CALCULATION OF OPTICAL PARAMETERS IN LASER ENGRAVING OF PHOTOMASKS

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ABSTRACT In laser engraving of photomasks, the linewidth is one of the critical characteristics in determining the quality of masks and depends mainly upon the laser focus spot size. In this paper, a theoretical equation relating the laser focus spot size to the optical parameters of the laser system, including resonator parameters, beam expansion ratio and focal length of the focussing lens is derived. Confirmatory experiments using a Q-switched Nd:YAG laser system and photomasks with iron oxide coatings were carried out. The obtained actual spot sizes lay within 10% of the theoretical value.

INTRODUCTION

The use of lasers in liquid crystal display (LCD) fabrication is an outgrowth of laser fabrication of photomasks used in semiconductor industry. The photomasks are needed in LCD fabrication to define the various circuit layers using a photolithography technique [1].

Photoreduction of a large scale waveguide or electrode model is a standard technique for mask making in mass production. For batch production, an electron beam is used to write the circuit pattern directly on the mask. This method requires a high vacuum working environment which therefore makes the whole process slow and expensive. A new simple and effective method to produce masks is laser direct writing. The circuit pattern is formed by vaporizing selectively the film coated on the substrate [2].

In laser engraving of photomasks, the linewidth is one of the critical characteristics in determining the quality of masks and is mainly dependent on the optical parameters of the laser system used. In this paper, a theoretical equation to calculate the laser focus spot size using the optical parameters of the laser system is derived. Some experiments were carried out with a Q-switched Nd:YAG laser system. The difference between theoretical spot diameter and actual linewidth is presented and discussed in the following sections.

DESCRIPTION OF THE LASER MACHINING SYSTEM

Fig. 1 shows a block diagram of the NEC M690B laser engraving system used in this study. A He-Ne laser is used to align the Nd:YAG laser beam to the surface of the photomask. The beam expander is used to obtain a laser beam with a small divergence and a large beam size to reduce the power density on the following optics. A dichroic mirror deflects the laser beam to pass through the focal lens vertically. A X-Y table controlled by a CNC controller is used to move the photomask for the required pattern. The CCD camera and TV monitor are used to observe the machining process and to check the machining position. The main specifications of the laser machining system are shown in Table 1.

Table 1 The Specifications of the Laser Machining System

Laser System	Laser mode: TEM_{00} Laser Average power: 7W(with Q-switch element) Q-switch frequency: 1-50kHz, 0.1kHz step
Laser Resonator	Plano-convex mirror M_1:Radius of curvature=0.8m & Transmittance=15% Plano-convex mirror M_2: Radius of curvature=0.8m & Reflectivity=99.5% Optical length of the cavity = 670mm
X-Y Table	Travel range: 200mm×200mm Resolution: 1μm Maximum speed: 6000mm/min
Beam Expansion Ratio	2×, 3×, or 5×
Focal Length	25mm, 50mm, or 75mm

CALCULATION OF PARAMETERS IN THE OPTICAL SYSTEM

1. Laser Beam of a Laser Resonator

Fig. 2 shows a schematic diagram of the optical system including laser resonator, beam expander and focal lens. The resonator consists of two mirrors M_1 and M_2 with radii of curvature of R_1 and R_2 respectively. The thermal effects of the Nd:YAG rod are represented by a thermal lens with a focal length f_0 . L' and n are the length and refractive index of the Nd:YAG rod in Fig. 2.

The pertinent parameters of a resonator equivalent to one with an internal thin lens are [3]

$$g_1 = 1 - \frac{L_2}{f_0} - \frac{L_0}{R_1} \qquad (1)$$

$$g_2 = 1 - \frac{L_1}{f_0} - \frac{L_0}{R_2} \qquad (2)$$

where $L_0=L_1+L_2-(L_1L_2/f_0)$, L_1 and L_2 are the spacings between the thermal lens and mirrors M_1 and M_2 respectively, as shown in Fig. 2.

In the resonator, the radius ω_0 of the beam waist and the distance L_{01} between the beam waist and mirror M_1 can be expressed as a function of the equivalent resonator parameters [4], i.e.

$$w_0^2 = \frac{lL_0\left[g_1g_2\left(1-g_1g_2\right)\right]^{\frac{1}{2}}}{p\left[g_2\left(L_0/R_1\right)^2 + g_1\left(1-g_1g_2\right)\right]} \qquad (3)$$

and

$$L_{01} = \frac{L_0^2 g_2 / R_1}{g_2\left(L_0/R_1\right)^2 + g_1\left(1-g_1g_2\right)} \qquad (4)$$

and the full-apex divergence angle in the far field is

$$q = \frac{2\,l}{pw_0} \qquad (5)$$

2. Beam Expander

The most common type of beam expander is derived from the Galilean telescope which usually has one negative input lens and one positive output lens. The input lens presents a virtual beam focus at the output. For low expansion ratios(1.3-20×) the Galilean telescope is most often employed due to its simplicity, small package size and low cost.

As shown in Fig.2, the lens M_3 focuses the laser beam from the laser generator on the front focus plane and the new beam waist ω'_0 and divergence angle θ' can be represented as

$$w_0{}' = \frac{f_3\,l}{pw(l)} \qquad (6)$$

and

$$q' = \frac{2\,l}{pw'_0} \qquad (7)$$

$$w(l) = w_0\sqrt{1+\left(\frac{l\,l}{pw_0^2}\right)^2} \qquad (8)$$

where $\omega(l)$ is the radius of the beam entering the lens M_3, l is the distance between the lens M_3 and the beam waist ω_0 (namely $l=L_3+L_{01}$), and f_3 is the focal length of the lens M_3.

Since ω_0' just lies on the back focus plane of the lens M_4 with a longer focal length, f_4, the Gaussian beam with a beam waist ω'_0 will be collimated by the beam expander. The collimation ratio of the beam expander for a Gaussian beam is as follows [5]

$$T = \frac{q}{q''} = T_1\sqrt{1+\left(\frac{l\,l}{pw_0^2}\right)^2} \qquad (9)$$

where $T_1 = f_4/f_3$. The beam waist ω''_0 and divergence angle θ'' after the beam expander are [3]

$$\omega_0'' = \frac{\lambda}{\pi \omega_0'} f_4 \tag{10}$$

$$\theta'' = \frac{\theta}{T} \tag{11}$$

Substituting Equation (6) into equation (10), we have

$$\omega_0'' = T_1 \omega(l) \tag{12}$$

From Equations (10) -(12), we can conclude that the beam expansion ratio and the collimation ratio for a Gaussian beam depend not only on the specifications of the beam expander, but also on the laser beam parameters as well as the positions of the optical lenses.

3. Focal Lens

One of the most important specifications of focusing lens is the achievable focal spot size. If we define effective diameter d_0 as the achievable focal spot size, which contains 86% of the focused energy, and at the edges of which the focused intensity is down to $1/e^2$=14% of its peak intensity, then [6]

$$d_0 = \frac{f\lambda}{\omega_0''} \tag{13}$$

Note that this equation gives an approximation of the focused spot size. It has not taken into account the beam propagation effects, lens aberrations, and ablation thresholds of the coating materials. However, practical equations that give similar results exist, e.g. [7]. Substituting Equations (8) and (12) into Equation (13), we get

$$d_0 = \frac{f\lambda}{T_1 \omega_0 \sqrt{1 + \left[\frac{l\lambda}{\pi \omega_0^2}\right]^2}} \tag{14}$$

Therefore, the focus spot size can be obtained by knowing the optical system parameters.

EXPERIMENTS AND ANALYSES

1. Experimental Results and theoretical Calculations

The experimental results are shown in Table 2. The optical parameters used in the theoretical calculations are: $R_1=R_2=-0.8$m, L=670mm, L_1=310mm, f_0=400mm [3], and L_3=920mm.

Table 2 The Experimental Results and Theoretical Calculations on Engraved Linewidths

Engraving Speed(m/min)	Pulse Repetition(kHz)	Average Power(W)	Focal Length(mm)	Expansion Ratio(times)	Theoretical Linewidth(μm)	Experimental Linewidth(μm)	Error
1	25	0.15	25	5	7.46	8.0	+7.2%
5.5	5	0.40	50	5	14.92	17.0	+13.9%
5	5	0.50	50	2	37.30	34.0	-8.8%
5	10	0.50	50	3	24.86	26.5	+6.6%

2. Analyses

It is found that the average experimental linewidths lay within 10% of theoretical values. The discrepancy can be attributed to the optical aberrations and material interaction [8]. The effect of laser average power, engraving speed, and material properties on the measured spot size and the linewidth will be discussed in other papers.

CONCLUSIONS

A theoretical equation for calculating focal spot size given the various optical parameters was derived. Confirmatory experiments were carried out. It is found from the study that processing parameters such as engraving speed, laser power and material properties would also play a major role in determining the spot size, and consequently the linewidth. However, it can be concluded that the obtained actual spot sizes lay generally within 10% of the theoretical values.

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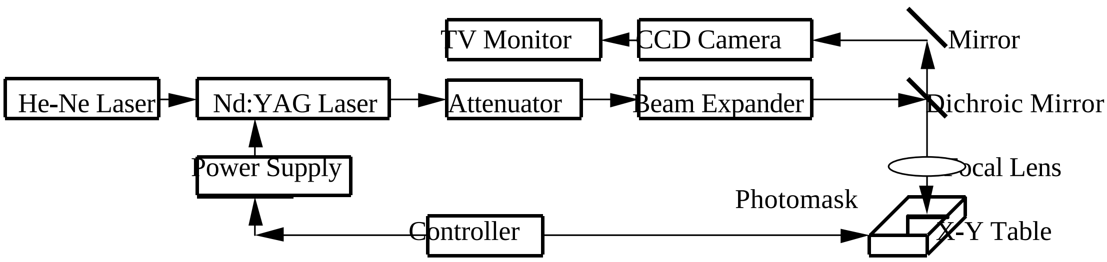

Fig. 1 Block Diagram of Laser Engraving System

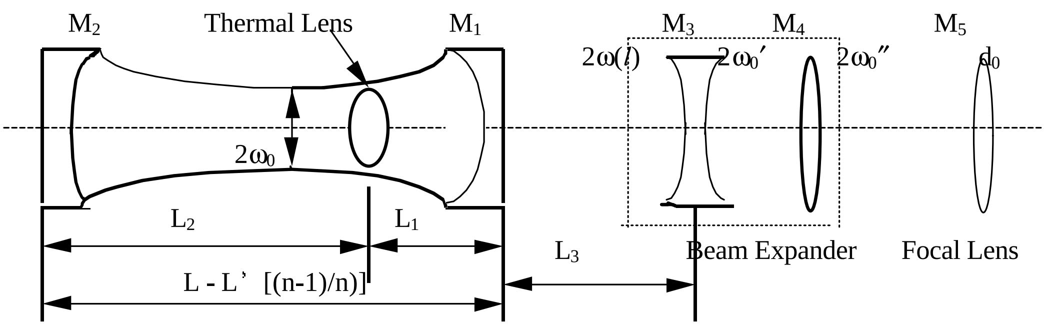

Fig. 2 Schematic Diagram of Optical System

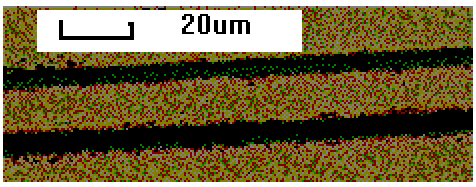

Fig 3. Photo of Engraving Lines