Mode-matching and fringe locking technique in preparation of squeezed states of light

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Abstract: Optical parametric oscillation is the critical part in the preparation of squeezed states of light. The mode-matching and fringe locking technique should be employed to improve the stability of the optical parametric oscillator cavity. How the mode-matching efficiency influence the squeezing degree of the squeezed light and the locking accuracy of the fringe locking technique were analyzed theoretically. Then the fringe locking technique was employed to stabilize the optical parametric oscillator cavity after the mode-matching between the laser mode and the fundamental mode of the cavity. The theoretical and experimental results show that a perfect mode-matching would improve the squeezing degree and the locking accuracy of the fringe locking technique, when the mode-matching is optimized, the length variance of the cavity is 7.35 nm and the locking time is no less than 2 h, which is sufficient for the detection of the squeezed states of light.

Key words: mode-matching; fringe locking technique; optical parametric oscillator cavity; squeezed states of light

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压缩态光场实验中的模式匹配与偏频锁定技术研究

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摘 要: 光学参量过程是产生压缩光的关键环节,为了提高实验中光学参量振荡腔的稳定性,必须将激光与光学参量振荡腔进行模式匹配,并用锁定技术稳定光学参量振荡腔。理论分析了模式匹配效率对压缩度和偏频锁定技术精度的影响。经过模式匹配之后,在实验上实现了光学参量振荡腔的锁定,并对锁定后的光学参量振荡腔进行了稳定性测量。理论与实验结果表明:模式匹配效果越好,压缩光的压缩度和偏频技术的锁定精度越高;在较好的模式匹配条件下,光学参量振荡腔的腔长锁定精度为 7.35 nm,稳定时间可达 2 h 以上,能够满足对压缩态光场的探测需要。

关键词: 模式匹配; 偏频锁定技术; 光学参量振荡腔; 压缩态光场

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0 Introduction

Mode-matching of lasers has been much more important since developments of laser technique. Mode selection is always adopted to meet application requirements for lasers[1]. However, the mode selection would decrease the laser′s power. To obtain the laser beam with high-power, one option is to amplify the laser′s power using an optical resonator. When laser beams with single mode are injected into an optical cavity, the laser mode and the fundamental mode of the cavity should be matched, otherwise higher order modes would be stimulated, which would cut the laser′s power down and destroy the purity of the output mode of the laser.

Optical Parametric Oscillator(OPO) cavity is one of the most effective methods to generate squeezed states of light[2]. However, the OPO cavity may be affected by external environmental disturbance, such as vibration and airflow, which will decrease significantly the squeezing degree, so a locking technique should be employed to stabilize the OPO cavity [3]. In fact, the mode-matching efficiency would affect the error signal of the locking technique and subsequently limit the stability of the squeezed light. In this respect, the mode-matching efficiency should be maximized.

In this paper, The mode-matching and fringe locking technique are employed to achieve the resonance between the OPO cavity and the injected beams[4]. Furthermore, how the mode-matching efficiency influences the squeezing degree and the precision of the fringe locking was analyzed. We also compared the transmission signal with and without mode-matching. Then the OPO cavity was stabilized using the fringe locking technique with a prefect mode-matching.

1 Theoretical analysis

1.1 Relation between the mode- matching and the squeezing degree

The structure of the OPO cavity is shown in Fig.1. a_{in} is the injected pump light, and b_{in} is the input fundamental beam. The pump light and the fundamental beam are injected into the OPO cavity through the input mirror M_1, the pump light passes through the crystal twice, and the infrared fundamental light is on resonance with the cavity. According to theory, the output quadrature noise of the squeezed light for an OPO cavity are calculated as follows[5]

$$V^{\pm}(\Omega)=1\mu\eta_{esc}\eta_{det}\eta_{hom}\frac{4\sqrt{P/P_{th}}}{(\Omega/\gamma)^2+(1\pm\sqrt{P/P_{th}})^2} \qquad (1)$$

Where V^+ and V^- are quadrature amplitude noise and quadrature phase noise respectively. $\eta_{esc}=T/(T+L)$ represents escape efficiency of the OPO cavity, η_{det} is quantum efficiency of photodiode, and η_{hom} describes matching efficiency of balanced homodyne detection, Ω is measured frequency, $\gamma=c(T+L)/(2d)$ is decay factor, T is transmissivity of the output mirror, L represents the intra-cavity losses of the OPO cavity, P_{th} is pump threshold, and P is pump power.

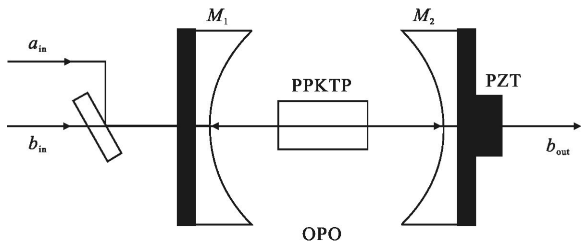


Fig.1 Optical parametric oscillation cavity

The power transmissivity of the outcoupling mirror is T in the condition of perfect mode matching. However, an inefficiency mode matching will decrease significantly the transmitted power, then the power transmissivity would be changed to εT, here ε is the mode-matching efficiency.

The effects of mode matching on squeezing (curve I) and anti-squeezing (curve II) are shown in Fig.2. To increase the observable squeezing, the mode-matching efficiency has to be optimized in realistic experiment, and more than −8 dB degree of squeezing could be derived when the mode-matching efficiency is increased to 1.

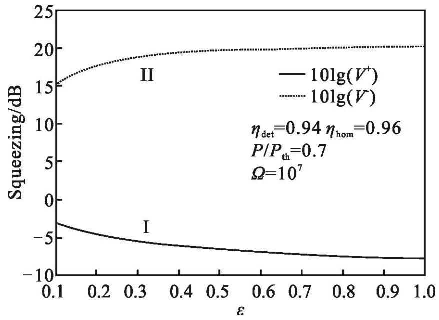


Fig.2 Squeezing level varying with the mode-matching efficiency

1.2 Relation between the mode-matching and the fringe locking technique

When a light beam is on resonance with the cavity, frequency of the beam can be written as $v=q\dfrac{c}{2d}$, where q is a positive integer, d represents the length of the OPO cavity. The transmission signal is given by

$$P_t=\frac{P_0}{1+F\sin^2\dfrac{\varphi}{2}} \tag{2}$$

Where P_0 is the input power of the signal light, $\varphi=\dfrac{2\pi}{\lambda}\cdot 2d$ is the phase, $f=\dfrac{4\sqrt[4]{R_1R_2}}{1-\sqrt{R_1R_2}}$ describes the finesse of the OPO cavity, R_1, R_2 correspond to the reflectivity of input mirror and output mirror respectively.

The transmission signal of the OPO cavity is presented in Fig.3. There is an one-to-one correspondence between the transmission power and the cavity′s length on a rising edge (or falling edge). If we were

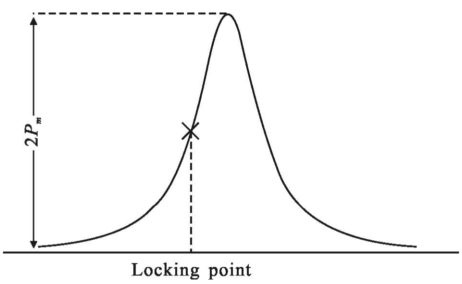


Fig.3 Theory of the fringe-locking technique

to operate just to one side of the resonance, but near enough that some light gets transmitted, then a small change in the laser frequency would produce a proportional change in the transmitted power. We could then measure the transmitted power of the light and feed this signal back to the OPO cavity to hold this power constant, this is the principle of the fringe locking technique.

The highest accuracy would be achieved when the locking point is tuned to the maximum slope of the transmission signal[6]. In a real experiment, the OPO cavity is tuned to the high slope region near the half height on the transmission signal, as depicted in Fig.3, since the maximum slope of the transmission signal is not easy to find. P_m is the power of the output beam at locking point. The error signal of the fringe locking technique can be expressed as $e=P_m-P_t$, it illustrates that the error signal shows the opposite trend with the transmission signal. When the transmission power of the OPO cavity is stabilized to half the maximum transmission signal, the error signal is described in Fig.4. Curve Ⅰ is the error signal with the cavity line width of 6 MHz. The control range of fringe locking technique is the rising edge (or falling edge) of the transmission signal, which means a high-rangeability would be achieved when the line width of the cavity is wide. However, a wide line width of the cavity would decrease obviously the precision of locking.

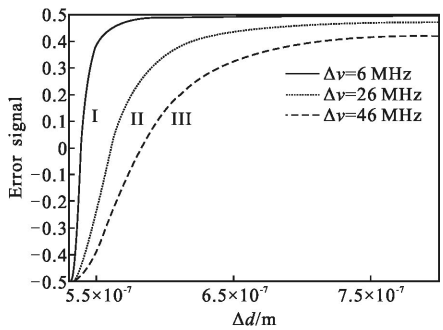


Fig.4 Error signal of the fringe-locking technique

Suppose that the fundamental mode of the signal is perfectly matched to the eigen mode of the OPO cavity, the power reflectivity and transmissivity of the OPO cavity are calculated as follows[7]

$$R_A=\frac{P_{ref}}{P_{in}}=\left(\frac{L_A\sqrt[4]{R_1R_2}}{1-\sqrt{R_1R_2}}\right)^2 \tag{3}$$

$$T_A=\frac{P_{trans}}{P_{in}}=\left(\frac{1-\sqrt{R_1R_2}-L_A}{1-\sqrt{R_1R_2}}\right)^2 \tag{4}$$

When the input signal beam resonates in the OPO cavity imperfectly, the mode-matching efficiency ε should be considered, and the power reflectivity and transmissivity become[8]

$$R_A=\frac{R_A'-(1-\varepsilon)}{\varepsilon} \tag{5}$$

$$T_A=\frac{A_A'}{\varepsilon} \tag{6}$$

So the losses of the OPO cavity could be expressed as

$$L_A=\frac{\sqrt{R_A'}\,(1-\sqrt{R_1R_2})}{\sqrt[4]{R_1R_2}} \tag{7}$$

Figure 5 clearly shows the losses of the OPO cavity varying with the mode-matching efficiency. The curve is simulated in the case of R_A=0.3. The losses would decrease linearly with the increase of the mode-matching efficiency. As a result, the line width of the OPO cavity would be much narrower with the decrease of the losses. When the mode-matching efficiency increases to 1, the loss is estimated to be 0.142% , which is caused by the absorption of coatings on the mirrors and the PPKTP crystal.

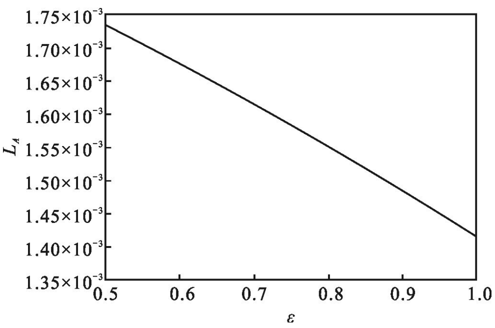


Fig.5 Loss of the OPO cavity varying with the mode-matching efficiency

The error signal of the fringe locking technique depends on the line width of the OPO cavity, and the locking precision would vary with the mode-matching efficiency. When the fringe locking technique is adopted to stabilize the OPO cavity, the mode-matching efficiency would affect the error signal obviously, as shown in Fig.4. Curves Ⅱ and Ⅲ are error signals corresponding to the cavity linewidth of 26 MHz and 46 MHz, respectively. Note that an error signal with quite large slope can be obtained when the mode-matching efficiency is perfect, which means a small change of the cavity length will produce an significant error signal, and result in a high locking accuracy. Therefore, a perfect mode matching between the signal beam and the eigenmode of the cavity is beneficial for improving the locking accuracy.

2 Experiment

In our experiment, the OPO cavity is a standing-wave cavity with the length of 60 mm, the cavity is formed by two mirrors and the nonlinear crystal in between. The two mirrors have the same radius of 30 mm. The input coupler mirror (M_1) has 99.5% and 70% power reflectivity for light of 1 064 nm and 532 nm, respectively. The length control of the cavity is accomplished by piezodriven outcoupling mirror (M_2), which has a transmission of 13.5% for the fundamental light and high reflectivity for the pump light.

The mode-matching system of the OPO cavity is presented in Fig.6. Here, w_0 and w_2 are the waist size radius of the laser light and the eigen mode of the

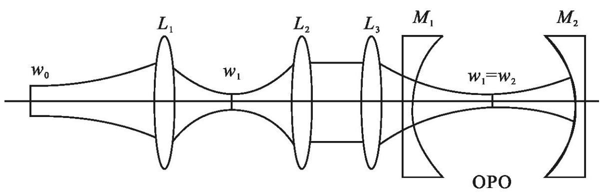
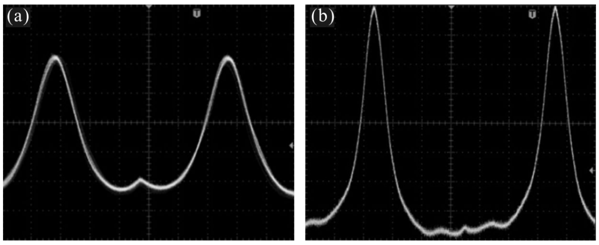


Fig.6 Mode matching of the OPO cavity

OPO cavity, respectively. The waist size radius of the laser is measured to be w_0=0.5 mm, which is located 120 mm outside the laser. The first lens(L_1) with focal length of 508 mm is used to transform the size of the beam waist into the desired waist size. Two lenses (L_2 and L_3) with the same focal length of 100 mm are employed to adjust the waist position appropriately without changing its size. The lens L_2 is placed a focal length away from the beam waist to collimate the beam, and L_3 is used to refocus the beam into the

OPO cavity. So the waist size depends directly on the lens L_1 and the mode-matching efficiency is improved by adjusting the focusing lens L_3[9].

Figure 7 (a) and (b) describe the transmission signal of the OPO cavity in the case of imperfect and perfect mode matching respectively. It clearly shows that the line width of the transmitted light is much narrower with the perfect mode-matching, the transmitted light has a clean spatial mode and higher finesse compared to that without mode matching.



(a) Transmission signal of the OPO cavity without mode-matching (b) Transmission signal of the OPO cavity with mode-matching

Fig.7 Transmission signal when the OPO cavity is mode-matching and out of mode-matching

In fact, when the laser mode is not matched to the resonance frequency of the cavity, the high-order modes would resonate in the cavity, and received by detector behind the OPO cavity. The detection of high-order modes would introduce background noise, and reduce Signal and Noise Ratio(SNR), as a result, the locking precision would be decreased.

The setup for fringe locking technique is shown in Fig.8. The laser is an all-solid-state, intra-cavity, frequency doubled, continuous-wave ring, Nd:YAG laser capable of providing 420 mW of 1 064 nm light and 880 mW of 532 nm light, respectively. The detectors used here are a pair of Epitaxx ETX−500 photodiodes with the quantum efficiency of 94%. The fundamental light from the laser is split into two beams by a polarizing beam splitter (PBS). One of the beams, the signal light, is injected into the OPO cavity, the output light of the cavity is detected by detector D_1, and then the current is sent into a port of the proportional and integrate (P−I) controller. The other beam, the reference light, is detected by detector D_2, and is sent into the B port. The error signal is generated from the voltage difference of the two ports. The error signal is then integrated, further amplified, and fed back to the piezoelectric transducer (PZT) on the OPO cavity. When the cavity is on resonance, the difference current is zero, and there would be no control signal fed back to the PZT. However, once the length of the OPO cavity is changed, the difference current would not be zero anymore, and a control signal would be generated to keep the cavity on resonance. In fact, the locking point on the transmission signal at which the cavity is locked to is determined by the power of the reference light relative to the peak power transmitted by the OPO cavity. The reference light also provides some suppression of any amplitude noise in excess of shot noise.

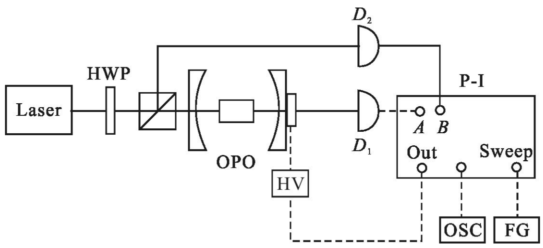
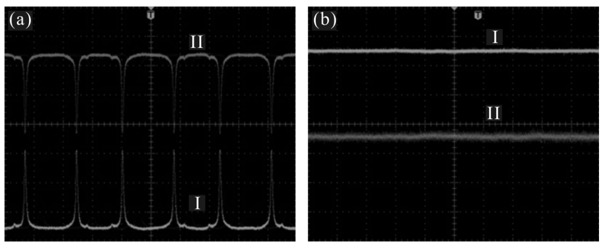


Fig.8 Schematic of the fringe-locking technique

When the OPO cavity is locked on resonance, the transmitted signal is shown in Fig.9. Curves Ⅰ and Ⅱ are transmission signal and error signal,



(a) Transmission signal and error signal of the OPO cavity without locking (b) Transmission signal and error signal with the fringe-locking technique

Fig.9 Transmission signal and error signal when the system is locking and out of locking

respectively. The peak value of the transmission signal is 130 mVpp. When locked on resonance, the transmitted light is estimated to be 70 mVpp and the locking time is no less than 2 h, as depicted in Fig.10.

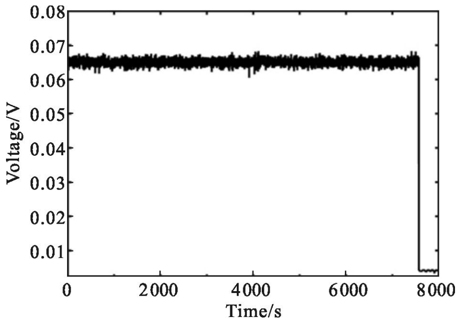


Fig.10 Ttransmission power of the OPO cavity

The relative variation of the transmission power is

$$\frac{0.0681-0.0634}{0.066}=7.14\% \tag{8}$$

When the transmission power drops by 50%, the frequency variation is the line width of the cavity, from Eq.(8), the frequency variation is

$$\Delta v=\frac{7.14\%}{50\%}\cdot 242=34.56\ \mathrm{MHz} \tag{9}$$

Relationships between variation of line width and variation of cavity length is[10]

$$\Delta v/v=\Delta d/d \tag{10}$$

Thus the length variance of the cavity is estimated as

$$\Delta d=\frac{\Delta v}{v}\cdot d=\frac{34.56\times10^{6}}{2.82\times10^{14}}\cdot 0.06=7.35\times10^{-9}\ \mathrm{nm} \tag{11}$$

3 Conclusion

We discussed how the mode-matching efficiency affects the quadrature noise of the squeezed light and the locking accuracy of the fringe locking. And the fringe locking technique was employed to lock the cavity length experimentally. The theoretical and experimental results show that the high mode matching efficiency is beneficial to obtain high degree of squeezing and improve the locking accuracy. This paper is quite conducive to the generation of squeezed states of light of high quality.

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