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Technologies of perforation of closely spaced micron holes with the help of neodymium – LiF : F_2^- lasers

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Abstract. **The picosecond (based on Nd : YLF – LiF : F_2^- crystals) and nanosecond (Nd : YAG – LiF : F_2^-) laser technologies are proposed for perforating closely spaced micron holes in aluminium foil for microelectronics, medicine, and biology. Two-dimensional matrices of holes with diameters of 2 – 20 μm spaced from each other by 8 – 30 μm are obtained in 20-μm-thick aluminium foil. It is shown that it is possible to increase the hole density and decrease their diameter by controlling the laser irradiation regime. A sample of perforated aluminium foil is obtained with the total area of micron holes comprising 30 % of the entire surface.**

Keywords: *Nd : YLF – LiF : F_2^- and Nd : YAG – LiF : F_2^- lasers, laser perforation, closely spaced micron holes.*

1. Introduction

At present, LiF : F_2^- crystals and lasers find more and more applications in laser physics and technology. This is caused by the following reasons. First, the wide absorption band of F_2^- colour centres in these crystals overlaps the luminescence lines of most neodymium lasers, because of which the LiF : F_2^- crystals are frequently used as passive *Q*-switches in these lasers; in addition, the use of gradiently coloured LiF : F_2^- crystals allows one to control the regime of nanosecond laser action on materials by changing the lasing parameters (energy, power, frequency, and pulse duration) [1, 2]. Second, the wide luminescence band of these colour centres, as well as the high gain and the high luminescence quantum yield of LiF : F_2^- crystals pumped by widely used neodymium lasers determine their application as a laser medium for generation and amplification of ultrashort (pico- and subpicosecond) laser pulses [3, 4].

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The micro- and nanotechnologies for material treatment are the most important fields of application of such solid-state laser pulses [1, 2, 5, 6]. The neodymium – LiF : F_2^- lasers are promising for these applications due to their reliability, simplicity, and efficiency. In this work, we study the picosecond (Nd : YLF – LiF : F_2^-) and nanosecond (Nd : YAG – LiF : F_2^-) laser technologies of perforation of closely spaced micron holes in aluminium foil for microelectronics and for production of medical micromasks and chemical microsensors.

2. Optical schemes of laser systems

The optical scheme of a picosecond laser system is shown in Fig. 1a. Here, the LiF : F_2^- crystals are used as laser amplifiers of 1.138-μm picosecond pulses pumped by laser radiation with a wavelength of 1.047 μm [4]. The master oscillator yields both a picosecond probe pulse and pulses for pumping the LiF : F_2^- laser crystals. As a master oscillator, we used a single-mode Nd : YLF laser operating at a wavelength of 1.047 μm in the passive mode-locked regime with intracavity stimulated Raman scattering in a $KGd(WO_4)_2$ crystal ($\lambda = 1.138$ μm). To increase the pump power for the end LiF : F_2^- amplifier, we placed in front of it an additional amplifier based on a Nd : YLF crystal. The single-mode output radiation of the picosecond laser is a train of three ultrashort laser pulses with a duration of ~1 ps and a pulse repetition rate of ~8 ns at a wavelength of 1.138 μm; the train energy exceeds 1 mJ, and the peak power is higher than 300 MW.

The optical scheme of a nanosecond laser system is given in Fig. 1b. In this scheme, the LiF : F_2^- crystal serves as a passive *Q*-switch for the Nd : YAG laser. The laser is a loop cavity with self-pumped phase-conjugation in each Nd : YAG active crystal and LiF : F_2^- passive *Q*-switch,

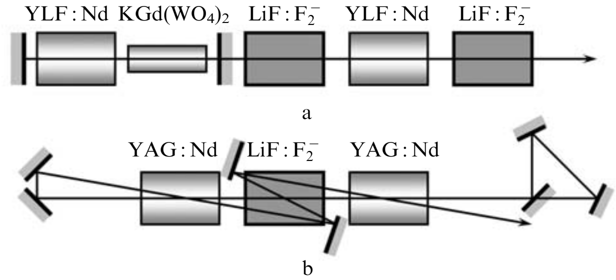

Figure 1. Optical schemes of (a) pico- and (b) nanosecond lasers.

which ensures self-compensation of distortions in the output radiation. The fundamental transverse mode was selected using a Sagnac interferometer as an end mirror [7]. The nanosecond laser emits single-mode mono-pulses with a duration of $\sim$20 ns and an energy of $\sim$100 mJ at a wavelength of 1.064 μm.

In both schemes, the output beam was expanded by a telescope to a diameter of a two-lens objective (1.3 cm) with a focal length of 1 cm; the incident radiation energy was varied using replaceable calibrated filters. A sample of 20-μm-thick aluminium foil was placed in the focus of the objective on a three-dimensional micrometer table. The beam spot on the aluminium foil surface was 3 – 4 μm in diameter; the pump pulse repetition rate was 10 Hz.

3. Results and discussion

The aim of the laser treatment was to produce two-dimensional matrices of micron holes spaced by the minimum possible distance $h_{\min}$ at which the walls between holes remain undamaged. We comparatively studied the parameters of holes perforated by the nanosecond and picosecond lasers as functions of the number of laser pulses needed to drill one individual through hole. To increase the number of these pulses, we decreased the laser energy by replaceable filters.

At a distance between holes below $h_{\min}$, we observed deformations and destructions of walls between holes, which spoiled the hole shape (circularity). Figure 2 shows the photograph of a produced matrix of holes with damaged walls spaced by $h = 15$ μm $< h_{\min}$. The matrix was made using the nanosecond laser with a 80-μJ pulse energy on the sample surface (the energy density is $\sim$700 J cm^{-2}). In this case, an individual hole was produced by about 20 laser pulses. The holes were pierced in vertical rows, and the vertical deformations of hole walls were most pronounced. This may occur because the thin (several microns) walls have no time to cool down and experience the combined effect of laser pulses.

Figure 3 shows the experimental dependences of parameters of laser perforation of micron holes spaced from each other by $h_{\min}$ on the number N of pump lamp flashes needed to drill one through hole by picosecond and nanosecond lasers. In the case of the picosecond laser, which generates three laser pulses per one pump pulse, the number of laser pulses perforating a through hole is $3N$.

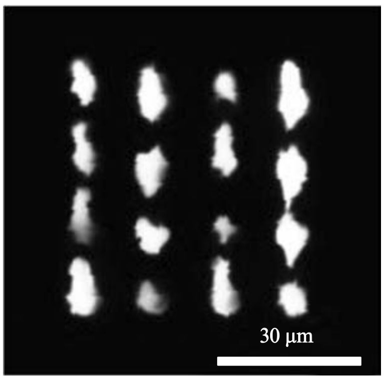

Figure 2. Photographs of a matrix of micron holes with damaged walls in 20-μm-thick aluminium foil.

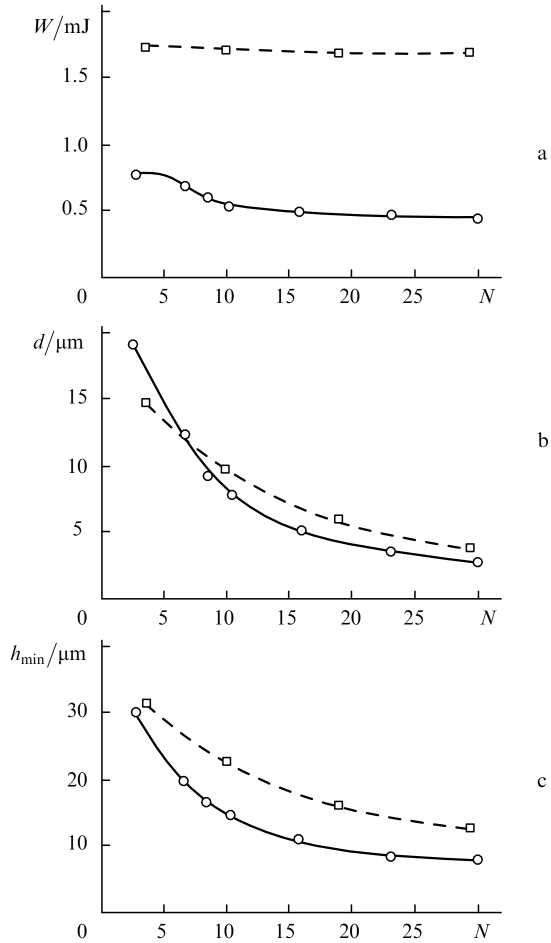

Figure 3. Experimental dependences of laser perforation parameters on the number N of pump lamp flashes needed to drill one though hole by (□) nanosecond and (○) picosecond lasers.

Figure 3a shows that the energy W spent for drilling one hole by the nanosecond laser is 1.6 mJ at any number N of pulses, while a decrease in N ($N \leqslant 7$) in the case of the picosecond laser leads to the increase in the energy W from 0.5 to 0.75 mJ. This can be explained by the fact that the visually observed near-surface plasma that appears due to the much higher radiation intensity of the picosecond laser considerably shields the laser radiation at a small number N. This agrees with the results of paper [6], where a noticeable shielding by the near-surface plasma was observed when the energy density of subpicosecond pulses exceeded 120 J cm^{-2}.

One can see from Fig. 3b that a decrease in N leads to a more rapid increase in the hole diameter d in the case of the picosecond laser than when using nanosecond pulses. This result is also explained by the formation of a near-surface plasma, which expands the hole [2, 6] when the energy density of picosecond pulses is above 30 J cm^{-2}, which takes place in our experiments. In particular, as N decreases from 30 to 3, the hole diameter d in the case of the picosecond laser increases from 2.5 to 19 μm, while the diameter of a hole drilled by the nanosecond laser increases from 3.5 to 15 μm, and, therefore, at small N, it is preferable to use the nanosecond laser to obtain holes of small diameters. With increasing N ($N > 30$), when plasma shielding is almost absent, the minimum hole diameter is 2.5 and 3.5 μm in the case of drilling by picosecond and nanosecond lasers, respectively. This can be explained by a much longer action of the laser pulse in the latter case, which, at the small difference in the energies spent for drilling a through hole by two different lasers, results in melting of the hole walls by nanosecond pulses and, hence, in an enlargement of the hole diameter. Thus, to obtain holes with the smallest diameters, it is reasonable to use picosecond lasers.

Figure 3c shows that the minimum possible space $h_{\min}$ between holes in perforated matrices also increases with decreasing N. One can see that, to obtain a higher hole density, it is preferable to use the picosecond laser even at small N. It is necessary to note that the ratio $h_{\min}/d$, which determines the hole density in matrices, increases with increasing N, while $h_{\min}$ and d themselves decrease; in particular, the ratio $h_{\min}/d$ increases from 1.6 to 3 in the case of picosecond drilling and from 2 to 4 in the case of the nanosecond laser. This indicates that the destruction of walls occurs due to their heating by a series of pulses, when, at a large N, the walls have no time to cool down between pulses, which is clearly demonstrated in Fig. 2. In the case of nanosecond irradiation, this heating is stronger, and, hence, holes must be spaced farther apart than in the case of picosecond treatment.

Figure 4 shows the photographs of matrices produced. The holes of the first matrix (Fig. 4a) are drilled using a small number ($N = 3$) of nanosecond pulses and, hence, have a large diameter ($d = 15$ μm). The spacing between holes is $h = 30$ μm, i.e., the total area of micron holes is 13% of the foil surface. The second matrix (Fig. 4b) is perforated using the picosecond laser with $N = 10$, owing to which we have $d = 6$ μm and $h = 15$ μm, i.e. the total area of micron holes is 20 % of the surface. The maximum total area of holes (31.5 % of the surface area) with $d = 19$ μm and $h = 30$ μm was obtained using the picosecond laser with $N = 3$.

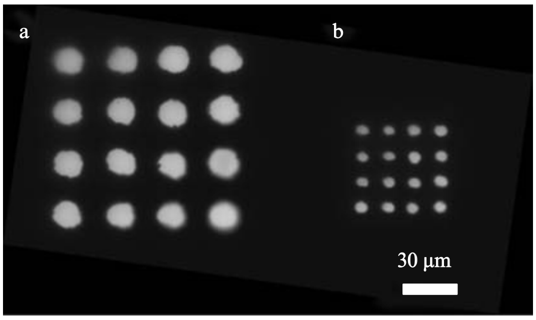

Figure 4. Photographs of matrices of closely spaced micron holes produced in 20-μm-thick aluminium foil.

4. Conclusions

Thus, we have studied the possibilities of perforating closely spaced micron holes by pico- and nanosecond lasers based on neodymium and $LiF:F_2^-$ crystals. Matrices of holes 2 – 20 μm in diameter spaced by 8 – 30 μm are obtained in 20-μm thick aluminium foil. The possibilities of increasing the hole density and decreasing the hole diameter by changing the laser irradiation parameters are shown. A sample of perforated aluminium foil has been obtained with the total area of micron holes exceeding 30 % of the surface, which is important for problems of microelectronics, medicine, and biology. We also can note that, using the second and fourth harmonics of these lasers, it is possible to produce nanomatrices with submicron holes in thin-film materials. It is expected that, using a more elaborate scanning scheme (when, instead of closely spaced rows, each subsequent hole is drilled at a larger distance from the previous one) will allow one to considerably decrease the minimum space between holes and increase the treatment rate.

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