Research of spacing stability of tunable Fabry-Perot filter in inertial confinement fusion facility

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In the 9th laser system of Shenguang II inertial confinement fusion (ICF) facility, tunable Fabry-Perot (F-P) filter is applied to compensate the FM-AM effect. According to the technical requirements of compensation device, a precise displacement monitor system using the capacitive displacement sensor with nanometer scale precision to stabilize the spacing of the tunable F-P filter is proposed firstly, then the basic structure and operating principle of the monitor system are analyzed. The scheme design of the driving circuit of capacitive displacement sensor, the data processing as well as the system controlling program are discussed in detail, and the precision of capacitive displacement sensor is calibrated. The experimental results show that the spacing stability of the tunable F-P filter is better than 15 nm/h and the modulation depth of the FM-AM effect is better than 4% by introducing the displacement monitor system.

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At the fore-end of the 9th laser system of Shenguang (SG) II inertial confinement fusion (ICF) facility, phase modulation device is used to expand the spectrum of laser to suppress the stimulated Brillouin scattering (SBS) effect in high flux system and protect silica optical elements with large aperture. But when the laser with broad spectrum transfers in the ICF system, the FM-AM effect happens. The FM-AM effect means the frequency modulation converts to amplitude modulation, which will influence the pulse quality and reduce the operating energy of ICF facility.

At present, one of the mature technologies is using the tunable Fabry-Perot (F-P) filter to compensate the FM-AM effect[1]. The operating principle of the tunable F-P filter is as follows. One glass plate of the F-P filter is mounted on a fixed slide, and the other mounted on the micro-displacement stage driven by piezoelectric actuators, which are used to implement the distance fine-tuning between two glass plates. In general, the spacing between two glass plates is $0.8-5$ mm or so.

However, in practical application, we find that the magnitude of creep will accumulate to several microns in 3 hours or so under open loop conditions owing to the inherent hysteresis and creep properties of piezoelectric ceramic, which results in the spacing between two glass plates drifting slowly with the elapsed time, and impacting the functions of dynamic compensation to the FM-AM effect. At present, in the 9th laser system of SG II facility, the Nd:YLF high-gain main amplifier mainly causes the FM-AM effect, so we can observe the waveform of light impulse behind the Nd:YLF amplifier using heavy current pipe and oscilloscope TDS694[2], by this way, we can obtain the modulation depth of the FM-AM effect. Experimental results show that the modulation depth is better than 4% primitively in open loop mode, three hours later, the modulation depth increases to 10%, as shown in Fig. 1. The spacing between glass plates increases 500 nm on the average, the modulation depth increases 2% correspondingly, which is unfavorable to the security of service.

According to the technical requirements of the compensation service, when the glass plates of the F-P filter have been adjusted to an ideal position, the spacing stability of the glass plates should be better than 15 nm/h. A precise displacement monitor system using the capacitive displacement sensor with nanometer scale precision is developed to stabilize the spacing of the tunable F-P filter. Experimental results show that the spacing stability of the tunable F-P filter is better than 15 nm/h and the modulation depth of the FM-AM effect is better than 4% by introducing the displacement monitor system.

Operational amplifier circuit, which is shown as Fig. 2[3], is used in the capacitive displacement sensor. The measurement equation can be written as

$$U_0 = -U_i \frac{C_0}{\varepsilon_0 S} \cdot \delta, \tag{1}$$

where C_0 is the reference capacitance, U_i is the standard input signal, U_0 is the output signal of the main

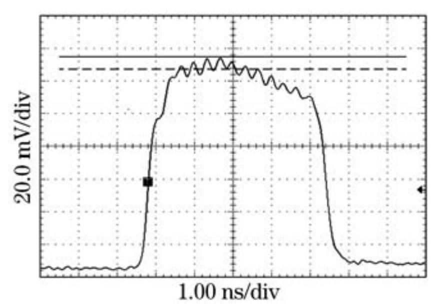

Fig. 1. Modulation depth of the FM-AM effect in open loop mode.

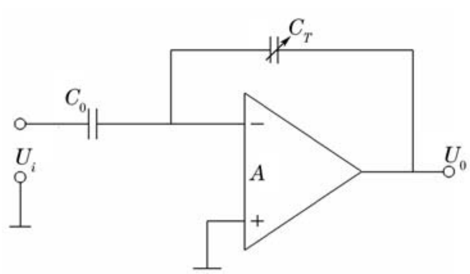

Fig. 2. Schematic diagram of operational amplifier circuit.

amplifier, δ is spacing between two polar plates, S is the effective polar area, C_T is the capacity of the sensor. Based on the basic principle of ideal planar capacitance, the output voltage signal U_0 is proportional to spacing δ.

The displacement monitor system is composed of capacitive displacement sensor, piezoelectric actuators, micro-displacement stage, serial communication interface, data processing and control program, as shown in Fig. 3. One polar plate of the capacitive sensor is mounted on the micro-displacement stage driven by piezoelectric actuators, and the other one is mounted on a fixed slide.

Owing to the inherent hysteresis and creep properties of piezoelectric ceramic, micro-displacement stage will deviate some initial preinstalled positions after a while, as a result, the spacing between glass plates of the tunable F-P filter and the spacing between polar plates of the capacitive sensor have the same change, therefore, we only need to measure the spacing variations of the capacitive sensor, the spacing variations of the tunable F-P filter can be obtained at the same time.

Capacitive displacement sensor detects the spacing variations of the polar plates on line, the measured result is transmitted to computer as the feedback value via serial communication interface, the displacement deviations between the feedback values and the initial polar spacing can be figured out by data processing and control program. Digital proportional-integral-differential (PID) control algorithm is applied to calculate the displacement deviations and figure out the driving voltage that the piezoelectric actuators need. Piezoelectric actuators drive the micro-displacement stage to move, accordingly alter, and stabilize the spacing of the tunable F-P filter. By this way, we can accomplish closed loop displacement control of the polar spacing, and eventually fulfill the dynamic compensation functions to the FM-AM effect.

Capacitive sensor circuit amplifies the tiny and weak analog electric signals obtained from sensor and decreases noise signals firstly, then, the enlarged analog voltage signals are converted into digital signals and transmitted to computer via serial communication interface, the input digital voltage signals are processed by data processing and control program, in this way, we accomplish closed loop displacement control of the spacing variations of the tunable F-P filter.

Figure 4 shows the composition diagram of driving circuitry[4−7], which consists of excitation voltage source, high-gain main amplifier, non-contact capacitive sensor,

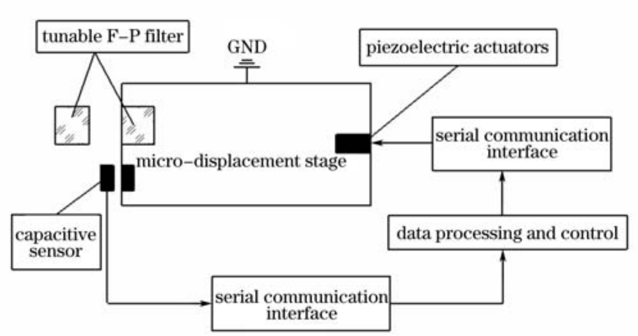

Fig. 3. Working principle of displacement monitor system.

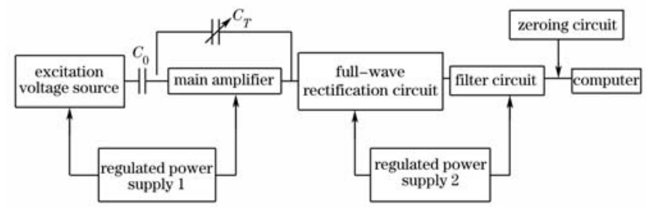

Fig. 4. Schematic diagram of driving circuit.

full-wave rectification circuit, filter circuit, zeroing circuit, and regulated power supply. Where excitation voltage source, main amplifier, reference capacitance C_0, and sensor capacity C_T compose the operational amplifier measuring circuit. Excitation voltage source is used to provide alternating current (AC) voltage with fixed amplitude that operational amplifier needs, thus its amplitude stability is strictly required. Therefore, we use the quartz crystal to generate sinusoidal carrier signal with the fixed frequency. First, frequency divider CD4060 is used to divide the 10M crystal oscillator reference signals by 2^9 and 20-kHz-frequency high precision square waveform signal is obtained, then, the 20-kHz square waveform signal is changed into high quality sinusoidal carrier using low-pass filter circuit. The amplitude of the excitation voltage source obtained in the experiment is $3 - 5$ V, with instability better than 1/10000, and the frequency error is negligible.

In order to achieve high input impedance and better anti-interference ability, bootstrap circuit and complete equipotential screening technology are applied in the design of main amplifier, besides, we use two-stage amplifiers to guarantee the operational precision and the effect of driving cable, the enlargement factor of each amplifier is about 200, and the total open loop gain $A_V > 50000$. The amplitude of the output voltage is proportional to the spacing of polar plates[8].

Output voltage signal from the main amplifier is rectified and filtered by full-wave rectification circuit and filter circuit, the function of zeroing circuit makes instrument have an appropriate operating point and achieve the maximal measurement range and the best linearity, in this way, the amplitude of output voltage can meet the demands of data processing and control program. Voltage signal that is demodulated is transmitted to computer via serial communication interface for further data processing, and this method is useful to increase the anti-interference ability of the sensor.

In order to ensure the measurement accuracy and stability of capacitive sensor, two independent regulated power supplies without the same earth connection are used in the monitor system. The output voltage of regulated power supply 1 is ± 12 V, which is used to supply the excitation voltage source and the main amplifier, the output voltage of regulated power supply 2 is ± 12 and $+5$ V, which is used to supply the rest circuit and the microcomputer system.

We use LABVIEW software to compile the data processing and control program, which calculates the input voltage signal obtained from the capacitive sensor and figures out the spacing of the polar plates. Displacement deviations can be obtained by comparing the actual displacement and the given one, which are also the variations of the spacing of the F-P filter.

Digital PID control algorithm is applied to calculate the displacement deviation and figure out the driving voltage that the piezoelectric actuators need[9]. Then, piezoelectric actuators drive micro-displacement stage to move and accordingly change the spacing of the F-P filter into its initial value.

As far as digital PID control algorithm is concerned, its controlling effect significantly depends on the selection of control parameters such as K_P, K_I, and K_D. We can determine the parameters of digital PID controller preliminarily using Matlab emulation program, which are adjusted in practical measurement process. In order to maintain the stability of the closed loop displacement control system, stability criterion should be satisfied in parameter selection.

Calibration system of the capacitive sensor consists of micro-displacement stage, capacitive displacement sensor that is to be calibrated, capaNCD620 displacement measuring system (which acts as reference system), TDS694 oscilloscope, and high-accuracy, multi-use instrument KEITHLET2000. We use the 6-DOF nanopositioning stage developed in SIOM as the micro-displacement stage, whose maximum stroke is 100 μm, the stability positioning precision is within ± 5 nm in closed loop mode. The maximum measuring range of capaNCD620 is 50 μm, with resolution better than 2 nm, linearity better than $\pm 0.2\%$ FSO.

Contrast method is used to calibrate the capacitive sensor in experiment, calibration steps are as follows. Step 1: we combine the polar plates of capaNCD620 with the circuit of the capacitive sensor that is to be calibrated, whose output voltage is displayed on the screen of the KEITHLET2000 multi-use instrument and converted into corresponding displacement using a computer. Step 2: we switch the polar plates to capaNCD620 measuring system, measure and record the displacement under the same circumstance. Step 3: we change the output voltage of piezoelectric actuators and execute steps 1 and 2 many times repetitively, record every measuring value. Finally, comparing the output voltage of the sensor that is to be calibrated with the output of capaNCD620 measuring system through multiple experiments, we can obtain the precision of the capacitive sensor that is to be calibrated. Experimental results show that the measuring range of the capacitive sensor that is to be calibrated is $10 - 50$ μm, with resolution better than 5 nm and precision better than 12 nm.

We combine the capacitive sensor that is calibrated with the displacement monitor system, movable polar plate of the capacitive sensor is mounted on the micro-displacement stage, the other one is fixed, and the initial spacing is adjusted to 25 μm or so. In order to prevent the generation of false signals, the movable plate should be earthed reliably.

When the micro-displacement stage drifts slowly owing to the hysteresis and creep properties of piezoelectric ceramic, the spacing between polar plates of the capacitive sensor changes. From 14:00 to 16:30 on the same day, recording the output voltage of the capacitive sensor and changing it into spacing variations, which are equal to the spacing variations of the tunable F-P filter, are shown in Table 1.

Table 1. Spacing Variations of Tunable F-P Filter

Time	Output Voltage (V)	Spacing of Polar Plates (μm)	Spacing Variations (nm)
14:00	4.5841	22.920	0
14:30	4.5856	22.928	+8
15:00	4.5864	22.932	+12
15:30	4.5827	22.914	−6
16:00	4.5853	22.926	+6
16:30	4.5854	22.927	+7

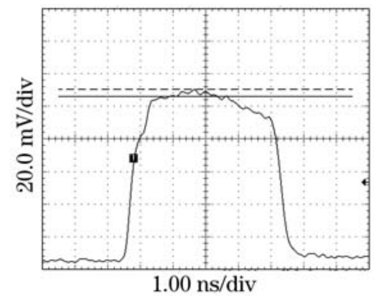

Fig. 5. Modulation depth of the FM-AM effect in closed loop mode.

Table 1 shows that the spacing stability of the tunable F-P filter is better than 15 nm/h by introducing the displacement monitor system, if we can suppress all kinds of disturbance in the working field and use better power supply, experimental results should be better.

We combine the displacement monitor system with the ICF facility, observe the waveform of light impulse using heavy current pipe and oscilloscope TDS694 from 14:00 to 16:30 on the same day, and record the modulation depth of the FM-AM effect, as can be seen in Fig. 5.

Figure 5 shows that the modulation depth is better than 4% all the time and the fluctuation quantity is very tiny by introducing the displacement monitor system. The displacement monitor system we developed meets the technology requirements of compensation system completely.

According to the technical requirements of the FM-AM effect compensation device in the 9th laser system of SG II facility, a precise displacement monitor system using the capacitive displacement sensor with nanometer scale precision to stabilize the spacing of the tunable F-P filter is developed. We use the operational amplifier circuit in the capacitive sensor, which is useful to eliminate the contributions of stray capacitance and parasitic capacitance; LABVIEW software is applied to compile the data processing and control program and digital PID control algorithm is applied to control the output of the micro-displacement stage. Experimental results show that the spacing stability of the tunable F-P filter is better than 15 nm/h and the modulation depth of the FM-AM effect is better than 4% by introducing the displacement monitor system.

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References

1. P. J. Wisoff, M. W. Bowers, G. V. Erbert, D. F. Browning, and D. R. Jedlovec, Proc. SPIE **5341,** 146 (2004).
2. B. Liao, Theoretical Study of FM-AM Issue on ICF Facility Shanghai (in Chinese) Ph.D thesis (SIOM, 2006) pp.50–51.
3. C. X. Shan, *Theory and Design Basis and Application of Sensor* (in Chinese) (National Defence Industry Press, Beijing, 1999) pp.140—168.
4. T. D. Moore, S. Turner, and C. C. Speake, Meas. Sci. Technol. **4,** 1519 (1993).
5. A. Fertner and A. Sjlund, Trans. Instrum. Meas. **38,** 870 (1989).
6. F. Restagno, J. Crassous, E. Charlaix, and M. Monchanin, Meas. Sci. Technol. **12,** 16 (2001).
7. Š. Lányi and M. Hruškovic, Meas. Sci. Technol. **12,** 77 (2001).
8. H. G. Zhang, *Study on the Key Technology of High Precision Capacitance Micrometer* (Tianjin University Press, Tianjin, 2000) pp.30–31.
9. H. J. Pahk, D. S. Lee, and J. H. Park, Intl. J. Machine Tools and Manufacture **41,** 51 (2001).