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Direct laser printing using viscous printer's ink

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***Abstract*. The results of experiments on direct laser printing using viscous printer's ink with the help of a copper vapour laser (CVL)-based device are presented. The highly reflecting CVL cavity mirror was replaced by a spatial mirror modulator (SMM). Viscous printer's ink was used for printing. A pressure pulse produced at the boundary (on which an intensified and diminished image of the SMM was projected) between the ink and a transparency was used for transferring the ink to the plastic card. It was shown that the use of a CVL allowed a maximum printing speed of ~ 80 cm^2 s^{-1}, a resolution of 625 dpi and up to 15 gradations. The dependence of the emission intensity of the element being projected (pixel) on its diameter is studied. It is shown that an increase in the brightness of this element with decreasing its size is caused by the summation of the laser and amplified radiation.**

Keywords: *laser printing, copper laser, application of lasers.*

1. Introduction

Interaction of laser radiation with matter is widely used in various technological processes. Application of lasers allows energy to be concentrated ($10^2 - 10^3$ J cm^{-3}) in a microscopic volume ($\sim 10^{-9}$ cm^3) at the surface of a substance ($10^{-4} - 10^{-5}$ cm) for a short time (no more than 10^{-8} s) during which heat almost does not diffuse to the surrounding medium. Ablation of material, which usually accompanies this process, is used in various technological operations, such as drilling of pinholes, engraving, deposition of various materials on growth substrates, etc.

The possibility of using a pressure pulse produced in a microscopic volume to control directly the transfer of a material on a given object is of considerable interest. In this case, laser radiation is focused through a transparent substrate on the material – substrate interface. Such a technique of material transfer is called the 'laser direct writing' (LDW). The LDW technique was used in [1] for preparing high-resolution displays. It was shown in [2] that the LDW technique leads to a considerable economy in the process of preparing electronic components of a medium size. The LDW technique was used for fabricating miniature power supplies [3]. In our earlier papers [4, 5], we studied the possibility of using the LDW technique for printing with viscous inks without any intermediate operations. The application of UV lasers in all the above-mentioned cases has the following advantages: a low threshold energy of material transfer, a low penetration depth ($\sim 10^{-5}$ cm) that allows the use of thin ($\sim 10^{-4} - 10^{-3}$ cm) layers of materials, and the possibility of increasing the image resolution to several thousand dpi. The drawbacks of this technique include a low efficiency, a high cost for an output power no less than 10 W, and the need for using special UV optics and materials stable to UV radiation. Note also that the LDW methods developed earlier do not allow transfer of an array with a large number of elements during a single pulse. These problems necessitated the quest for other possibilities of realisation of LDW [6].

In this work, we study the possibility of using a copper vapour laser (CVL) in the image intensification mode for transfer of materials. For this purpose, we use viscous inks based on polymer compounds and modelling a wide range of materials suitable for various applications, for example, for fabricating organic light-emitting diodes (LEDs). Investigations of the optical characteristics of viscous inks used for printing show that the lowest energy threshold for transfer of inks in the visible spectral range can be achieved by using green ($\lambda = 510$ nm) and yellow ($\lambda = 578$ nm) CVL radiation.

2. Experimental setup and results

Figure 1 shows the experimental setup. Spatial mirror modulator (SMM) in the form of a transparency (*1*) was mounted in front of the highly reflecting mirror of a CVL. In most experiments, the transparency was a blackened metal plate with holes whose size and numbers were changed. The copper vapour tube of a modernised CVL [7] with the average output power enhanced to 10 W was used as active medium (*2*). The output laser mirror was made of plane – parallel glass plate (*3*). Transparent carrier (donor) (*7*) is a glass plate or a transparent polymer film on which the material is deposited. The diminished SMM image is projected with long focus lens (*5*) on the boundary between carrier (*7*) and material (*8*). The image reduction factor was determined by the distance between the lens and the SMM and is equal to about 13.5 in our case. Carrier (*7*) was mounted on a moving platform over substrate (*9*). The reduced SMM image can be displaced across carrier (*7*)

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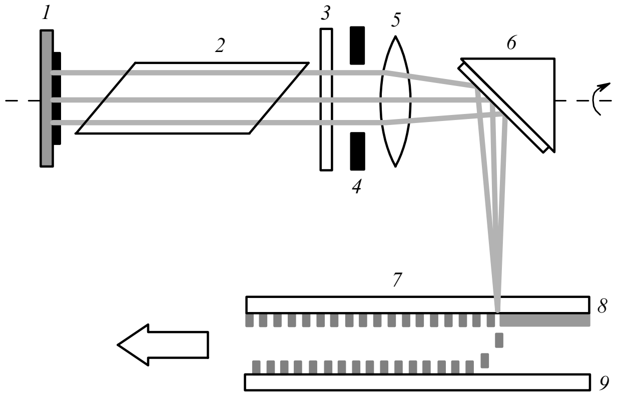

Figure 1. Scheme of the experimental setup: (*1*) SMM; (*2*) CVL active medium; (*3*) output mirror; (*4*) diaphragm; (*5*) lens; (*6*) rotating mirror; (*7*) glass substrate; (*8*) transferable material; (*9*) plastic card.

with the help of rotating mirror (*6*). Offset printing ink, mainly black, was used as the material being transferred. Blank plastic cards were used as the substrates on which the image was transferred. The potentialities of colour printing were demonstrated by using red, green, blue and yellow inks.

Inks of all colours were transferred. The minimum threshold energy density (~ 0.1 J cm^{-2}) was required for transferring black ink, while the transfer of yellow ink required the highest energy density (~ 1 J cm^{-2}). The dependences of the radiation power on the diameter d of a single central hole in the SMM were measured in two cases: (i) for a constant diameter $D_{\max}$ of output diaphragm (*4*) and a gradual increase in the diameter d of the hole to $D_{\max}$ [curves (*1–3*) in Fig. 2]; (ii) for a gradual increase in the hole diameter d and a cutoff of the amplified (nonlaser) component of radiation by diaphragm (*4*), which was accomplished by reducing the diameter D of diaphragm to $D = d$ [curve (*4*), Fig. 2]. The power was measured with an IMO-4 calorimeter mounted behind lens (*5*). Figure 2 presents the obtained theoretical and experimental results. Figure 3 shows the photograph of an enlarged fragment of the plastic card with directly printed pixels (150 μm × 150 μm), each consisting of nine subpixels of diameter 30 – 15 μm. In this case, the SMM was a 2 mm × 2 mm transparency with nine symmetrically arranged holes of diameter ranging from 500 to 250 μm. When only a single hole was used at the SMM centre, the maximum diameter of the pixel ($\sim$ 700 μm) was achieved for $d = 9$ mm, while the minimum pixel diameter ($\sim$ 15 μm) was achieved for $d = 200$ μm.

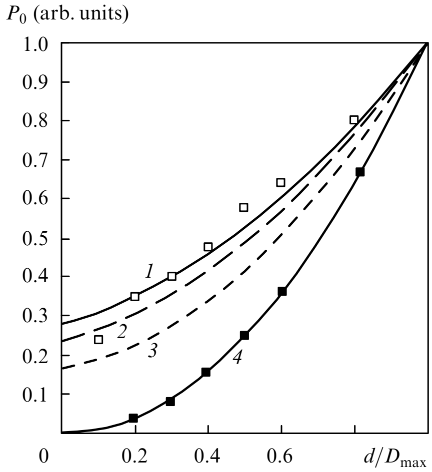

Figure 2. Experimental (symbols) and theoretical (curves) dependences of the relative emission power P_0 on the ratio $d/D_{\max}$ for the gain $k = 1.2$ [curve (*1*)], 1.3 [curve (*2*)] and 1.8 [curve (*3*)], and for the cutoff of the amplified (nonlaser) component of radiation [curve (*4*)] by diaphragm (*4*) (Fig. 1).

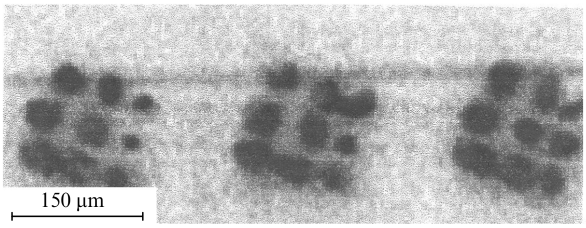

Figure 3. Photograph of a magnified fragment of the plastic card with pixels (150 μm × 150 μm). Each pixel consists of nine subpixels.

The possibilities of colour printing were demonstrated by preparing negative photographs of the jacket (dustcover) of Paul Eluard's book 'Letters to Gala', which were then used as transparencies. Inks of four colours: black, red, green and blue, were used in this case. Figure 4 shows the photograph of the jacket of the book with the portrait of Paul Eluard by Fernand Leger, as well as plastic cards with the colour image transferred by LDW technique.

Figure 4. Photograph of the jacket cover of the book 'Letters to Gala' with Paul Eluard's portrait by Fernand Leger, and plastic cards with the coloured imprint transferred on them.

3. Discussion of experimental results

Figure 5 shows a simplified equivalent optical scheme of the experiments on measurement of output radiation power behind the focusing lens. The diaphragm diameter D can be varied from $D_{\max} \gg d$ to $D = d$. One can see that the input aperture of the lens collects both the directed laser beam in

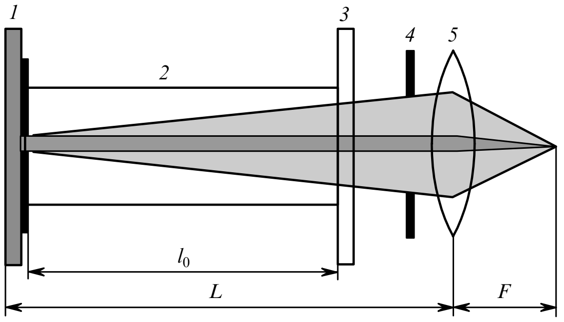

Figure 5. Equivalent scheme of the optical setup for measuring the output radiation power as a function of the ratio $d/D_{\max}$: (*1*) SMM; (*2*) active medium; (*3*) output mirror; (*4*) diaphragm; (*5*) lens.

the form of a cylinder and the amplified radiation limited by a truncated cone with a highly reflecting mirror at its tip. In the geometrical optics approximation, the total radiation power incident on the lens aperture can be estimated from the expression

$$P = V_1 n_0 + V_2 n_0 (k-1), \tag{1}$$

where V_1 is the volume confined by the truncated cone; V_2 is the volume confined by the cylinder; n_0 is the specific power of the active medium radiation in the amplification regime; $k = n/n_0$ is the gain during lasing; and n is the specific radiation power of the active medium during lasing.

By substituting the volumes of the truncated cone and cylinder into (1), we obtain

$$P = \frac{1}{3}\pi\frac{D^2}{4} l_0 n_0 \left[1 + \frac{d}{D} + \left(\frac{d}{D}\right)^2 (3k-2)\right], \tag{2}$$

where l_0 is the distance between the cavity mirrors; $D \geqslant d$; and d is the diameter of the highly reflecting mirror, which coincides here with the diameter of the central hole in the SMM. For $D = d$, only directional laser radiation passes through the lens aperture. In this case, the maximum power is given by

$$P_{\max} = \frac{\pi D^2}{4} l_0 n, \tag{3}$$

while the relative variation of power is

$$P_0 = \frac{P}{P_{\max}} = \frac{1}{3} k \left[1 + \frac{d}{D} + \left(\frac{d}{D}\right)^2 (3k-2)\right]. \tag{4}$$

One can see from Fig. 2 that the calculated variation in the relative power P_0 at the output behind the diaphragm agrees well with the experiment for various values of k and the ratio $d/D_{\max}$. When the amplified radiation is cut off by the diaphragm by varying d [curve (*4*), Fig. 2], only the intrinsic laser component is left and we obtain the relative variation of power $P_0 = (d/D_{\max})^2$. The experimental points were obtained for $D_{\max} = 0.5$ cm and for variation of $d/D_{\max}$ from 0.1 to 1. As d is decreased, the radiation intensity at the lens focus increases approximately as $1/d^2$, as mentioned in [8]. The variation in the relative intensity can be determined from the expression

$$I_0 = \frac{I}{I_{\max}} = \frac{1}{3} k \left[1 + \frac{d}{D} + \left(\frac{d}{D}\right)^2 (3k-2)\right] \left(\frac{d}{D}\right)^{-2}. \tag{5}$$

To provide the transfer of inks of main colours used for colour printing, the maximum threshold energy density E_{th} must be increased up to ~ 1 J cm^{-2}. For a given area S of the pixel, the threshold energy density E_{th} and clock pulse repetition rate F, the average laser radiation power P_{av} must be higher than or equal to $E_{\text{th}}SF$. Note that the average laser radiation power may be lowered considerably by using less viscous inks with a high absorption coefficient. Moreover, it can be assumed that the above effect of intensity enhancement due to summation of laser and amplified radiation can also lead to a considerable decrease in power required for a simultaneous transfer of four pixels constituting a 300 μm × 300 μm cell with subpixels of diameter 40 μm occupying ∼ 50 % of the cell area. The threshold radiation power in this case must be about half its value for a 100 % filling of the cell area.

4. Main parameters of the device for direct laser printing

The main parameters of the device include the printing rate, pixel transfer rate, spatial printing rate, resolution and the number of colour gradations. The printing rate is defined as

$$W = FS_0, \tag{6}$$

where S_0 is the area of the pixel array being transferred during a radiation pulse. The value of S_0 is determined by the threshold energy density E_{th} and the energy $E_{\text{p}} = P_{\text{av}}\gamma/F$ emitted per pulse, where γ is the coefficient characterising the total energy loss. One can easily see that

$$S_0 = \frac{E_{\text{p}}}{E_{\text{th}}} = \frac{P_{\text{av}}\gamma}{FE_{\text{th}}}. \tag{7}$$

In our case, $F = 10^4$ Hz, $P_{\text{av}} = 10$ W, $\gamma \sim 0.8$, and the threshold energy density E_{th} varies from 0.1 to 1 J cm^{-2} depending on the colour and characteristics of the ink. By substituting these values into (7), we find that the area S_0 of the pixel array being transferred during a radiation pulse is $\sim 8 \times 10^{-3}$ cm^2 for an average radiation power of 10 W. In this case, the maximum printing rate $W_{\max} = FS_0 = 80$ cm^2 s^{-1}, while the maximum rate of pixel transfer (for $S = 150$ μm × 150 μm $= 2.25 \times 10^{-4}$ cm^2) $W_{\text{p}\max} = W_{\max} \times S^{-1} = 10^5$ pixels s^{-1}.

In the case considered by us, the spatial frequency (number of pixels per inch) is $A^{-1} = 167$, the resolution (number of subpixels per inch) is $B^{-1} = 625$, and the total number of gradations is $G = (A/B)^2(g-1) + 1 = 15$, where g is the number of half-tones of the subpixels (in our case, $g = 2$).

5. Conclusions

Our studies have demonstrated the possibility of using image intensifiers for direct laser printing. We employed viscous inks that are used widely in offset printing. Such laser technology of controlled transfer of matter can also be used in electronic industry for preparing passive elements of microcircuits (capacitors, resistors, inductors, etc.), high-resolution displays and organic LEDs.

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