Continuous-wave optical enhancement cavity with 30-kW average power

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Optical enhancement cavity (OEC) is a powerful tool for fundamental research and diagnostics. In this paper, the progress of a continuous-wave OEC to realize of megawatt cavity for a novel light source based on a steady-state microbunching (SSMB) mechanism, is reported. After efficiently suppressing all external noise and optimizing the alignment, mode-matching, and polarization matching, stable and long-term locking is achieved with the help of two feedback loops. The modal instability phenomenon caused by the surface thermoelastic deformation is observed. A pair of D-shape mirrors are utilized to remove the high-order modes. Finally, an intra-cavity average power of 30 kW is reached.

Keywords: optical enhancement cavity, continuous-wave laser, modal instability, high power cavity

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1. Introduction

Optical enhancement cavity (OEC) is applied in a wide range of precision optical experiments. OEC working in pulse mode enables the advances in high harmonic generation,[1–3] high X/γ flux production,[4] and polarized positron generation.[5] OEC working in continuous mode also plays an important role in fundamental physics. Gravitational waves can be detected by using a grounded-based gravitational-wave interferometer, *i.e.*, OEC, such as Advanced LIGO[6] and Advanced Virgo.[7] OEC also has the potential to utilize the high-power continuous-wave laser beam to implement a photoneutralizer in a fusion reactor building.[8]

Several megawatts of laser stored in OEC also can act as a powerful phase-locked laser modulator in a novel photon source based on a steady-state microbunching (SSMB) mechanism.[9,10] By replacing the radio frequency cavity with a continuous-wave OEC in an electron storage ring, microbunching forms and maintains a steady-state after going through a radiator every time. As a promising future photon source, SSMB combines the characteristics of both high repetition rate and high peak power, which is expected to meet the need for the kilowatt level EUV source for advanced lithography in the semiconductor industry. Recently, an initial task force has been established among Tsinghua University and several other institutes to promote the study of SSMB and has experimentally demonstrated the SSMB mechanism in the Metrology Light Source Storage Ring.[10] As the key ingredient of SSMB, high-power high-stable continuous-wave OEC is necessary.

In this paper, we report our recent progress in building a continuous-wave OEC, intending to realize of megawatt cavity. The stable lock has been achieved by using two feedback loops, one digital slow loop, and the other analog fast loop. The modal instability induced by thermoelastic deformation is observed. A pair of D-shape mirrors are utilized to remove the high-order modes successfully and a stable intra-cavity average power of 30 kW is reached. Although this OEC is oriented toward SSMB, it is still useful in other fields.

2. Experimental setup

The experimental setup is schematically shown in Fig. 1. The four-mirror bow-tie external cavity,[11] consisting of two planar mirrors, M1 and M2, and two spherical mirrors, M3 and M4, needs to be placed in a high-vacuum vessel to reduce noise and obtain a stable lock. The cavity length is around 3.78 m, corresponding to the free space range (FSR) of 79.3 MHz. M1 which has a reflectivity higher than 99.9% is acting as the coupling mirror. The reflectivity of M2 is more than 99.999%. M3 and M4 have a reflectivity of higher than 99.95%. A pair of D-shape mirrors are used to remove the high-order modes[12] in horizontal and vertical directions caused by the surface distortions of cavity mirrors under high power. A continuous-wave seeder with low phase noise, Koheras Y10 from NKT Photonics operating at 1064 nm, is used as the injection of the amplifier Azurlight whose maximal output reaches around 100 W. The EOM modulates the phase of the incident beam at the frequency of 8.2 MHz. A telescope consisting of two lenses is mainly used for mode matching between the input beam and the cavity mode. A half-wave plate and a quarter wave-plate are utilized for polarization matching

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to improve the coupling. Two mirrors provide good alignment to reduce the coupling of high-order modes. The cavity reflected laser is directed onto a beamsplitter. Half of the beam is measured by the photodiode PD2 used in the Pound–Drever–Hall (PDH) technique.[13,14] Its output is firstly amplified at the modulation frequency of 8.2 MHz, then demodulated to the correct phase which produces the error signal for the feedback. The error signal is separately fed into two feedback loops. In the analog fast loop, the AOM working at a frequency modulation mode directly shifts the laser central frequency to compensate for the high-frequency noise. In the digital slow loop, the regulating voltage through a proportional–integral–differential (PID) regulator is applied on a PZT to compensate for the low-frequency noise. The transmission intensity monitored by the photodiode PD1 is used as the trigger for the lock. The two loops guarantee a stable and good lock and keep the cavity on resonance all the time. The other half of the intensity goes through PD3 for the coupling measurement. The photodiode PD4 is used to measure the intra-cavity power.

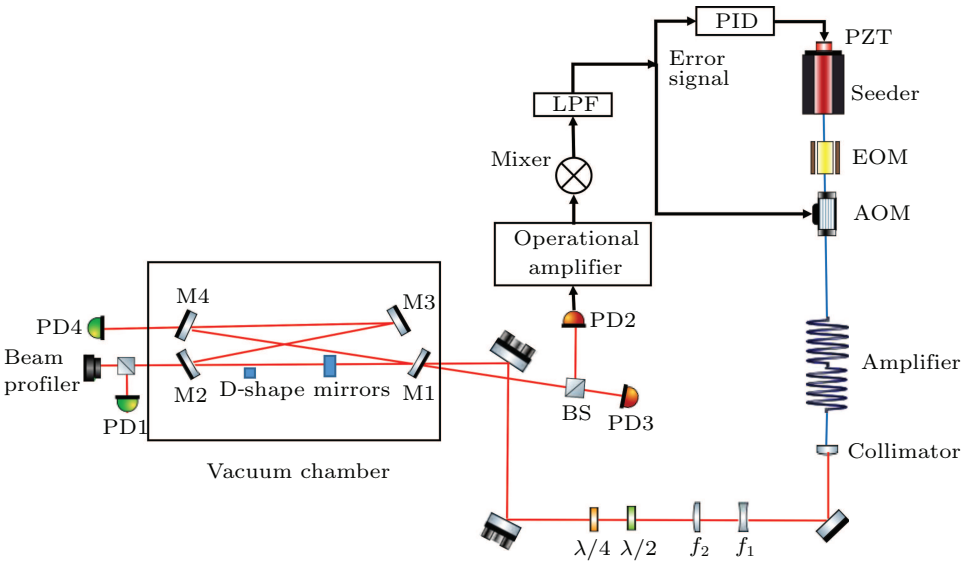


Fig. 1. Experiment setup. M1, M2, M3, and M4 are OEC mirrors. PD1, PD2, PD3, and PD4 are photodiodes. EOM is an electro–optic modulator. AOM is an acouso–optic modulator. $\lambda/2$ is a half-wave plate. $\lambda/4$ is a quarter wave-plate. BS is a beam splitter. LPF is a low-pass filter. PZT is a piezo electric transducer.

3. Results and discussion

In the experiment, the first step to lock the laser to the cavity is to find the resonance between the incident laser and the cavity modes. A periodic triangle scanning signal applied on the PZT of the seeder shown at the top of Fig. 2 is used to scan the cavity length for tuning the optical frequency of the injection laser. After the careful optimization of the two lens positions and good alignment adjustments of two alignment mirrors, the intensities of higher-order modes are suppressed and the intensity of the fundamental mode improves. Cavity transmission monitored by PD1 is shown in the middle of Fig. 2. One can see that the fundamental mode TEM_{00} resonates strongly and dominates the resonance during the scanning.

Cavity coupling evaluates the mode-matching and alignment, defined as follows:

$$C = 1 - \frac{P_{\mathrm{ref}}}{P_{\mathrm{in}}}, \tag{1}$$

where P_{ref} and P_{in} are the cavity reflected power and the cavity injected power, respectively. To get high transmission and high coupling, the cavity should work in a low-noise environment and one needs to efficiently suppress all external noises, such as the noise from the air conditioner, the airflow, and so on. The coupling is still limited to the parameters of cavity mirrors. Through the above efforts, OEC is optimized to the most efficient coherent stack and the coupling 45% as shown at the bottom of Fig. 2 is achieved.

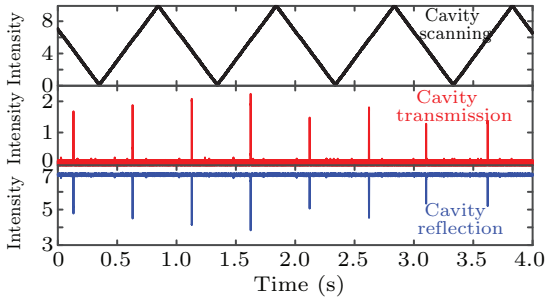


Fig. 2. Experimental measurement. When the triangle scanning signal (top black curve) is applied on the PZT of the laser, the optical frequency is adjusted. The intensity of cavity transmission (middle red curve) and cavity reflection (bottom blue curve) are obtained.

To keep the cavity at resonance, an error signal that is proportional to the difference between cavity resonance frequency and the laser frequency is required. Many techniques to generate such error signals have been reported.[13–17] We adopt the most commonly used method PDH technique.[13,14]

The error signal shown in Fig. 3 is linear in the detuning near the resonance and crosses zero at the maximum of the transmission peak. Two feedback loops are utilized to compensate for all sources of noise.

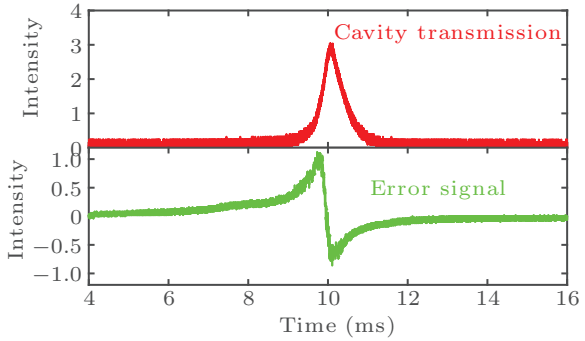


Fig. 3. Experimental measurements of cavity transmission (top red curve) and error signal (bottom green curve).

A stable lock shown in Fig. 4 is achieved with the assistance of the two feedback loops. The black curve is the voltage signal applied to the PZT of the laser cavity to adjust the frequency. The red curve is the cavity transmission. The transmission signal maintains the maximum after cavity locking. The blue curve is the cavity reflection and the coupling is more than 40%.

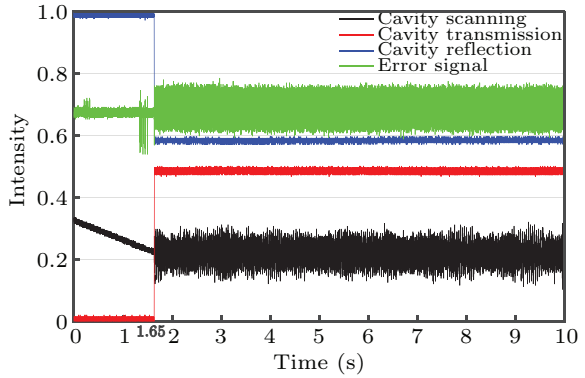


Fig. 4. Experimental measurements of cavity scanning applied on PZT (black curve), cavity transmission (red curve), cavity reflection (blue curve), and error signal (green curve) evolution in 10 s. Lock starts at around 1.65 s.

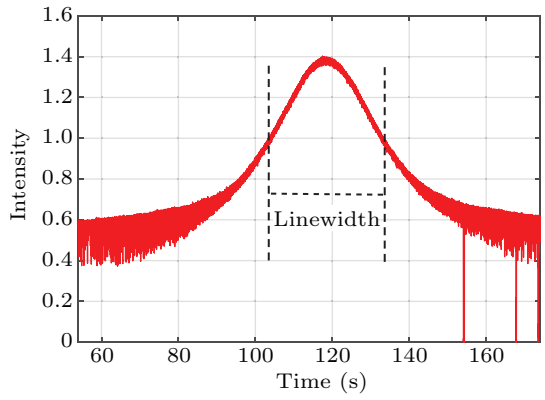


Fig. 5. Cavity finesse measurement. From the Airy function of cavity transmission, one obtains the FSR of 78.793 MHz and the linewidth of 12.3 kHz.

Cavity finesse is measured by using the EOM-based frequency modulation method.[18] The idea is to determine the FSR and the linewidth of the cavity and divide one by the other, as in the definition of finesse. By adding the other EOM after the seeder with frequency modulation of Ω close to FSR, one can reconstruct the Airy function. This makes it possible to precisely measure FSR and the linewidth. Finally, the curve shown in Fig. 5 is obtained, which gives the Airy function of the cavity as detected by the transmission photodiode PD1. This method yields an FSR of 78.793 MHz and a linewidth of 12.3 kHz. The finesse is around 6402.

After increasing the injection power gradually, the modal instability phenomenon[12,19,20] comes out due to the surface distortion of cavity mirrors under high power. The intra-cavity power is coupled from the fundamental mode to the degenerated high-order modes. The higher-order mode $\mathrm{TEM}_{15,10}$ shown in Fig. 6 resonates with the fundamental mode at the same time. The eigenmodes of the cavity vary with the thermoelastic distortions of cavity mirrors, resulting in the accidental frequency degeneracy and power coupling between $\mathrm{TEM}_{0,0}$ and higher-order degenerated modes. In the experiments, the degenerated high-order mode appears under the power of several kilowatts and changes along with the increasing intra-cavity power. The modal instability phenomenon appears at a much lower power in our experiment than that in Ref. [12]. The most likely reason is the higher absorption in the mirror coatings or dust contaminations on the mirror surfaces. In consideration of the cavity to be used for SSMB, the fundamental mode is designed to modulate the electrons to form microbunching. It is necessary to remove the high-order modes. The D-shape mirrors in vertical and horizontal directions are installed between the two planar mirrors[12] shown in Fig. 7. By using a pair of D-shape mirrors that reflect off the high-order modes and destroy the boundary conditions, the modal instability is suppressed successfully and only the $\mathrm{TEM}_{0,0}$ fundamental mode resonates.

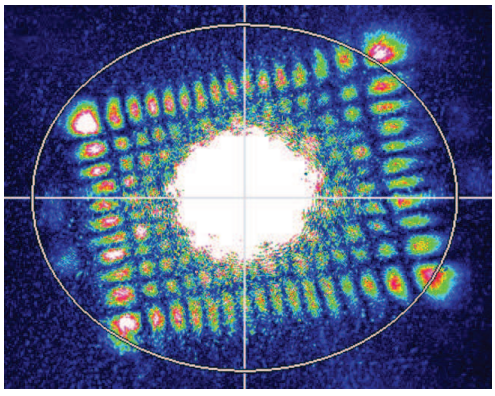


Fig. 6. Higher-order mode $\mathrm{TEM}_{15,10}$ resonates with the fundamental mode simultaneously.

The transmission coefficient of cavity mirror M4 is measured to determine the stored power in the cavity. Since the

reflectivity of the coating also depends on the incidence angle, the alignment of cavity mirrors makes it possible to measure the transmission in its final position. We obtain $T_4 =$ 69.84 ppm. When the injection power is 46.8 W and the stable coupling is around 28%, the intra-cavity reaches as high as 19.6 kW, corresponding to the gain of 1496. We achieve a stable maximal average intra-cavity power of 30 kW at the injection of 80 W.

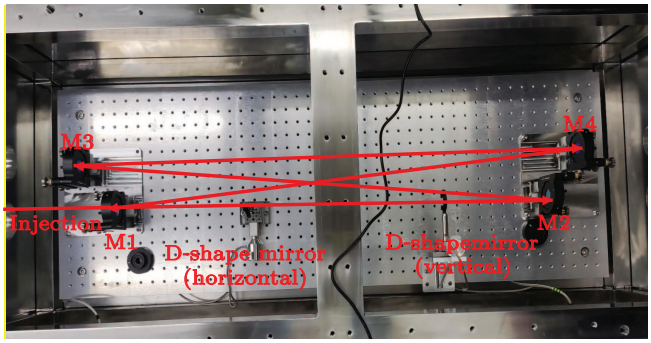


Fig. 7. Photograph of the optical cavity. M1 is the input planar mirror, and M2 is the high-reflectivity planar mirror. M3 and M4 are high-reflectivity spherical mirrors. The D-shape mirrors in vertical and horizontal directions are placed between M1 and M2.

4. Conclusion

In conclusion, a four-mirror bow-tie OEC injected by a continuous-wave laser system with low phase noise has been built. A clean error signal is observed and the cavity is locked successfully by using two feedback loops, one fast analog loop, and the other slow digital loop. The two loops guarantee a stable and long-term lock. The cavity finesse is 6402, measured by the EOM-based frequency modulation method. The modal instability phenomenon, namely the fundamental mode and the degenerated higher-order modes resonates simultaneously, is observed. A pair of D-shape mirrors are utilized to remove the high-order modes. We achieve the intra-cavity power of 30 kW, corresponding to a gain of around 1500. This work paves the way to establishing the high-power OEC to be used in the novel light photon source based on the SSMB mechanism.

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