difference of homodyne detection as the error signal and the driving voltage without temperature compensation
b) The error signal and the driving voltage with temperature compensation

that two pulses are separated in the time domain. Then, the sender couples the two beams to the same fiber with a polarization beam splitter (PBS). The receiver separates the two beams with a PBS and synchronizes them in time domain using another delay fiber. At last, the receiver measures two quadratures of the signal field by performing heterodyne detection with a 50/50 coupler and two homodyne detectors[18]. The DC signal of the homodyne detection is used as an error signal input to PID1 to control a piezo-based phase modulator to suppress the fast fluctuations. After a reverser, the output signal of PID1 is sent to PID2 as the input. The output signal of PID2 is sent to the temperature controller to drive a oven based on a peltier element to heat or cool the delay fiber to adjust its length. In this way, the temperature drift compensation is achieved.

The actual parameters of our PLL are as follows: K_d is $5/\pi$, τ_1 and τ_2 are both 10^{-3}s, K_P is 1, T_I is 5×10^{-3}s, T_D is 5×10^{-3}s, L_0 is $c/(100\times10^6\text{Hz})$, K_a is 10^{-6}, T_a is 10^{-4}s, K_b is 6.63×10^{-6}, T_b is 10^{-1}s, K_P' is 10, T_I' is 10s.

Without the temperature compensation, PID1 conngnal is easy to drift to the output saturation level (±15V) and the locking time is not long. The DC signal difference of homodyne detection as the error signal and the driving signal on the phase modulator are shown in Fig. 9 a). When the dual PID control with temperature compensation is adopted, the locking time is drastically extended. The environment temperature does not always drift in the same direction, thus the PID2 and temperature controller are enough to compensate the slow drift of the fiber. The two PID controllers are unlikely to reach the output saturation level (±15 V). The error signal and the driving signal on the phase modulator for dual PID control are shown in fig. 9 b). We characterize the steady-state error by the fluctuation of DC signal of homodyne detection(error signal). As shown in the right part of Fig. 9 a) and b), when the system approaches stabilization, the ripple and offset of error signal with the dual PID control are smaller than those with the single PID control. Therefore, adopting dual PID control scheme in fiber phase locking has obvious advantages at aspects of locking time, steady-state error and phase noise.

5 Conclusion

This paper proposes an optical fiber phase control method using dual PID for a long term locking. Using dual PID regulator in a PLL to adjust the phase modulator and the temperature controller at the same time, the fiber system can overcome fast disturbance and slow drift to achieve a long-term phase locking. In theory, we establish a mathematical model of the optical fiber phase control system. The disturbance term caused by the environment variation has been considered into the model. These simulation results show that the dual PID control scheme reduces the steady-state error and also has obvious advantage in adjusting time, overshoot etc. In addition, the experiment results accord well with the simulation. Therefore, the dual PID control scheme is a promising candidate for highly stable, low phase noise optical fiber phase locking.

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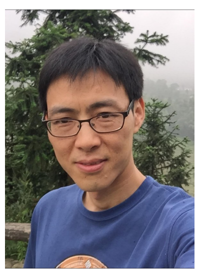

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