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Noise Suppression of a Single Frequency Fiber Laser *

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We present an experimental demonstration of fiber laser noise suppression by the mode cleaner. The intensity noise of a single frequency fiber laser is suppressed near the shot noise limit after a sideband frequency of 3 MHz. Two series mode cleaners are used to improve the noise suppression. The noise reduction is over 27 dB at 3 MHz.

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Narrow-linewidth and stable-operation fiber lasers[1,2] have been developed very recently. They have become an important kind of laser because of their potential applications in optical sensors, optical communications, precise measurement and quantum information. However, the intensity noise of normal single frequency fiber lasers is very large and severely limits their use in quantum information applications such as entanglement generation,[3] quantum teleportation,[4] quantum computation[5] and quantum secret sharing.[6]

Fiber laser intensity noise includes beating noise, environmental perturbations, thermal noise and fluctuations in pump power.[7] Various methods for partially reducing output noise have been proposed. High frequency beating noise from fiber ring lasers can be reduced by intracavity spectral filtering.[8,9] Relaxation oscillation noise can be suppressed by integrating a negative feedback circuit.[10,11] In 2009, we suppressed the intensity noise of a fiber laser significantly by opto-electronic feedback at 6 MHz,[12] however the noise suppression bandwidth was narrow and was limited by the bandwidth of the opto-electronic feedback loop.

A mode cleaner[13,14] was proposed to filter the laser beam both spatially and temporally for gravitational-wave detection. Willke *et al.*[15] used a mode cleaner to suppress intensity noise of a 10-W laser-diode-pumped Nd:YAG master oscillator power amplifier (MOPA), and the intensity noise reached the shot noise limit after 10 MHz. In 2005, Hald and Ruseva[16] used a Fabry–Perot cavity as a mode cleaner to suppress the phase noise of an amplified diode laser. Recently, a mode cleaner was used successfully to suppress the intensity noise of a high-power photodiode array to the shot noise limit.[17]

In this Letter, we report the experimental intensity noise suppression of a fiber laser with mode cleaners. Using two series mode cleaners, the intensity noise is suppressed near to the shot noise limit after 3 MHz, the noise reduction over 27 dB is obtained.

In general, the output of a single frequency fiber laser always has a great deal of excessive intensity noise, especially at lower sideband frequencies. For example, the intensity noise of a fiber laser is 27 dB above the shot noise limit (SNL) below 3 MHz in Fig. 1.

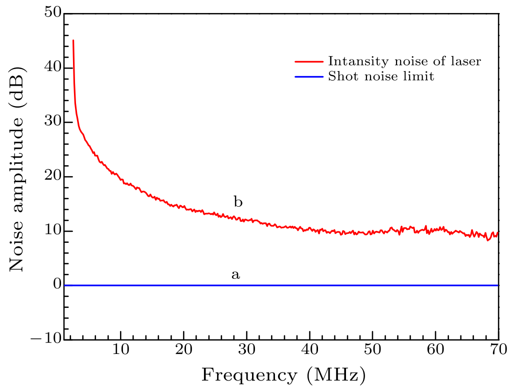

Fig. 1. The intensity noise of a fiber laser: (a) SNL, (b) intensity noise.

A mode cleaner cavity consists of symmetric input and output couplings, as shown in Fig. 2. M1 and M2 are the input and output couplings, respectively. The equation of motion for a two-ended cavity with one input and one output coupler can be expressed as[18]

$$\begin{aligned}\dot{\hat{a}}(t) = & -\gamma\hat{a}(t) + \sqrt{2\gamma_{\rm ic}}\hat{a}_{\rm ic}(t) + \sqrt{2\gamma_{\rm oc}}\hat{a}_{\rm oc}(t) \\ & + \sqrt{2\gamma_l}\hat{a}_l(t), \end{aligned} \quad (1)$$

where $\hat{a}$, $\hat{a}_{\rm ic}$ and $\hat{a}_{\rm oc}$ is the intracavity field, input field and input vacuum field from the output coupling, respectively; $\hat{a}_l$ is the vacuum noise term corresponding to intracavity loss; $\gamma_{\rm ic}$, $\gamma_{\rm oc}$andγ_l are the resonator decay rates corresponding to the input cou-

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pler, output coupler and intracavity loss, respectively; $\gamma{=}\gamma_{\rm ic}+\gamma_{\rm oc}+\gamma_l$ is the total decay rate.

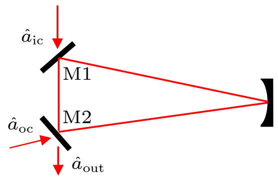

Fig. 2. Scheme of the present mode cleaner.

We have the steady-state equation at $\dot{\hat{a}}\,(t){=}0$,

$$0=-\gamma\alpha+\sqrt{2\gamma_{\rm ic}}\alpha_{\rm ic}, \tag{2}$$

where $\alpha=\langle\hat{a}\rangle$, $\alpha_{\rm ic}=\langle\hat{a}_{\rm ic}\rangle$; $\langle\hat{a}\rangle$ and $\langle\hat{a}_{\rm ic}\rangle$ are the mean value of fields $\hat{a}$ and $\hat{a}_{\rm ic}$, respectively; $\langle\hat{a}_{\rm oc}\rangle{=}0$, and $\langle\hat{a}_l\rangle{=}0$.

Then, we obtain the steady-state solution

$$\alpha=\sqrt{2\gamma_{\rm ic}}\alpha_{\rm ic}/\gamma. \tag{3}$$

Then, the output field from the mode cleaner is

$$\alpha_{\rm out}=\sqrt{2\gamma_{\rm oc}}\alpha=2\sqrt{\gamma_{\rm ic}\gamma_{\rm oc}}\alpha_{\rm ic}/\gamma. \tag{4}$$

For simplification, the operators in Eq. (1) can be expanded in terms of their coherent amplitude and quantum noise operator, $\hat{a}_i=\langle a_i\rangle+\delta\hat{a}_i$ with $\langle\delta\hat{\alpha}_i\rangle=0$, and the second-order terms in the quantum noise operators are neglected. Then, Eq. (1) can be rewritten as

$$\begin{aligned}\delta\dot{\hat{a}}\,(t)=&-\gamma\delta\hat{a}\,(t)+\sqrt{2\gamma_{\rm ic}}\delta\hat{a}_{\rm ic}\,(t)+\sqrt{2\gamma_{\rm oc}}\delta\hat{a}_{\rm oc}\,(t)\\&+\sqrt{2\gamma_l}\delta\hat{a}_l\,(t)\,.\end{aligned} \tag{5}$$

It can be easily solved by taking the Fourier transform into the frequency domain. We can obtain the amplitude and phase quadratures of the field with the definition $\hat{X}_i^+=(\hat{a}_i+\hat{a}_i^\dagger)$ and $\hat{X}_i^-=(\hat{a}_i-\hat{a}_i^\dagger)/i$.

$$\begin{aligned}\delta X^{\pm}(\omega)=&\big[\sqrt{2\gamma_{\rm ic}}\delta X_{\rm ic}^{\pm}(\omega)+\sqrt{2\gamma_{\rm oc}}\delta X_{\rm oc}^{\pm}(\omega)\\&+\sqrt{2\gamma_l}\delta X_l^{\pm}(\omega)\big]/(\gamma-i\omega).\end{aligned} \tag{6}$$

The output field from the resonator can be directly obtained by using the input-output formalism:[18] $X_{\rm out}^{\pm}=\sqrt{2\gamma_{\rm oc}}X^{\pm}-X_{\rm oc}^{\pm}$.

The fluctuations of the output field can be expressed as

$$\begin{aligned}\delta X_{\rm out}^{\pm}(\omega)=&\big[\sqrt{4\gamma_{\rm ic}\gamma_{\rm oc}}\delta X_{\rm ic}^{\pm}(\omega)+(2\gamma_{\rm oc}-1)\delta X_{\rm oc}^{\pm}(\omega)\\&+\sqrt{4\gamma_l\gamma_{\rm oc}}\delta X_l^{\pm}(\omega)\big]/(\gamma-i\omega).\end{aligned} \tag{7}$$

The intensity noise spectrum of the output field is

$$V_{\rm out}(\omega)=<\delta {X^+}_{\rm out}{}^2(\omega)>=1+\frac{V_{\rm in}(\nu)-1}{1+(\frac{\nu}{\delta\nu})^2}, \tag{8}$$

where $\nu=\omega/2\pi$ is the sideband frequency; $\delta\nu=\frac{\gamma c}{2\pi l}$ is the bandwidth of the mode cleaner (c is the velocity of light in vacuum, l is the cavity length); $V_{\rm in}(\nu)$ is the initial input noise, $V_{\rm in}(\omega)=<\delta {X^+}_{\rm in}{}^2(\omega)>$. It is obvious that noise suppression ability is dependent on the bandwidth of the mode cleaner. For a fixed cavity length, the ability will be high if the total decay rate γ is low, that is, we have a mode cleaner cavity with high finesse.

The transmission efficiency of the mode cleaner is

$$\eta=\left(\frac{\alpha_{\rm out}}{\alpha_{\rm ic}}\right)^2=\frac{4\gamma_{\rm ic}\gamma_{\rm oc}}{\gamma^2}. \tag{9}$$

As mentioned above, a mode cleaner is a cavity with symmetric input and output coupling, so $\gamma_{\rm ic}=\gamma_{\rm oc}$. The transmission efficiency of a mode cleaner can be written as

$$\eta=\frac{4\gamma_{\rm ic}\gamma_{\rm oc}}{\gamma^2}=\left(1-\frac{\gamma_l}{\gamma}\right)^2. \tag{10}$$

From Eq. (10), we can see that when $\gamma_l<<\gamma$, the transmission efficiency can reach 1.

It is difficult to obtain a very high finesse cavity with high transmission efficiency because of unavoidable cavity losses γ_l. If we need suppress noise more, we can use more than one mode cleaner worked in series, and one's output field is connected to the input of another. The output intensity noise spectrum of two mode cleaners can be expressed as

$$V_{\rm out}(\nu)=1+\frac{V_{\rm in}(\nu)-1}{\Big(1+(\frac{\nu}{\delta\nu_1})^2\Big)\Big(1+(\frac{\nu}{\delta\nu_2})^2\Big)}, \tag{11}$$

where $\delta\nu_1$ and $\delta\nu_2$ are the bandwidths of the first mode cleaner and the second mode cleaner, respectively.

The transmission efficiency of the system is

$$\eta=\eta_1\cdot\eta_2, \tag{12}$$

where η_1 and η_2 are the transmission efficiencies of the first mode cleaner and the second mode cleaner, respectively.

In general, by using N mode cleaners in series to suppress laser noise, the intensity noise spectrum of the output field can be calculated by

$$V_{\rm out}(\nu)=1+\frac{V_{\rm in}(\nu)-1}{\prod\limits_{i=1}^{N}\Big(1+(\frac{\nu}{\delta\nu_i})^2\Big)}, \tag{13}$$

and the transmission efficiency of system is

$$\eta=\prod_{i=1}^{N}\eta_i. \tag{14}$$

Here N is the number of mode cleaners, $\delta\nu_i$ is the bandwidth of the ith mode cleaner and η_i is the transmission efficiency of the ith mode cleaner.

Figure 3 schematically shows the experimental setup. The laser system consists of two parts: a single frequency fiber laser source with 20 mW output at the wavelength 1080 nm and a fiber laser amplifier with 2 W output. We suppress the laser noise by two mode cleaners, MC1 and MC2, which construct a ring cavity with two flat mirrors (input and output coupling) and one concave mirror of 1 m curvature radius. After passing through the mode cleaners, the noise can be suppressed significantly. The laser is locked to MC1 to stabilize the frequency of the laser, and MC2 is locked to the laser.

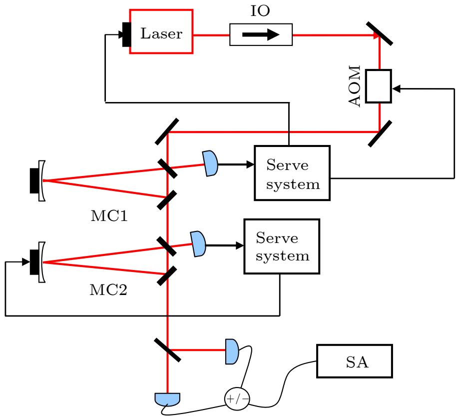

Fig. 3. The experimental setup of intensity noise suppression of the fiber laser with the mode cleaner. Laser: Fiber laser; AOM: audio-optical modulator; MC1 and MC2: mode cleaner; SA: spectrum analyzer.

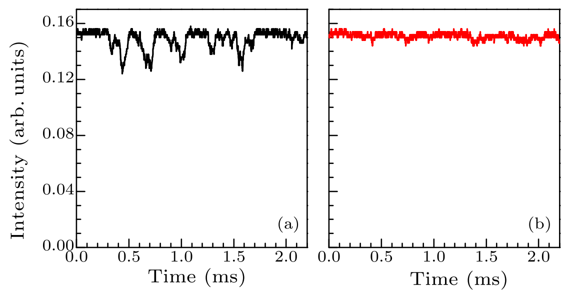

Fig. 4. Fluctuation intensity of the laser after locking it to MC1: (a) without AOM, (b) with AOM.

If the fineness of the cavity is high, the error signal will be sharp. The response of the feedback loop and the laser system must be rapid enough to lock the laser frequency on the mode cleaner 1. Otherwise, it is difficult to lock the laser on the cavity steadily. In the experiment, we use an audio-optics modulator (AOM) as a fast response control.[19] The transmissions from MC1 without and with the AOM are shown in Fig. 4(a) and 4(b). We can see obviously that Fig. 4(b) is much better than Fig. 4(a). The fast response control is necessary in the locking system. Furthermore, the laser is steadily locked to MC1.

The fineness of MC1 is 1000; the cavity length is 42 cm and the bandwidth is 0.7 MHz. Transmission loss of the input coupler and the output coupler is 0.38%; the intracavity loss is 0.24%; the total loss is 1%, and the transmission efficiency of MC1 is 58%. The noise spectrum after mode cleaner MC1 is shown in Fig. 5, green (dashed) line is the initial noise of the laser, black (dotted) and blue (solid) lines are the experimental and theoretical results as Eq. (8) after noise suppression, respectively; the red (dot-dot-dashed) line is the SNL. As shown in Fig. 4 in comparison with the initial noise of the laser, the laser noise after the mode cleaner is reduced by about 20 dB and the noises reach the SNL after 7 MHz.

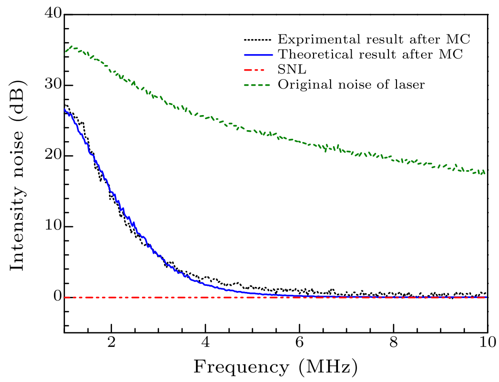

Fig. 5. The output noise through MC1.

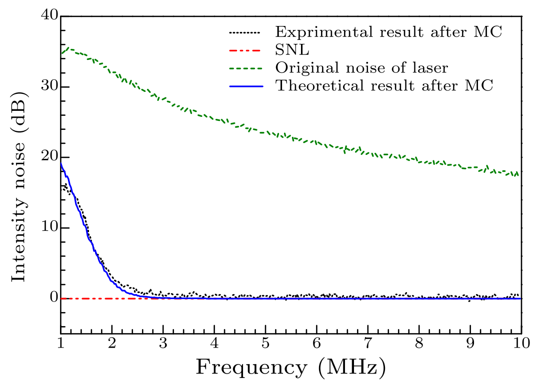

Fig. 6. The output noise through MC2.

The fineness of MC2 is 680; the cavity length is 50 cm and the bandwidth is about 1 MHz. Transmission loss of the input coupler and the output coupler is 0.38%; the intracavity loss is 0.24%; the total loss is 1%; the transmission efficiency of MC2 also is 58% and the total transmission efficiency of the system is 34%. After mode cleaner MC2, the noise is suppressed further. The noise spectrum is shown in Fig. 6, the green (dashed) line is also the initial noise of the laser, the black (dotted) and blue (solid) lines are the experimental and theoretical results as Eq. (11) after noise suppression, respectively; the red (dash dot dot) line is the SNL. Compared with the initial noise of the laser, the noise of the laser after two mode cleaners is reduced by over 27 dB, as shown in Fig. 5, and the noises reach the SNL after 3 MHz.

The degree of noise suppression depends on the bandwidth of the mode cleaner. To decrease the bandwidth, there are two methods: increase the cavity length and decrease the total loss of the cavity [Eq. (8)]. Increasing the cavity length will make machine stability of the system poor and this method is not practicable. The cavity losses are due to the transmission of two flat mirrors (input and output mirror), the concave mirror and other intracavities. In the experiment, only decreasing the transmission of the two flat mirrors can reduce the bandwidth, whereas the transmission efficiency is also decreased [Eq. (9)]. To decrease the bandwidth and to improve the transmission efficiency simultaneously [Eqs. (8) and (10)], the loss of the concave mirror must be largely decreased to improve the cleanliness of the cavity ($\gamma_{\rm ic} = \gamma_{\rm oc} >> \gamma_l$). Using this method, we can suppress the noise better and make the transmission efficiency above 90%.

In summary, the intensity noise of a fiber laser is successfully suppressed with two series mode cleaners, and the noise of the output laser reaches the SNL after 3 MHz. The frequency of the laser locked to MC1 is also stabilized at the same time. After noise suppression, the fiber laser with low noise can be used in quantum optics, quantum information, for example, to be applied in quantum key distribution,[20] to generate entangled states,[3] which is an important resource for future quantum information technology.

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