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Laser microplasma as a tool to fabricate phase grating applied for laser beam splitting

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ABSTRACT

In this paper, we present the method of phase gratings (PGs) formation on the fused silica by laser-induced black body heating (LIBBH) technology with irradiation of ytterbium fiber laser ($\lambda = 1.064$ µm, $\tau \sim 4$–200 ns, $\nu \sim 10$–100 kHz). Formed PGs have sinusoidal profile with possible depth modulation of 0.5–2 µm. The PGs formation time, depending on its size and the period, ranged between 1 and 5 min. The optical characteristics of the PGs are studied and gained results are compared with the diffraction theory. This result shows that it is possible to fabricate different PGs with necessary optical characteristics by LIBBH technology. The potential application of such optical elements is beam splitting. Thus, the experiment with interference of laser beams has also been carried out in this work. The result of metal film processing by interference pattern is presented in the article.

1. Introduction

At the present moment, methods based on registration of interference pattern from several beams are actively used in the field of laser processing. The application of microprocessing base on interference of several laser beams in the field of micromachining allows to form one-dimensional as well as two- and three dimensional structures of submicron size [1–3].

The implementation of interference schemes for microprocessing is possible using mirrors and prisms [4,5], but the problem of such systems is that when the number of participating beams increases, the complexity of their implementation increases significantly as well. The diffraction optical elements (DOE), which can separate the initial beam into the required number of beams with the intensity calculated in advance, show great potential in the systems for laser microprocessing.

An individual case of DOE is the phase gratings (PG), which are one-dimensional periodic microrelief on the surface of material, which is transparent for the incident laser radiation. Such PG is capable of divide the incident laser beam into several beams localized in one plane. The ratio of energy of the diffracted beams may be regulated by means of PG microrelief parameters. This explains why the application of such gratings in double-beam interference schemes of laser microprocessing is so popular.

Along with PG having rectangular profile, which is capable of provide the redistribution of energy between the diffraction orders and raising the efficiency up to 40% in the first two orders [6], the PG with sinusoidal profile are also often used. The variation of the relief depth in such PGs allows the implementation of the double-beam interference schemes for microprocessing using the most common wavelengths of 1.06 µm and 0.532 µm [7,8]. For the PG having sinusoidal profile, the maximum diffraction efficiency in first two orders is 33.8%. In this case (as it is evident from the diffraction theory) for $\lambda = 1.06$ µm such efficiency is achieved at the relief depth of $h = 1.4$ µm, and for $\lambda = 0.532$ µm – at the relief depth of $h = 0.7$ µm [9].

The increase of effective interference area created by PG in comparison with mirror schemes makes their application preferable for the realization of laser microprocessing [10]. Since zero diffraction order significantly reduces the contrast of interference pattern, the fabrication of PG with low diffraction efficiency in zero order and high one in the first orders (± 1) is an important subject for a study [7].

But extensive application of DOE is restricted due to the technological problems of their fabrication. Traditionally, the DOEs are manufactured by means of photolithography [11], which consists of application of a thin photoresist layer on the glass substrate. This layer is subsequently irradiated through a special mask by visible and near-UV radiation. After that, the irradiated areas of photoresist, which loose significant part of their chemical stability, are removed by means of chemical processing in organic solution. The chemical processing is followed by a reactive ion etching of areas, which are not protected by photoresist layer, to the required depth. This way, the grating relief is

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formed, which is followed by the removal of photoresist remnants from the substrate surface in alkaline solution. The modification of photolithographic method based on half-tone or gray-scale masks application is also known [12]. The set of binary masks is used for fabrication of complex surface microrelief of future phase grating and all of the sequence of operations mentioned above is repeated for each phase element. The main shortcomings of photolithographic technology are the long duration of manufacturing process and the complexity of its realization. In contrast to ordinary photolithography, in half-tone, or gray-scale, photolithography only one mask with required spatial transmission distribution is used. This allows to obtain continuous surface profile of manufactured DOE with simultaneous reduction of the number of technological operations. However, the cost of manufacturing of high-quality half-tone mask is about the same as the cost of manufacturing of the set of binary masks required for the same purpose. Besides, when the half-tone masks are used, the manufacturing process is more sensitive to fluctuations of lithographic materials properties and etching process parameters than when the binary masks are used. That is why to reduce the number of technological operations as well as the cost of the DOE manufacturing process, the method of continuous profile formation of DOE, based on the smoothing of initially binary structures created by photolithographic method, by means of CO_2-laser radiation [13]. However, the precision control of radiation energy characteristics is required to form the required surface profile of DOE.

Also, technologies such as focused ion beam etching [14,15], electron beam lithography [16,17] and nanoimprint lithography, or hot embossing [18,19] are used for the production of the DOE. All of these methods allow to obtain nanoscale structures. In the first two techniques the removal of the surface layer of the material occurs in a vacuum chamber when exposes by a focused beam of ions or electrons with high energy. This makes it possible to produce high quality DOEs with precise control of relief surface, but the manufacturing process is quite time-consuming and requires special equipment, which leads to an increase in the cost of the DOE. In the nanoimprint lithography nanostructured template is used, which is pressed into the surface of the material that is heated to the softening temperature. The most significant results were obtained in the formation of the DOE on polymethylmethacrylate, the softening temperature of which is located at about 100 °C [20]. Hot stamping is technologically simple and cheap method of the DOE manufacturing with a large area and a fairly high quality, but its use for the formation of the DOE on the surface of the fused silica is problematic (due to the high softening temperature of the material ~ 1600 °C [21]).

Due to this, the laser-induced technologies of optical materials structuring, where structured surface is in close contact with highly absorbing material, became widely used. Combined technology, based on strong absorption of laser radiation by inorganic [22,23] or organic [24,25] solution and metal [26,27] contacting with the back side of the glass plate, may be used for DOEs fabrication on fused silica. One of them is a laser-induced backside wet etching (LIBWE), which was described in the first work [24] and was developed by a research team of Wang and Niino in works [25,28–31]. Along with Niino's team, other groups of researchers worked to improve the LIBWE technology. These groups consists of Kopitkovas [32–34], Zimmer [35,36] and Cheng [37–39]. The key features of the LIBWE technology are high temperature and pressure jump in glass–liquid contact due to strong absorption of the incident laser beam. As a result, shock waves appear and form a relief on the glass surface. Today, the LIBWE technology becomes widely spread in microstructuring of various materials transparent in UV spectral range [22,30–36,40–43]. It was shown in various schemes such as: mask projection [30,32,34]; diffractive gray-tone mask usage [22,33,34]; laser scanning systems [31,44,45]; and interference of two beams [2]. NIR laser sources have been recently used [44,45] in this technology. The laser induced backside dry etching (LIBDE) technology is based on strong absorption of laser radiation by solid material placed under the transparent material, so it is close to the LIBWE technology [26,27,41]. Laser-induced plasma assisted ablation (LIPAA) technology is quite similar to the LIBDE. In this case, a solid target is placed behind the transparent sample at a distance up to a few micrometers [46–48].

The development and improvement of new technologies connected with DOEs fabrication on the glass surface is very important. In this article, we report about laser technology used for fused silica surface modification, which is called laser-induced black body heating (LIBBH) [49–51]. The technology is based on the heating of the glass by a pressed graphite plate in direct contact with the back of the glass surface. This method differs from the LIBDE by the choice of another, much more efficient target. Graphite has a higher absorbance, which does not depend on the wavelength of incident radiation. Thus, this allows to use lasers with any required wavelength, for which the glass is transparent. In comparison with the LIPAA technology, the configuration of the LIBBH is more optically simple and more suitable for the picture topology computer control. The disadvantages of LIBBH technology can be described as follows:

1. The microstructure size is restricted by the focused laser beam size in the area of glass micromachining.
2. Difficulties in the description of the processes during the interaction of nanosecond laser pulses with graphite target complicate the search of crack-free regime.

In the works [49,50] it was reported that PG was produced by means of LIBBH technology, but the dependence between the optical and geometric characteristics of PG and the parameters of laser treatment was not discussed. Thus, the knowledge of the dependence of relief depth on laser treatment parameters that is needed for the manufacturing of the PG suitable for application in laser microprocessing setups based on laser beams interference.

The purpose of this work is the calculation and manufacturing of one-dimensional PG with sinusoidal profile on fused silica by LIBBH technology and its testing in interference setup for microstructuring of thin metallic films.

2. Experiment

The formation of PG on fused silica plate is performed on experimental setup (Fig. 1a), which includes pulse fiber ytterbium laser (1) of $\lambda = 1.06$ µm wavelength, pulse duration $\tau = 4$–200 ns, pulse frequency $\nu = 1$–100 kHz; 2-coordinate galvanometric scanning device (2) based on drivers (G325DT «GSI Lumonics»); the lens (3) with focal length $f = 210$ mm and field of processing 100×100 mm focuses laser beam waist up to $d_0 = 50$ µm; the stationary table (4), on which pressed graphite plate (5) and quartz glass plate (6) are placed; the computer (7) is used for the control of the scanning system and laser beam parameters.

Fused silica surface was completely covered with graphite particles after the PG formation. The surface cleaning is carried out on the same experimental setup (Fig. 1b), but the graphite plate is removed from the treatment area while fused silica plate is flipped rear side up. Laser radiation focuses on the soiled side of the fused silica plate which was previously covered with a thin layer of distilled water to minimize the

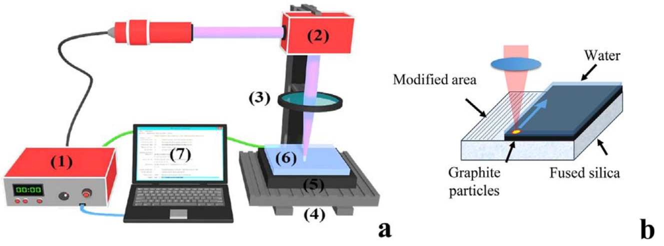

Fig. 1. Experimental setup for phase grating fabrication (a); the stage of laser wet cleaning (b).