Design of High Precise Focusing System in Laser Direct Writer

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Abstract. In order to improve the accuracy and efficiency of fabricating lines with laser pattern generator, a novel focusing system was designed. Focusing system is based on optical off-axis detection principle. The detector is a two-quadrant photocell and the defocus signal is constructed by division. Focusing system has the character of second-order system with overdamp. The new embedded PID controller improves the performance of focusing system and upgrades the closed-loop precision to 0.2 μm. Furthermore focusing system has the fabrication capabilities for alterable-width lines under various defocus amount.

1. Introduction
The important instrument for manufacturing the micro optical elements is laser pattern generator [1-3], which has various fabricated objectives including simple line and arbitrary binary pattern [4], even grey-scale mask [5,6]. Exposure of resist can be used for forming 3D relief surface to satisfy various applications. Besides error of later manufacture, the greater impact to relief surface is control precision of laser pattern generator in the process of fabricating 2D pattern. Among various correlative technologies, the precision of focusing system [7] is very significant, which will directly influence linewidth and will affect energy distribution of light using for exposure after change of linewidth, ultimately making pattern aberrant.

In order to fabricate more wide line efficiently or more complex binary phase gating with alterable linewidth, defocusing method [8,9] can be used. Defocusing method can once produce several to several tens μm linewidth through scanning of laser head, so that line fitting is unnecessary, efficiency is improved and precision is guaranteed. To meet these requirements applicability of focusing system should be very well. It should be adaptable to both single point application and multipoint application.

Therefore there is a new kind of design of optical focusing system in this article. It includes two-quadrant detector and unshaped elliptical beam as focusing assistant light source and focus error signal is produced by division. We have completed the research of system’s dynamic property. An appropriate adjustment unit is added to the system in order to make system have more perfect dynamic property and precision to reach the design aim.

2. Optical focusing principle
Figure 1 gives the focusing optics. There is a off-axis detecting scheme based on two-quadrant detector, that is there is a distance between axis of reflected beam and quadrant boundary of detector. The optical axis does not coincide with the center boundary of two-quadrant detector, and their clearance (i.e. off-axis amount) may produce defocus information. In the region near focus, when the
substrate closes to the objective the laser spot on the detector will enlarge, otherwise the laser spot will shrink. If the area variation of laser spot can be detected, then the focus error signal can be calculated, too.

He-Ne laser is used as focusing light resource. Its beam shape is circle, and its intensity fluctuates at random because of instability of laser power supply. Moreover it is disadvantage that He-Ne laser has a bigger volume. Intensity of laser diode (LD) is stable and it is compact, but spot of LD is elliptical and its quality is worse. Theoretic analyse and experiments indicate it is feasible to adopt elliptical spot.

![Focusing optics](Figure 1)

For defocusing application four-quadrant detector cannot be used. Two-quadrant detector is the simplest type that can detect both defocusing amount and direction.

FES is produced by division, that is to say photoelectric signal $S_1$ divided by $S_2$ is $FES$. In the process of light spot expanding, the increase speed of $S_1$ is different from that of $S_2$, so $FES$ is variational. We can acquire defocusing amount and direction from information of light spot. Beam illumination is assumed uniform, so photocurrent of each quadrant is only relative with illuminated area. With simple calculation we can conclude $FES$ as follow

$$FES = \frac{S_1}{S_2} = \frac{\pi a + 2d \sqrt{1 - \left(\frac{d}{a}\right)^2} + 2a \arcsin \frac{d}{a}}{\pi a - 2d \sqrt{1 - \left(\frac{d}{a}\right)^2} - 2a \arcsin \frac{d}{a}}$$

where $d$ is off-axis amount, distance between optical axis and center boundary of two-quadrant detector. $a$ is ellipse axis that is normal to the center boundary of detector. After optics is determined, parameter $a$ is the only variable, which is correlatve with defocus amount $\delta$. So focus error signal $FES$ can be written by using the simple relation

$$FES = FES(\delta)$$

Figure 2 is simulation result of equation 1, where $f$ is focus length of objective lens, $d_1$ is distance between objective lens and detector, and $b$ is the other elliptic axis. The simulation figure shows that $FES$ has monotonic relationship with defocus amount $\delta$, and elliptic axis $a$ will efficiently affect sensitivity of focusing system. Furthermore, $FES$ will not be zero even if focusing system is in focus.
The property of this principle is that optics is impact, $FES$ is monotone (always above zero), calibration is easy and result is not prone to be impacted by fluctuation of intensity. In this way system can be utilized in focusing and defocusing application. The relationship between $FES$ and actual defocusing amount can be achieved by calculation and experiment.

### 3. Analysis of system dynamic property

Figure 3 is schematic diagram of the focusing control system. Input $X(s)$ is anticipative defocus amount, and output $Y(s)$ is actual defocus amount. Defocus amount is correlative with the linewidth fabricated. The closed-loop transfer function $G(s)$ can be described as follows

$$G(s) = \frac{G_1(s)G_2(s)}{1+G_1(s)G_2(s)H(s)} \quad (3)$$

where $G_1(s)$ and $G_2(s)$ are transfer functions of amplification section and actuation section, respectively, $H(s)$ is transfer function of feedback channel.

Amplification section $G_1(s)$ play the role of proportional amplification. Amplified $X(s)$ is used to drive micro-displacement actuator, but it shouldn’t be considered as a simple proportional section. Because PZT has higher capacity relatively, in order to avoid the damage to the amplification circuit caused by high current, current limitation section is added to the amplification circuit. When step signal $X(s)$ is input, there is a slowly climbing process in amplification circuit before reaching anticipative stable state.

Micro-displacement section is constituted of PZT and flexible hinge. PZT obviously has nonlinear hysteresis property, which is disadvantage to stability of control system. Dynamic property of micro-displacement actuator is similar with that of “spring-mass-damper”, which can be regarded as

**Figure 2.** Simulation for relationship with displacement and focus error signal $FES$.

**Figure 3.** Schematic diagram of control in focusing system.
second-order segment. Because PZT has higher response velocity than flexible hinge and air damping is small, in the second-order system under-damped oscillation will take place.

Feedback channel $H(s)$ picks up output signal and converts it into $FES$. In the broad range $FES$ has monotone nonlinear relation with defocusing amount, but saying from small range the relationship between $FES$ and defocusing amount is approximately linear. So in the closed loop system it can be deemed as a proportional segment.

In the experiment of open loop step response, forward channel constituted of $G_1(s)$ and $G_2(s)$ produced overdamping response without overshoot and oscillation. It did not produce anticipative oscillation. The reason is that inertia property of forward channel plays the key role.

In order to enhance the dynamic performance of focusing system, the PID phase compensator was inserted in front of $G_1(s)$. It shortens the transient time and improves the response speed of focusing system.

4. Experiment of dynamic property and fabrication of defocusing lines

To testify and reflect actual performance of focusing system, we have done the dynamic property experiments of open loop and closed loop respectively. Furthermore we have tried fabrication of lines with alterable width based on defocusing amount.

![Figure 4](image_url)

**Figure 4.** $FES$ oscillogram of focusing system under (a) open loop and (b) closed loop.

The test is proceeded in polar laser direct writer. Substrate adheres to turntable and rotates with it. Laser spot scans on the surface of substrate with relative velocity 50 mm/s. Figure 4 is the waveform obtained from test. In the Figure 4(a), control system is set to open loop. PZT works at fixed voltage (line part). Here micro-displacement actuator doesn’t provide dynamic displacement or compensation for defocusing amount. Detector extracts photoelectric signal and transforms it into $FES$ (curve part), $FES$ reflects the dynamic defocusing state of substrate. In the Figure 4(b), system is set to closed loop and focusing state. The curve of upside represents driving signal to PZT. The higher PZT’voltage is, the better its linear performance is. Accordingly we can acquire defocusing amount and defocusing variation from the shape of curve. The curve of downside represents $FES$. Curve of PZT’static
relationship between input and output is known. Proportion of “displacement-defocusing amount” calibrated through experiment is $1 \mu m/V$. We can know that precision of defocusing amount in the closed loop condition is $0.2 \mu m$.

Figure 5 shows the lines fabricated by different defocusing amount. Turntable rotates with fixed angle speed, so line speed of laser head to substrate changes with radius of fabricated circles. In order to keeping the exposure dose invariable, we compensate the intensity. Starting position of each circle is random. But defocusing amount of arc of each circle is increasing, so width of arc is increasing in the picture. Range of linewidth is from several to several tens $\mu m$. The outline of head and end of each arc is perfect. So we conclude that focusing system has the capacity of fabricating lines with alterable width by defocusing laser and whole system has favorable dynamic performance.

5. Conclusion

Two-quadrant detector and elliptical laser spot used in the system is compact. FES brought by division is appropriate for not only focusing application but also defocusing application. The experiment of fabricating line indicates that it is feasible to produce lines with alterable width by means of various defocusing amount.

Affected by the current limitation section of amplification circuit, focusing system in the open loop condition has overdamping property of second-order system. The embedded PID adjuster improves the dynamic performance of whole closed loop focusing system and makes the precision great enough for practice.

In the face of problem caused by lower speed of PZT, improving the capacity of outputting high current in the driving and amplifying section is the ultimate solution. In this way focusing system can be modulated with higher frequency.

Later research is improving the stability and repeatability of relationship between FES and actual linewidth fabricated. Besides making use of intensity control we can modulate linewidth in larger range.

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