Laser induced damage threshold testing of DUV optical substrates

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Laser induced damage threshold (LIDT) testing is the effective methods to research the lifetime of optical elements. According to ISO 11254 standards, a LIDT testing system of ArF excimer laser is established. The laser beam size on the sample surface can be varied from 0.3 to 0.6 mm in diameter. The maximum laser energy density is larger than 4.5 J/cm^2. Besides the Nomarski microscope, He-Ne scattering is used and demonstrated as an effective and reliable method for the on-line monitoring of laser damage. The uncertainty of LIDT results and the main effecting factors are analyzed. The laser induced damage of fused silica substrates with different absorptions and CaF$_2$ substrates with different absorptions are investigated in 1-on-1 mode, respectively. The roles of absorption on the LIDT results of the two kind substrates are discussed.

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During the last decades, ArF excimer laser and its applications have been rapidly developed and widely expanded. Besides the most important applications in lithography of electronic information industry, ArF laser has many applications in medical surgery, material drilling, micro-material machining, and life sciences[1,2]. For ArF excimer laser itself and its applications, one of the main problems was the lifetime or damage of the optical components in such optical systems, which induced high prices and maintenance cost of such systems. As well know that, even at low energy fluency, the deep ultra-violet (DUV) optics can be changed or damaged by the ArF laser irradiation[3−6]. In theory, the change or damage was due to the relative higher material absorption at shorter wavelength and high photonic energy of DUV. But in fact, the practical factors for damage may be very complex and specific. In order to get better understanding of the damage processes, laser induced damage testing was necessary and useful to develop DUV optical coatings and substrates with longer lifetime[7,8].

In this letter, according to ISO 11254 standards, a laser induced damage threshold (LIDT) testing system is established at the wavelength of ArF excimer laser. In this LIDT testing system, He-Ne scattering method is adopted to the on-line monitoring of laser damage. The sensitivity and repeatability of this method are tested and discussed. The main factors inducing the uncertainty of LIDT results are analyzed. The laser induced damage on fused silica substrates and CaF$_2$ substrates are investigated using 1-on-1 mode, and the role of absorption on the LIDT results are researched.

The experimental apparatus for the investigation of DUV laser damage threshold is schematically shown in Fig. 1. An ArF excimer laser from Coherent (IndyStar-193 nm) was used for irradiation sources on the samples. The ArF excimer laser pulse has duration of 12 ns, average power of 8 mW, and repetition rate up to 1 000 Hz. By focusing and imaging the ArF laser beam, a uniform laser spot with dimensions in diameter from 300 to 600 μm can be obtained on the surface of the testing sample. The laser spot size was determined by an ultra-violet (UV) beam profiler (BC106-UV, Thorlab). A variable attenuator was used to adjust the energy of the ArF laser that irradiated on the sample. The output pulse energy of ArF laser was strongly fluctuated with the age of the laser gas. An energy meter with high repetition rate up to 1 000 Hz was used to the on-line monitoring the energy of each laser pulse. The average pulse energy Q_{av} was calculated and used to determine the damage thresholds for other testing modes than the 1-on-1 modes.

In order to determine the occurrence of the damage, the standard method of Nomarski microscope was used. Besides this standard method, a fast on-line damage monitoring method was also adopted[9,10]. This monitoring method was functioned by comparing the He-Ne laser scattering from the ArF laser irradiated sample site before and after ArF laser irradiation. This method can realize a fast on-line registration of damage events and an automatic control of the laser irradiation[10,11]. But it should be noted that the sensitivity of this method was lower than the method of Nomarski microscope. In order to improve detecting sensitive of this on-line monitoring system, an objective lens with large vision angle was

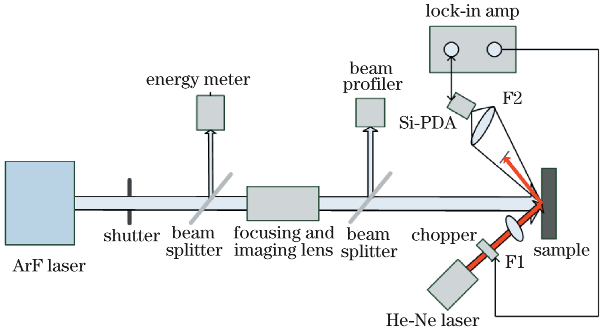

Fig. 1. Schematic of the He-Ne scattering measurement setup.

was selected to collect the scattering light of He-Ne laser.

The on-line monitoring of damage by detecting He-Ne scattering light can significantly facilitate the laser induced damage testing[9,10]. For most of the time or samples, this method appeared very high detecting sensitivity. As an example, Fig. 2 shows the typical experimental results of the detecting sensitivity of the He-Ne scattering method. The experiment was carried on the same point of a fused silica in 1-on-1 mode. During the experiment, totally twenty times of laser damage testing were performed and the corresponding amplitude ratio of He-Ne scattering were recorded. For the first ten measurements, the ArF laser was powered off, namely no ArF laser was irradiated on the sample. Then for the eleventh measurements, the ArF laser was powered on and irradiated on the sample. The inset in Fig. 2 shows the damaged profiler of the sample obtained by the Nomarski microscope. For last ten measurements, the ArF laser was powered off again. By this experiment, both the sensitivity and repeatability of the He-Ne scattering method can be evaluated. From Fig. 2, it can be seen that the fluctuation of amplitude ratio was below ±0.02 for all the measurements that no ArF laser was irradiated on the sample. While for the measurements that ArF laser was irradiated on the sample, the value of amplitude ratio reached to 1.5 even for the slight damage. It means that the sensitivity and repeatability of He-Ne scattering method are very nice and enough for reliable detecting of laser damage in this experiment.

However for the situations that the damaged points are very small or the sample surface has been changed but the surface quality does not become bad, the signal amplitude ratio of He-Ne scattering will be close to 1.0, just as some results shown in Fig. 3(a). In these situations, the results of the on-line monitoring must be checked with the Nomarski microscope. In fact, the He-Ne scattering of different optical samples were different and complex. According to ISO 11254-1, all the damage must be determined by Nomarski microscope.

Figures 3(a) and (b) shows the LIDT testing results of an UV fused silica substrate in 1-on-1 mode. In the measurement, different energy density levels of ArF laser were adopted to irradiate on the sample. For each level of energy density, eleven different sample points were irradiated, and the He-Ne scattering amplitude ratio of each sample point was measured and recorded. Then all the irradiated points were observed using the Nomarski microscope, and were finally determined if the point was damaged. The damaged possibility at this level of energy density was calculated. All the damaged possibility for each energy density level of ArF laser were collected and plotted with the energy density. The LIDT value of the sample was obtained by extrapolating the curve of damaged possibility with energy density to zero damaged possibility, as shown in Fig. 3(b). It should be noted that the scattering amplitude ratio lower than 1.0 was not correct. It was due to the detecting of scatter light had started before the shifting of sample position was stopped.

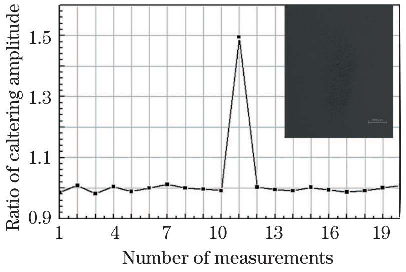

Fig. 2. He-Ne scattering amplitude ratio obtained with or without ArF laser irradiation on the same point (inset is the profile of the damaged point on the sample surface).

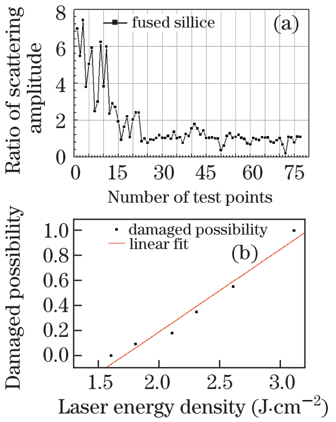

Fig. 3. (a) He-Ne scattering amplitude ratio of an fused silica substrate during LIDT testing in 1-on-1 mode; (b) damaged possibility of different energy density and the fitting of LIDT.

There are three main factors that will introduce errors to the measurement results of the LIDT[11]. They are energy testing errors, laser spot size testing errors, and errors originating from fitting of the measurement data. Relative to the other two errors, the errors from data fitting may be more serious and uncertainty. In fact, in our testing system, the uncertainty originated from ArF laser energy testing errors and spot size testing errors was relative stable and its value was low than 5%. The errors from data fitting will vary from sample to sample and become worse when the uniformity of the sample is bad, especially when the uniformity of the surface conditions is bad.

Many researching investigations have revealed the quality of DUV substrates, such as surface roughness, absorption, and LIDT, have important influence on the corresponding optical properties of the coating deposited on the DUV substrates[12,13]. Even for the substrates of DUV, the specific factors that induced the ArF laser damage were very complex and different. But the factors can be simply divided into two main aspects, namely the sample absorption that originating from the impurity or the defects, and the surface quality that including the cleanness, the polishing methods, and quality[14−16]. It means that, besides the laser induced damage testing system, the absorption and surface quality were the two most important characterizations for investigating the ArF laser induced damage of DUV substrates. In this letter, the surface roughness was characterized by an “EASYSCAN 2” atomic force microscopy (AFM, Nanosurf), and the absorption was measured by an ArF laser calorimeter with high resolution[6]. In order to thoroughly evaluate the absorption, the variation of absorption behavior with

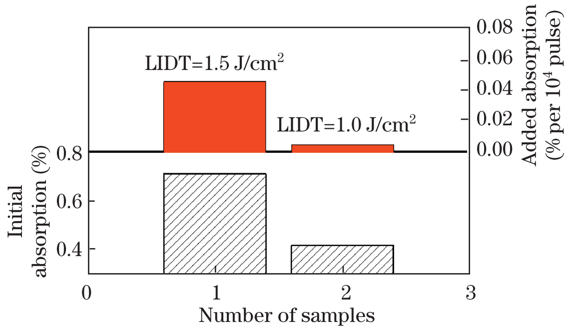

Fig. 4. Initial absorption, added absorption, and LIDT of two different fused silica substrates.

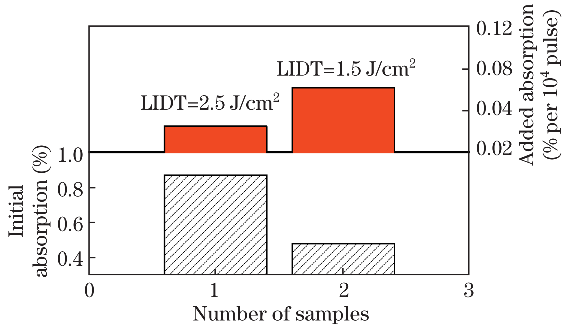

Fig. 5. Initial absorption, added absorption, and LIDT of two different UV CaF_2 substrates.

the shot numbers of the ArF laser pulse was measured and the curve of the absorption with the shot number of the laser pulses was obtained. Then the absorption was divided into the initial absorption and the added absorption. The initial absorption was the truncated value of the curve of absorption with the zero shot number of the laser pulses. The added absorption was the slope of the absorption curve with the shot numbers of the laser pulses. The added absorption reflected the degradation of the substrates due to the color center formation during the irradiation of ArF laser[6].

As the first step of the laser induced damage research of DUV materials, the relations of the LIDT with the absorption was investigated on the two kinds DUV substrates, namely the fused silica substrates and the CaF_2 substrates.

Two fused silica substrates with similar surface roughness but different absorption behaviors were selected and measured the LIDT. The surface roughness was about 0.5 nm for the two fused silica substrates. Figure 4 shows the results of the absorption and the LIDT of the two fused silica substrates. The initial absorption, the added absorption, and the LIDT of the first fused silica substrate were about 0.7%, 0.045 %/10^4 pulses, and 1.5 J/cm^2, respectively. While the initial absorption, the added absorption and the LIDT of the second fused silica substrate were about 0.4%, 0.005 %/10^4, pulses, and 1.0 J/cm^2 respectively. It means that the fused silica substrate with higher initial absorption and higher added absorption has a relative higher LIDT values.

Similar experiments were performed on two CaF_2 substrates. Both of the surface roughness of these two substrates was equal to about 0.60 nm. Figure 5 shows the results of the absorption and the LIDT of these two substrates. The initial absorption, the added absorption, and the LIDT of the first CaF_2 substrate were about 0.87%, 0.025%/10^4 pulses, and 2.5 J/cm^2, respectively. While the initial absorption, the added absorption, and the LIDT of the second CaF_2 substrate were about 0.48%, 0.062%/10^4 pulses, and 1.5 J/cm^2, respectively. It can be seen that the relations of the LIDT with the absorption of CaF_2 substrates is different with and more complex than that of the fused silica substrates.

The above results of the two kind substrates indicated that although the absorption played a very important role on the LIDT results, the relations of the LIDT with the absorption was very complex and different. One reason for this complex relation was originated from the different energy density applied in the absorption measurement and the LIDT measurement[14]. At the same time, the surface quality may play important role on the LIDT results. But it should be noted that the surface quality included not only the surface roughness, but also the sub-surface damage[16].

In conclusion, according to ISO 11254 standards, a LIDT testing system of ArF excimer laser is constructed. In this system, besides the standard Nomarski microscope method, a He-Ne scattering method is used to the on-line monitoring of laser damage. The main factors that induced the uncertainty to the LIDT results are discussed. The errors from the fitting of the measurement data is thought to be the main error factor. In order to research the role of the absorption on the LIDT results, the relations of the LIDT with the absorption of the fused silica substrates and that of CaF_2 substrates are investigated respectively. The obtained results indicate that the relations of the LIDT with the absorption are more complex than expected. One reason for this complex relation is originated from the different energy densities applied in the absorption measurement and in the LIDT measurement. At the same time, the sub-surface damage may play important role on the LIDT results. In the future, more detailed experiments should be performed to reveal those relations.

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