Phase-locked laser coherent interference

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A method of locking the relative phase to provide stable constructive or destructive interference between the phase-modulated sidebands from a pair of phase modulators is demonstrated. It is discussed theoretically for optimal fringe visibility related to the phase noise from faulty system. After phase locking using the phase modulating and lock-in technique, the drift of the relative phase is focalized around ± 0.0016 rad and the fringe visibility is restricted to 2×10^{-4}.

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Phase interference is the addition of two or more waves with different phases that cause the redistribution of intensity. The optical paths influence the final phases, thus affecting the result of interference, for which it has been used in precision measurement[1,2], quantum tunneling[3−5], and quantum information[6−11].

Phase encoding is the most popular method of quantum protocol[8]. The fiber transmission of delay-coded quantum key distribution mainly used Mach-Zehnder interferometer for phase encoding and differential phase encoding[9]. In this case, the sender uses two different optical delay paths, which causes different relative phases between the two patterns and determines the interference situation of each photon. In practice, the problem is that the existence of thermal drift and mechanical vibration in the interferometer affect stability. In order to address this problem, many groups have proposed various methods based on the Faraday rotation mirror system[10−12] for active compensation and the use of acousto-optic modulator or multi-photon[13] for encoding information, all of which gained good results but also brought new problems. In 1999, Mérolla *et al.* presented a method for phase interference through a pair of phase modulators[6]. The laser beam is phase modulated by the sender's phase modulator (PM1), resulting in sidebands; it is then modulated by the receiver's phase modulator (PM2) with the same frequency, resulting in the same sidebands as well. Constructive and destructive interferences are obtained through the change in the relative phase of the two modulators. The advantages are that 1) the use of electro-optic modulator to eliminate thermal drift can improve system stability and 2) it does not require synchronous detection as usual single-photon interference measurement. However, phase drift still exists due to varying environments.

In this letter, we first analyze the influence of phase noise on visibility. We then propose a method of phase locking by using phase modulation and demodulation to achieve well stability of fringe visibility and an excellent stability of interference.

As shown in Fig. 1, the reference laser beam with angular frequency ω_0 emitted by laser diode and injected in the PM1 could be expressed as $E = E_0 \exp(\mathrm{i}\omega_0 t)$, and the light obtained at the PM1 output is expressed as

$$E_1(t) = E_0 \exp\{\mathrm{i}[\omega_0 t + m_1 \sin(\Omega_1 t + \phi_1)]\}, \quad (1)$$

where $\varphi_1(t) = m_1 \sin(\Omega_1 t + \phi_1)$ is the phase modulation introduced by PM1, and m_1, Ω_1, and ϕ_1 are its modulation index, angular frequency, and phase, respectively.

This light field is sent to PM2, yielding a light field expressed as

$$\begin{aligned} E_2(t) &= E_1(t) \exp\{\mathrm{i}[m_2 \sin(\Omega_2 t + \phi_2)]\} \\ &= E_0 \exp\{\mathrm{i}[\omega_0 t + m_1 \sin(\Omega_1 t + \phi_1)]\} \\ &\quad \cdot \exp\{\mathrm{i}[m_2 \sin(\Omega_2 t + \phi_2)]\}, \end{aligned} \quad (2)$$

where $\varphi_2(t) = m_2 \sin(\Omega_2 t + \phi_2)$ is the phase modulation introduced by PM2, with m_2, Ω_2, and ϕ_2 being the modulation index, angular frequency, and phase, respectively.

Setting $\Omega_1 = \Omega_2$ and $\Delta\phi = \phi_2 - \phi_1$, we obtain

$$\begin{aligned} E_2(t) =& E_0 \exp\{\mathrm{i}(\omega_0 t + m_1 \sin \Omega t)\} \\ & \cdot \exp\{\mathrm{i}[m_2 \sin(\Omega t + \Delta\phi)]\}. \end{aligned} \quad (3)$$

This can be calculated by expressing the latter two of Eq. (3) as a series of Bessel functions. We select fixed angular frequency (for example, $\omega_0-\Omega$) through the Fabry-Perot (FP) cavity's mode selection, which is the result of the interference of the sidebands introduced by the pair of phase modulators. Different strength could be obtained by changing $\Delta\phi$.

The visibility of laser phase interference is $V = \frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}$, which reflects the contrast between the strongest and the weakest interference light. Greater

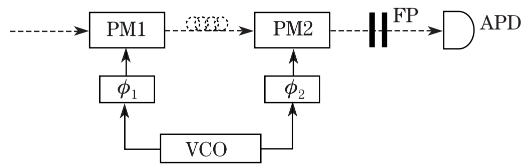

Fig. 1. Diagram of laser-phase interference (dashed line for the light signal, solid line for the electrical signal). FP: Fabry-Perot cavity, APD: avalanche photodiode detector, and VCO: voltage control oscillator.

visibility means bigger contrast. When the visibility equals $1(V=1)$, the fringe shows the clearest contrast and $I_{\min}=0$; there is no interference when the visibility equals 0 $(V=0)$.

From Eq. (3), we obtained a diagram of the corresponding relationship between the visibility and the modulation index ratio m_2/m_1 for PM1 and PM2, which is shown in Fig. 2, indicating that the visibility reaches the maximum when the ratio is 1.

Setting $m_1=m_2=m$, then Eq. (3) could be written as

$$\begin{aligned} E_2 \approx\, & J_0\left(2m\cos\frac{\Delta\phi}{2}\right)E_0\exp[\mathrm{i}(\omega_0 t)] \\ & - J_1\left(2m\cos\frac{\Delta\phi}{2}\right)E_0\exp\left\{\mathrm{i}\left[(\omega_0-\Omega)-\frac{\Delta\phi}{2}\right]\right\} \\ & + J_1\left(2m\cos\frac{\Delta\phi}{2}\right)E_0\exp\left\{\mathrm{i}\left[(\omega_0+\Omega)t+\frac{\phi_1+\phi_2}{2}\right]\right\}, \end{aligned} \quad (4)$$

where $(\omega_0+\Omega)$ and $(\omega_0-\Omega)$ are the frequencies of the first sidebands introduced by PM1 and PM2, respectively. Taking $(\omega_0-\Omega)$ as the FP cavity's nature frequency, then the intensity in the center band detected at the FP output is expressed as

$$\mathrm{i} = E_0^2 J_1^2\left(2m\cos\frac{\Delta\phi}{2}\right) \approx 4m^2E_0^2\cos^2\frac{\Delta\phi}{2}. \quad (5)$$

This intensity is the maximum when $\Delta\phi=0$ and the minimum when $\Delta\phi=\pi$. In practice, the minimum may not be 0 because of the existence of phase noise, which means that $0<V<1$.

$\Delta\phi$ in Eq. (5) should be expressed as $\Delta\phi=\phi_2-\phi_1+\phi_{\mathrm{noi}}$[14,15], where ϕ_{noi} is the phase noise due to the faulty system. From Fig. 3, we see that the visibility changes along with the phase fluctuations of the system. Hence, it is necessary to take effective activities to arrive at a stable relative phase to achieve stable visibility, i.e., well interference.

The experimental system is illustrated in Fig. 4, where the laser beams are generated by a 1 550-nm laser diode with 20-kHz frequency band (DL-BX10- CLS101B-S55) and emitted into PM1 (Model KG-RF-10) through 20 km of single-mode fiber and then sent to PM2 (Model KG-RF-10). Modulators PM1 and PM2 are pigtailed $LiNbO_3$ integrated phase modulators[16]. Their half voltage and electrical bandwidth are 6 V and 8 GHz, respectively.

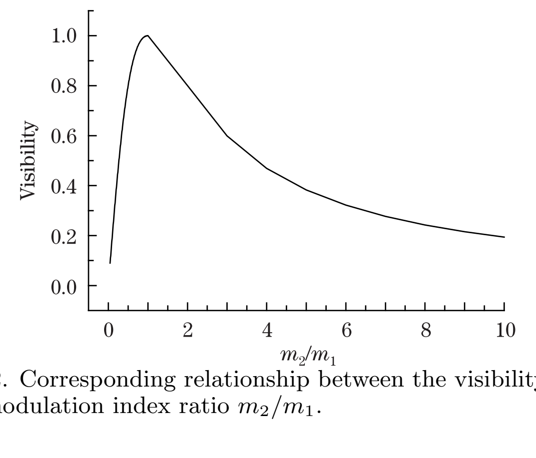

Fig. 2. Corresponding relationship between the visibility and the modulation index ratio m_2/m_1.

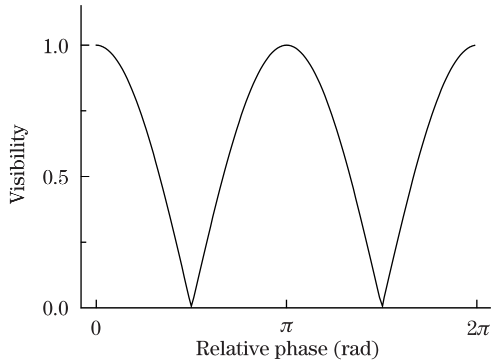

Fig. 3. Visibility changes with the relative phase.

The modulation signal is 50 MHz sine wave. The FP cavity (FPI100) is operated as a scanning FP, i.e., as a spectrum analyzer, with finesse of 150. In the phase control electrical channel for PM2, we insert a phase shifter to introduce a variable phase difference between the driving voltages applied to PM1 and PM2. The voltage characteristic of the phase shifter is linear according to the phase shift. The phase shift changes according to the voltage by 0.089 rad/V. We take 8-V DC and 1.55-V sine wave with 10-kHz frequency from the lock-in amplifier (SR830) to scan and modulate the phase shift, and then demodulate the signal to achieve the derivative, which works as the feedback error signal for phase locking through a proportional-integral-derivative (PID) controller.

Figure 5(a) illustrates the typical laser modulation intensity with scanning the FP cavity. Figure 5(b) illustrates the amplitude of the first sideband change with phase shift through the FP cavity operating in the scanning mode. The intensity is minimum when $\Delta\phi_{\min}$=2.62 rad. From Eq. (5), there is a phase shift of (π–2.62) rad induced from the optical transmission system. In the phase modulation $\phi(t)=\phi_0+m_{\mathrm{p}}\sin(2\times10^8\pi t)$[17], where m_{p} is the phase modulation index, we obtain the error signal as shown in Fig. 5(c) through lock-in amplifier demodulating. When $\Delta\phi>\Delta\phi_{\min}$, the error signal is negative and the phase shift will be cut down; when $\Delta\phi<\Delta\phi_{\min}$, the error signal should be positive and the phase shift will be increased.

In Fig. 6, the top diagram illustrates the phase fluctuation of the first sideband versus time without phase locking. The phase fluctuation is about 0.2 rad within 2 250 s. However, the fluctuation will be significantly decreased after adding the feedback error signal into the

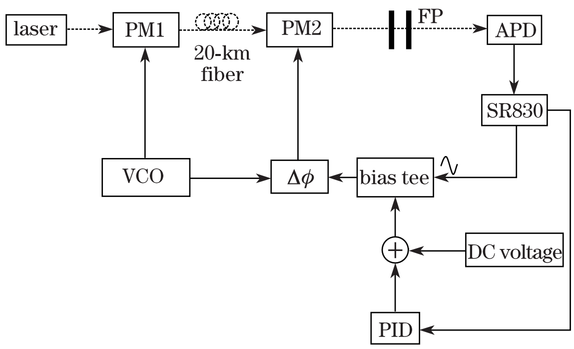

Fig. 4. Experimental setup.

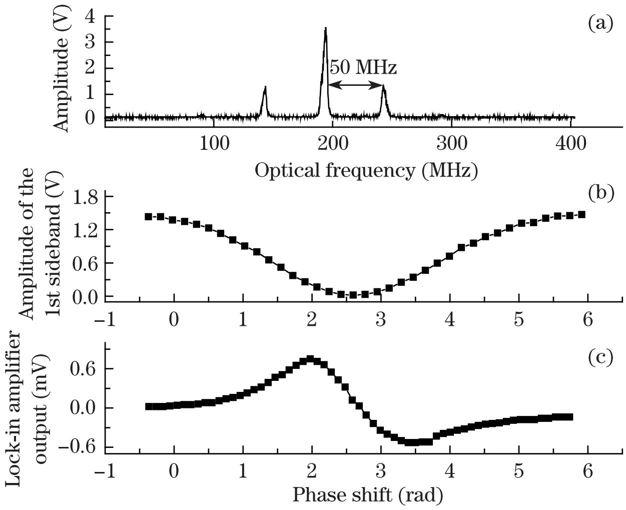

Fig. 5. (a) Typical laser modulation intensity detected with FP scanning; (b) amplitude of the first sideband changes with phase shift; (c) error signal for phase locking from the lock-in amplifier.

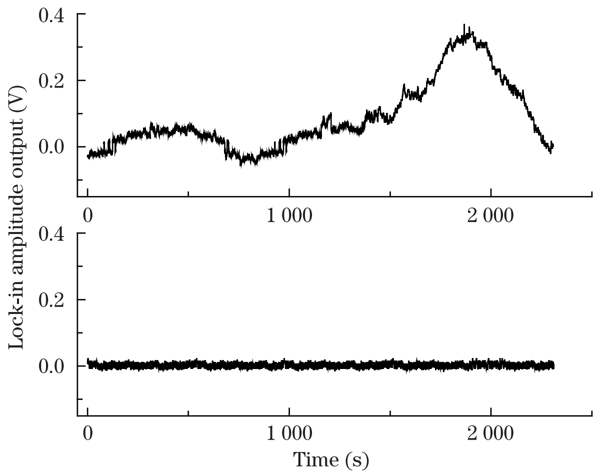

Fig. 6. Phase drift of the first sideband interference versus time without (top) and with (bottom) phase locked.

phase shifter (the bottom trace). With the phase locked, we have achieved a phase drift of only ±0.0016 rad, and the range of visibility fluctuation is less than 2×10^{-4}, which indicates that our activities are very valid.

In conclusion, we report a system for locking the relative phase involving interference produced by a pair of phase modulators. In this letter, the drift of phase is limited within ±0.0016 rad within 2 250 s. It effectively suppresses the phase noise presented in the system. The residual fluctuation is due to the varying of the PM's modulation indices, which are determined by the modulation voltage. In future research, we will control the modulation voltage actively in order to achieve more stability interference.

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