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Simple Optical System for Manufacturing Point Diffraction Interferometer Plates in Titanium Films Using a Low Intensity CW Laser Beam

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We propose an optical system for making pinholes in titanium films for applications in point diffraction interferometry. The optical system for fabrication is easy to implement and to align and, as a result of this, it is possible to obtain pinholes in the range of 1 to 8 μm of diameter. The technique is based on laser ablation and, since we use a green laser, the spot produced by the focus of the optical system can be observed. Also, the damage over the titanium film can be monitored with the aid of a microscope objective lens in real time. The new technique is described and the resulting plates with the pinholes are shown. A successful application of the plates in interferometry is presented as well.

Keywords: point-diffraction interferometer, interferogram processing

1. Introduction

Micro-fabrication is the process of fabricating structures at micrometric scale and even smaller. Ablation using short pulsed lasers is one of the most common micro-fabrication techniques, where the width of pulses goes from nanoseconds to femtoseconds. This is used for the drilling of high precision pinholes or for doing cuts and patterning on metallic or dielectric materials.[1,2] Laser ablation is the process of removing material from the surface of a solid by irradiating it with a laser beam. At low laser flux, the material is heated by the absorbed energy and eventually evaporates or sublimates. Usually, laser ablation refers to removing material with a pulsed laser. At high laser flux, the material is typically converted into plasma. With the use of femtosecond pulses, it is possible to produce sharp borders on the surface with little or no thermal damage of the surrounding illuminated area. This is in contrast with the case of nanosecond pulses and even picosecond pulses.[1,2] However, it is possible to ablate material with a continuous wave (CW) laser, provided the laser intensity is high enough. Ramirez-San-Juan et al. have illustrated the possibility of making pinholes in the range of 600 nm to 1.2 μm of diameter, by means of the sublimation of a titanium film of 65 nm of thickness, using CW low power infrared laser.[3)]

On the other hand, point diffraction interferometer (PDI) has been applied in many fields of optics, going from optical testing to optical tomography.[4–8] The nucleus of this interferometer is a glass plate covered with a thin film wherein a pinhole has been made. We show the typical set up of a PDI system in Fig. 1. The wave front associated with the object beam is focused onto the pinhole in the semi-absorbent thin film deposited on a glass plate. The object beam passes through the plate according with the transmittance of the film, while a reference beam is generated by the light passing through the pinhole. These two beams interfere in the far field. The number of fringes in the corresponding interferogram can be increased as the PDI plate is tilted. However, an inconvenient reduction of contrast comes as well.[8] The contrast of the interferogram can be increased also if the size of the pinhole is made bigger, but this is at the expense of some reduction in sensitivity. When the pinhole diameter is of several micrometers, the name of the interferometer is known as a hole diffraction interferometer.[9]

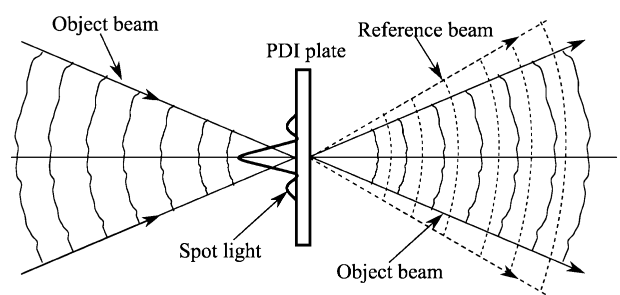

Fig. 1. PDI basics. Two beams are produced, one coming from de pinhole on the PDI plate which is the Reference beam and interferes with the object beam.

In this work we present an optical system for manufacturing pinholes on titanium films of 100 nm thickness. A low power laser with wavelength of 532.8 nm is used but, since we work in the visible region, the alignment of the optical system is easier than the case of infrared laser, as previously reported.[3] The diameters of the obtained pinholes can be from 1 to 8 μm. To our knowledge, the application of laser ablation for fabricating PDI plates has not been reported. In the next section we present the theory that helps us to understand the application of our proposed technique; then in Sect. 3, the optical setup is described. The results are

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presented in Sect. 4. Finally, remarks and conclusions are given in Sect. 5.

2. Theory

Many systems for doing micro-fabrication are developed considering a microscope objective; nevertheless, the size of the spot is in the order of microns, thus, possibly resulting in damage at the micrometric dimension. However, the size of the spot can also be produced by a lens with a larger diameter and focal length. The ideal diameter (ϕ) of the spot can easily be calculated using the following equation:[10]

$$\phi = 2.44\lambda \frac{f}{D}, \tag{1}$$

where λ is the wavelength, f is the focal length and D is the diameter of the lens. Lenses in the range of, for example, 2.5 to 5 cm of diameter and 20 to 30 cm of focal length can be well used for micro-fabrication.

Infrared radiation is commonly used for micro-fabrication because titanium film has a good coefficient of absorption which is around $7 \times 10^5\,\mathrm{cm}^{-1}$. Nevertheless, the coefficient of absorption for green light (around $6 \times 10^5\,\mathrm{cm}^{-1}$) is enough for making damage on the film. The clear advantage of using green light and lens with the values afore mentioned over typical infrared systems is the easy alignment of the optical setup.

The point diffraction interferometer is a common path interferometer wherein the fundamental element is a thin film with a pinhole. The film is deposited on a glass plate which is known as PDI plate. When a focused beam (in this case, the object beam) falls over the PDI plate, the light passing through the pinhole produces a spherical divergent beam, which is the reference beam. Consequently, we will have interference between these two beams at the far field. The size of the pinhole has to be small enough in order to get a good approximation of spherical wave. It is worth developing an expression of the total complex amplitude of the field; this is given by the sum of the amplitudes of the reference beam $U_\mathrm{R}(x, y)$ and that of the object beam $U_\mathrm{O}(x, y)$.[11,12] We denote the transmittance of the titanium thin film as τ, so the transmittance of the total PDI plates is given as

$$\tau + MH(1 - \tau), \tag{2}$$

where MH represents the form of the pinhole with circular symmetry. Thus, the expression is

$$MH = \mathrm{circ}\left[\frac{\sqrt{x^2 + y^2}}{r_\mathrm{hole}}\right], \tag{3}$$

where the circ function is defined as:

$$\mathrm{circ}(\rho) = \begin{cases} 1 & \rho \leq 1 \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

where $\rho = \sqrt{x^2 + y^2}$. Then the total complex amplitude (U_t) after Eq. (2) is given by the sum $U_\mathrm{t}(x, y) = U_\mathrm{O}(x, y) + U_\mathrm{R}(x, y)$, hence:

$$\begin{aligned} U_\mathrm{t}(x, y) = \frac{A}{i\lambda f} &\left\{ \tau\delta(x, y) + 2\pi r_\mathrm{hole}^2 (1 - \tau) \frac{J_1(2\pi r_\mathrm{hole}\sqrt{x^2 + y^2}/\lambda z)}{2\pi r_\mathrm{hole}\sqrt{x^2 + y^2}/\lambda z} \right\} \\ &* \left\{ \mathrm{circ}\left(\frac{f}{z}\frac{\sqrt{x^2 + y^2}}{D}\right) \exp\left[i2\pi W\left(\frac{f}{z}x, \frac{f}{z}y\right)\right]\right\} * \exp\left[i\pi \frac{f}{\lambda z^2}(x^2 + y^2)\right], \end{aligned} \tag{5}$$

where the Dirac delta represents a point source which produces the reference beam; the Bsinc function in the second term represents the diffraction pattern of the pinhole with a radius r_hole; the circ function in Eq. (5) comes from the diffraction due to the pupil of the lens with focal length f and diameter D; W corresponds to the wave aberration function of the focusing lens and the symbol $*$ refers to the convolution operation.[13] We can see that $U_\mathrm{t}(x, y)$ is distorted due to the convolution with the diffraction expression representing the pupil of the lens, wherein at the same time contains the aberrations of the system. So, it is important to understand that the diffraction pattern appearing in some parallel plane to the PDI plate does not correspond only to the pinhole. When the size of the pinhole is small enough, the diffraction pattern dominates over the contribution coming from the object and, the size of the pinhole can be estimated from this diffraction pattern. But, when the pinhole is not so small, the diffraction is a superposition of the similar contributions, one from the object and the other from the pinhole. In this case it is not advisable to estimate the size from the diffraction pattern.

3. Experimental Setup

The optical system for the manufacture of the pinholes is shown in Fig. 2. We use a microscope objective lens of 20× (0.4), which is collimated and focused with two lenses respectively, both of them are 20 cm of focal length and a diameter of 2.54 cm. The wavelength of the laser beam is 532.8 nm at 126 mW of output power. The ideal diameter of the spot can be easily calculated using Eq. (1) and for the present case approximates 10 μm.

However, the losses of power of the light due to the pass through the two lenses and the microscope objective, gives a final power of 26 mW. At the same time, we use a microscope objective of 50× (0.85) with the aid of the illumination of a white light source in order to observe the damage produced by the focused beam on the PDI plate; this is shown in Fig. 3. Nevertheless, if Lens 2 is moved in the axial direction, the size and the shape of the spot on the plate is modified due to the possible presence of aberrations in the optical components, as shown in Fig. 4. The spots are also observed with the aid of the microscope objective of 50× (0.85) when laser light is used. Some of these spots will be

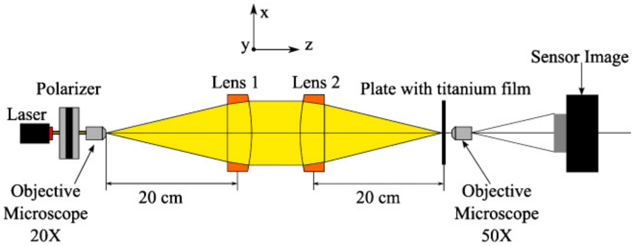

Fig. 2. (Color online) Optical set up for manufacturing the pinholes over plates with a deposited titanium thin film.

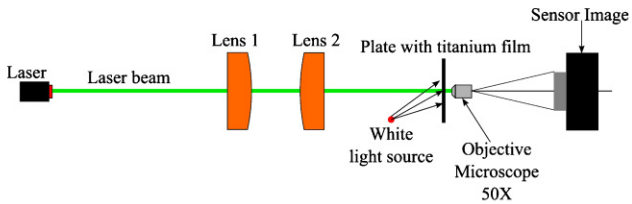

Fig. 3. (Color online) Easy form of visualizing and monitoring the damage produced on the titanium film that coats the plate. A laser light or white light source can be used.

useful for making pinholes as we show in the next section. The plate is fixed in a micrometric translation stage; thus, it is possible to make axial and lateral micrometric displacements of the plate. We have to say that all the pinholes were fabricated on the same plate, and this is because it is big enough ($7.5 \times 2.5\,\text{cm}^2$); after every axial displacement a lateral movement was performed, resulting in a distribution of pinholes in the same coated plate.

Now we describe the method for estimating the size of the pinholes. The maximum resolution of the translation stage is around $10 \pm 0.5\,\mu\text{m}$. We start making a pinhole of any size in some position A in the plate, then a lateral displacement $L = 10 \pm 0.5\,\mu\text{m}$ of the translation stage was made to the position, let us say, B and, another pinhole is created in that position B. The captured image behind the 50× objective of both pinholes, separated by an L distance, is then analyzed. The distance, in pixels, in the captured image between the centers of the pinholes at A and B, corresponds to L. Therefore, the diameter of the pinhole can be estimated with an uncertainty of $0.7\,\mu\text{m}$.

4. Results and Applications

In this section we show our obtained results. As an example of the damage we can produce with this method, we are showing in Fig. 5(a) a strip of $8\,\mu\text{m} \pm 0.2\,\mu\text{m}$ wide. Also some other pinholes are shown under the strip in the same Fig. 5(a). For making these damages we used the spot appearing in Fig. 4(c). With the polarizer it is possible to increase the intensity and so make bigger pinholes as we are showing in Fig. 5(b). Actually, it is possible to obtain pinholes with diameters ranging from $1\,\mu\text{m} \pm 0.2\,\mu\text{m}$ to $8\,\mu\text{m} \pm 0.2\,\mu\text{m}$ by changing the intensity; this is shown in Fig. 5(c). Using the next spots, the sizes of the pinhole diameters are around the $3\,\mu\text{m} \pm 0.2\,\mu\text{m}$ to $4\,\mu\text{m} \pm 0.2\,\mu\text{m}$; there is a reduction in the range. However, if we move the

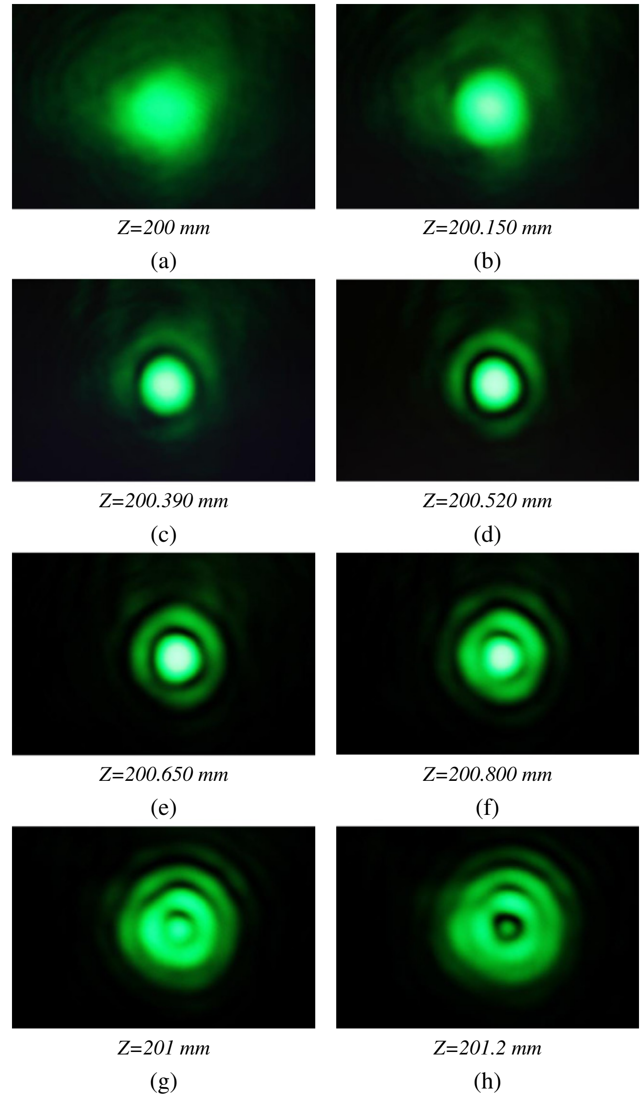

Fig. 4. (Color online) Different shapes of the spots light over the plate when lens 2 is moved along the Z-axis in Fig. 2. The uncertainty in each axial length measurement is $5\pm\,\mu\text{m}$.

plate further in the Axial direction, that is to say, introduce more defocus, the rings in the spots get more energy and can produce damage at the area surrounding the central disc, resulting in a useless pinhole as is shown in Fig. 5(d).

In this work we did not control rigorously the exposure time, but only monitored the size of the pinhole by visual observation with the aid of the CCD camera. However, a verification of the pinhole size was made as we have explained above. In Fig. 6, we show a typical arrangement for interferometry with a PDI. We use a PDI plate with a pinhole made with the procedure described before and the setup described in Sect. 2. Then the PDI is applied to get the interferogram of a candle flame, where the flame is located as the test object. We choose a pinhole of $4\,\mu\text{m}$ diameter, approximately. This size was selected because we obtain a good contrast of the fringes. The results are shown in Fig. 7. In Fig. 7(a), the interferogram is in infinite mode, meaning the reference beam and the object beam, almost match and

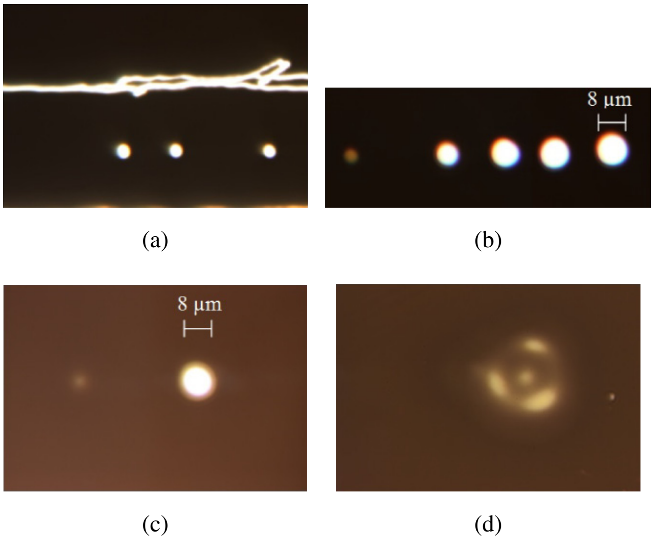

Fig. 5. (Color online) Examples of different damages that can be produced with some of the spots shown in Fig. 4. (a) Damage produced by the spot appearing in Fig. 4(c). (b) Damage produced by changing the intensity in the spot shown in Fig. 4(d). (c) Size comparison of the pinholes produced by changes in the intensity on the spot in Fig. 4(d). (d) Damage produced by the spot in Fig. 4(h).

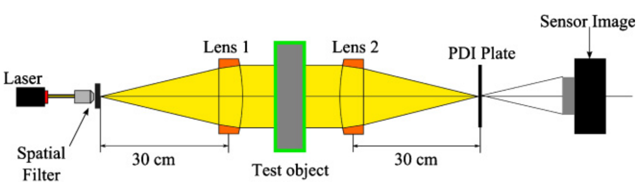

Fig. 6. (Color online) Application of plates created with our optical system shown Fig. 2 in a PDI setup.

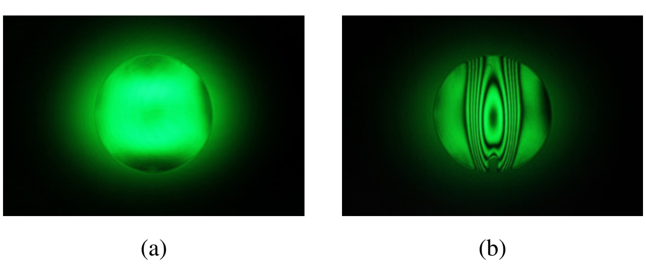

Fig. 7. (Color online) Interferograms coming from the PDI using a pinhole created with the optical system shown in Fig. 2. (a) Infinite mode. (b) Infinite mode but, with fringes produced by testing a candle flame.

start to diverge at the focal plane. Then, there are no fringes in the interferogram. It can be seen from Fig. 7(a) that we do not have a clean interferogram of fringes due to the aberrations of the used optical components. The elliptical form of the diffraction pattern coming from the pinhole can be seen too; this is also the effect of the aberrations over the diffraction pattern described in Eq. (5). In Fig. 7(b), it is possible to appreciate the good quality of the interferogram of a flame produced by the pinhole made with the optical setup introduced in this work.

5. Remarks and Conclusions

We showed the possibility of removing material of a titanium film with a simple optical system. The amount of removed material depends on the penetration of the beam inside the sample and also depends on the laser wavelength. We can make pinholes in titanium film of 100 nm thickness, which is applied to the Point Diffraction Interferometer. The size can be controlled by changing the intensity with the polarizer.

The shape of the spot at the focal plane of the focusing lens sets the quality of the pinhole. However, the quality also depends on the aberrations of the optical components in the setup; lenses with spherical aberration could produce acceptable pinholes but lenses with astigmatism will give pinholes that are not acceptable for being applied on the PDI.

We have shown that the pinholes made with the technique proposed here have good performance in the application on the Point Diffraction Interferometer. The resulting interferograms have enough quality to be processed for recovering the phase of the object under test, and finally to collect important physical information of the object, like temperature, density, thickness, aberrations, etc.

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