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Xerox treated tracing paper as suitable and accessible material for development of new laser beam–profiler technique

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On the base of systematic investigation, we have introduced as suitable and accessible material for the laser beam profile study appropriately treated tracing paper by standard Xerox type copy machine. As we show, the whitening of this material by laser illumination in combination with appropriate computer analysis can be a base for development of very competitive non-electronic technique for complex laser spot energetic profile study. Such whitening of the accidentally taken, non-defined, blacked materials and without any quantitative treatment, is used previously in the literature and in the laboratory practice only for visual illustrative marking (including also successfully - for the interesting cases) of laser spot. We have taken into account that the discussed registration presents, as a potential, some essential advantages in competition with the modern electronic beam-profilers - the registration is in very wide spectral range (from UV to IR - e.g. 0.3 - 3 μm and longer), cannot be disturbed by the electromagnetic noise and such spot visualization is extremely cheap and accessible. Via a complex investigation, we have developed a suitable technique of noted above type for real laboratory and practical laser spot study applications. As first important point in this development, we have found suitable, reproducible and widely accessible materials for spot registration that, in defined range of illumination (sufficiently large), offer possibility by using a standard computer treatment to obtain a good quantitative spot energetic parameters determination. The noted advantages of such type technique are shown in the work.

Keywords: material for laser beam profile study; new non-electronic technique for energetically laser spot study; registration in very large spectral range; non-disturbance by the electromagnetic noise.

INTRODUCTION

The work presents a systematic study of a treated by standard Xerox type copy machine tracing paper as a suitable and accessible material for laser beam profile evaluation. We show that this material combined with computer processing can be a base for development of very competitive apparatus of non-electronic Thermo-Paper Registration Approach (TePRA) for laser spot profile study. The principle of the TePRA is the whitening within the laser beam illuminated area of the black thermo-sensitive material. This registration is used in the literature and in the laboratory practice only for visual illustration of the laser spot marking [1] on the randomly chosen sensitive materials and without any quantitative processing. However, looking in details, the TePRA registration presents as a potential some essential advantages in competition with the electronic beam-profilers [2]. Firstly, as we have shown also in our experiments including two-wavelength lasers [3], a correct registration is not spectrally sensitive in a very wide range, for example - from UV to IR (e.g. 0.3 - 3 μm and longer). Secondly, this registration cannot be disturbed by electromagnetic noises and in addition such spot registration is extremely cheap and accessible. The adaptation of such laser spot marking as suitable technique for real laboratory and practical applications needs essential development. Important issues must be solved as i) to find suitable, reproducible and widely accessible materials for spot marking, ii) to determine the range of variation of the illuminating light intensity for correct and usable response of the materials and iii) to develop convenient procedure combined with standard computer processing of the marked spot. This is the aim of the present work.

EXPERIMENTAL

There are many blackened paper-materials, on which a laser beam makes a spot within the illuminated area. As laser beam sources we used pulsed Nd:YAG and Nd:Glass lasers. The laser output energy in most of the experiments was equal

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to the energy of the beam, illuminating the studied material, except the case where a fine plate filtes was used. The energy was measured with FIELDMAX energy meter, Coherent, USA and the pulse duration - with a 250 MHz storage oscilloscope. The study was performed at different laser parameters, generally for the energy between 0.3 J to 10 J and pulse length from 100 μs to 3000 μs. This was obtained by the Nd:YAG free mode of operation with spectrally and energetically controlled output, variable from 0.3 J to 1.8 J, repetition rate – single pulse to 1 Hz, and pulse length of 150 μs to 350 μs; with tuned lines – at 1.06 μm and at 1.32 - 1.36 μm. The second Nd:Glass laser in free lasing mode of operation produced output energy up to 10 J at 1.06 μm with pulse length from 2500 μs to 3000 μs. Also, we have investigated the laser beam in a short pulse, produced by passively Q-switched operation of the Nd:YAG laser with pulse length of 1 μs and energy of 0.4 J to 0.9 J at the line 1.06 μm. The lasers operated in a multimode regime.

Following the aim of the work, we performed a sequence of related experiments.

We started with testing of different blackened papers - conventional paper and blackened Xerox copy paper, and observed a common effect. If such paper is illuminated on the blackened side, the produced white spot has “mustaches“ and black traces within the spot (Fig. 1a,b). We explain this unfavorable fact with action of the light pressure on the formed cloud of vaporized (generally – ablated) micro-particles. The pressure returns back part of the particles to the spots area. Adhering of the heated ablated micro-particle also contribute to the noted undesired effect.

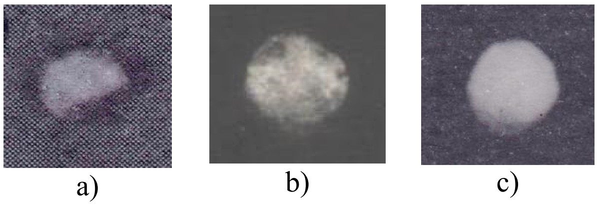
a) b) c)

Fig. 1. Whitened by laser illumination materials: (a) Usual black paper; (b) Xerox blackened tracing paper, illuminated on the blackened side and (c) - illuminated on the non-blackened side

Typical example of the described spot type is shown in Fig. 1: (a) is in usual black paper; (b) is made on the blackened side of Xerox- blackened tracing-paper (one passing, copy of the black paper) and (c) – at its opposite side.

Thus, the suitable material must be transparent, or partially transparent with a black layer on the one side and the illumination must be done at the non- blackened side. We have tested different paper and plastic materials of this type. Our attention was focused on paper-materials, which can be well defined and easily accessible for a large number of users. In summary, we found that most suitable for application is the tracing paper, blackened at one side by Xerox type copy machine. We have used the widespread tracing paper A4 92 gr/m^2 from Sihl Digital Imaging Company (the light transmission measured with a bulb lamp of pure tracing sheet gives ≈ 55 %). Note that we have compared the blackening, in a manner described below, for several different type Xerox-machines: Konica Minolta Dialfa Di 5510 – used basically in the work, also as testing - Sharp-MX-3500; Toshiba 2500c with standard toner powder (such as Toner Cartridge 360 for use in Konica digital copier, India). We did not observe noticeable difference of the blackened tracing-paper behavior. The same, not critical difference was observed using spot tracing with different scanners - BENQ S2W 3300u, CANON LIDE 25, Canon Pixma MX320. Our test of scanning spots from the tracing paper gives correct results when at the back side is placed white sheet (non-black or coloured one). The illumination of the blackened tracing paper by free-lasing beams with the described above parameters, made good white spot on the impact area, as a typical one, shown in Fig. 1(c). Under other conditions – Q-switching operation, noted above, the formed spot has white-brown color. Firstly, we tested the simplest procedure – to use transmission through the white spots under illumination with a low-power (~mW) homogeneous laser light (spot by spot) to determine the incident spot energy distribution. However, we found non-acceptable difference of typically ~ 40% and more. The tracing, point by point, along the diameter of the white spots, of transmission with a system composed from diaphragm-receiver-oscilloscope - also gave non-acceptable results. We explain this fact with appearance of white products due to the burning of the black layer and remaining products of the black layer, which combination leads to non-proportionality to the transmitted incident light intensity. The actual photograph of the part of whitened by the laser illumination spot (on the border with non-treated part black side) of the sheet is shown in Fig. 2. The formation of the layer of white burning products can be seen. Important for the purpose of the work is that at large energy density range from ≈ 0.5 J/cm^2 to ≈ 4 J/cm^2 the whitening is proportional to the illuminating energy density.

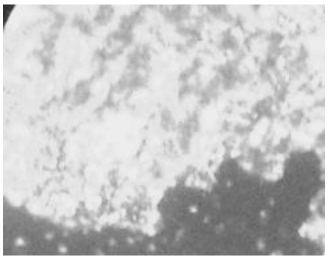

Fig. 2. Actual photograph of the part of whitened paper within the laser illuminated spot.

From series of measurements, we obtained that the whitening is proportional to the light energy density in a wide range. To describe the whitening we introduced the function $W_w(x,y)$ whose value in a given small area (dxdy) around the point (x,y) is proportional to the illuminating energy density $W_E(x,y)$ in the considered area. The coefficient of proportionality is denoted as k_1. This schematically is shown in Fig. 3.

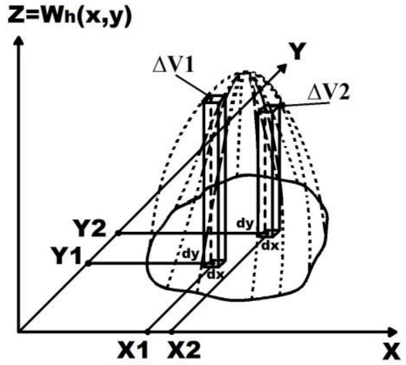

Fig. 3. To the analysis of the relation beam illumination energy - volume of the spatial figure within the whitening boundaries.

After the integration, we obtain:

$$V = \int_x \int_y k_1 \cdot w_E(x,y) dxdy = k_1 \cdot E_{jb} \qquad (1)$$

Here V is the volume below the given surface by the function $k_1 \cdot W_E(x,y)$, E_{jb} is the illuminating beam energy and k_1 is accepted to be constant. Thus, if the whitening is proportional to the energy density, the energy in the incident spot is proportional to the volume under the laser spot whitening envelope surface. This gives us good and easy approach to determine the energy density distribution in the marked laser spot (Fig. 4a) by taking the 2D trace (the radial distribution-Fig. 4b) and 3D volume envelope surface (the distribution in the spot plane – Fig. 4c), built by computer scanning of the whitening. The description can be done in relative units or knowing one of the values of $W_w(x_1,y_1)$ preliminary obtained at a given point x_1,y_1, to know the absolute value of energy density distribution in the different point (x,y). The correctness of the description can be verified taking as measure the ratio R of computed volume V versus illuminating pulse energy E or V/E = R. If R is equal for the group of spots on the blackened tracing paper with different energies, R can be considered as a proof for correctness of using the envelope surface (3D) and diametric lines (2D) for description of energy density distribution by the computer graphs. The correctness of whitening – computer processed energy density-description is in good agreement with the electronic technique of the type point by point (ITBRO) by moving a diaphragm within the spot on the paper and receiver-oscilloscope registration [3]. The cross-section lines of the volume envelope–2D image give the energy distribution in the spot cross-section, where the line is traced. If the 3D image has radial symmetry (at good laser adjustment) the tracing in the cross section across the peak gives the energy intensity distribution along the spot diameter (Fig. 3c).

a) b) c)

Fig. 4. (a) The spot on the tracing black paper and the computer image from the computer processed spot: **(b)** - the volume envelope (3D) and **(c)**-along the diameter.

Important issue is how the blackness of the tracing-paper impacts the whitening and the limits of linear whitening versus illuminating energy density. For this purpose, we prepared series of Xerox- blackened tracing paper by most common and widely accessible procedure.

The first three type sheets – the series A were produced by: one time blackening, noted as 1x, two times - 2x and three times - 3x, at “maximum” blackening regime of the machine and completely open shutter (day light illumination). For the considered corresponding series we added the notation of the series – A1x, A2x, A3x respectively. Second series (B sheets) was blackened in the same manner, but for operation regime “normal”. Also, we prepared the tracing-paper sheets, blackened by one time copy (C1x) and two times copy (C2x) of black paper at “normal” operation (with closed shutter). The corresponding measurements of the transparency, as characterization of the paper, gave for the transmissions: A1x – (10±1)%; for A2x- (1±0.1)% and A3x ≈ 0.1%; for B1x - (7±2)%, and for the sheet C1x - (7±1.5)% and C2x - (4.4±1)%. The observed fluctuations are related to transmission variation from place to place at the sheet, being practically negligible for A3x. In Fig. 5 are given the microscope photographs of pure parts of the sheets A (1x, 2x and 3x), illuminated underneath with the microscope bulb-lamp; the shown spots are with ~ 1 mm diameter. In the same figure, 2D and 3D images, corresponding to marking spots computer processing for the sheets A1x and A3x, are also shown. The pulsation of A3x is negligible in comparison with the case when A1x is used, where incompletely uniform blackening and many transparent points are presented.

This was one of the reasons to prefer application of A3x (or A2x - low pulsation as for A1x).

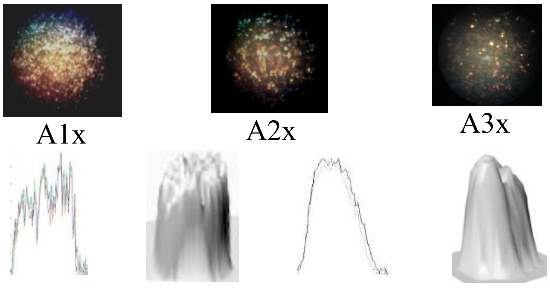

Fig. 5. The microscope photographs of the non laser light marked parts of the sheets with microscope bulb-lamp illumination in transmission –top; he bottom images correspond to marked spots 2D and 3D processing for the sheets A1x and A3x.

Important for the purpose of the work is that at large energy density range from ≈ 0.5 J/cm^2 to ≈ 4 J/cm^2 the whitening is proportional to the illuminating energy density. Given limits are for the sheet A3x, however they are not essentially different for the other samples, noted above. We have found these limits by studying the whitening in the spots, formed by the laser beam at different distances from the laser output, exploiting the beam spot divergence, or the spots enlarging by the lens, an example of the experiment that is given in Fig. 6. We studied correctness of registration thoroughly for the noted series of papers – prepared in very reproducible and widespread accessible manner. Thus we prepared the samples of stacked with each other pieces of the sheets A1x, A2x and A3x (Fig. 7a) and we formed the white spots with diameters varying between 6 and 7 mm and for energy density that is in range of 0.5 J/cm^2 and 4 J/cm^2 (Nd:YAG laser, multimode, near bell-like shape of energy density distribution by combination of TEM$_{00}$ +TEM $_{01}^*$ modes at 1.06 µm and 1.36 µm, and pulse length ~ 200 µs). As a quantitative measure of the suitability of the corresponding sheet to give correct energy density, we took, as stated above, the range of illuminating density that conserved the value of K$_1$ constant, given by the ratio V/E = R, where V is the computed volume and E is the illuminating energy. The plot of the parts of investigated sheets A1x–A3x with registered spots is shown in Fig. 7(a). In Fig. 7(b) are given the line of blackness for corresponding sheets. The spots on the sheet A3x in increased scale and their 2D and 3D computer processing images are given in Fig. 7(c)-7(e).

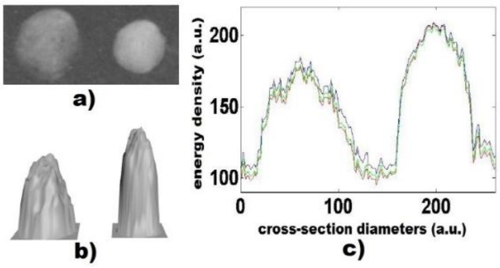

Fig. 6. Example - the enlargement of the spot of whitening with a distance for energy density dependence study.

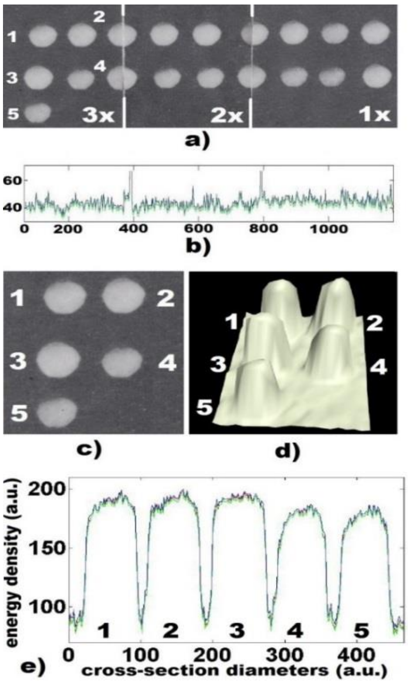

Fig. 7. **(a)** The plot of the parts of sheets under investigation A1x–A3x with registered spots; **(b)** the line of blackness for the different sheets; **(c)** the spots on the sheet A3x in increased scale and their **(d)** 2D and **(e)** 3D computer processing obtained images.

Processing of each sheet will be detailed on example of A3x, for which best results are obtained. After computer processing of the shown five (1,2,3,4,5) spots and with known energy that formed each of them, we obtained the average R_{av} = $(\sum V_i / E_i) / N$ where sum is for i=1-5, V_i and R_i are the volume and the energy of the spots numbered i and N=5: $R_{av}=(0.63/0.53 + 1.038/0.86 + 0.977/0.75 + 0.888/0.78 + 0.595/0.51) / 5 = 1.2$. We defined the deviation (or error) ΔR_i for each spot as $\Delta R_i = (R_i - R_{av})$ and the relative average deviation for the considered group spots of A3x sheets was $\Delta R_{av} = (|-0.01| + 0.01 + 0.1 + |-0.06| + |-0.04|)/ (5.Rav) = 0.036 \approx 4\%$. We calculated also the relative maximal deviation $\Delta R_{max} = (R_{max} - R_{min})/ \{(R_{max} + R_{min}) / 2\}$, where R_{max} and R_{min} are maximal and minimal deviation from R_{av}, respectively for the group, in practice a single case. For A3x we obtained $\Delta R_{max} = (0.1 + |-0.06|) / \{(1.3 + 1.14) / 2\} = 0.13 = 13\%$. Note that if we exclude the exceptional case of deviation for the spots, in our consideration, ΔR_{av} is ≈ 2 % with ΔR_{max} ≈ 6 %. In the same manner we have treated the noted other cases. The results are given in Table 1. The case B is very close to the case A2x - A3x and case C2x is better for the C type blackening. The investigations show that more suitable for the aim of spot registration is the tracing paper A3x (some illustration – Table 1).

Table 1. The experimental results confirming the correctness of the spots treatment (details in the text)

Sheet	ΔR_{av} (a.u.)J^{-1}	ΔR_{av} %	ΔR_{max} % (single case)	ΔR^{wec}_{max} %
A1x	1,1	6 %	24%	18%
A2x	1.3	5,8 %	18%	16%
A3x	1.2	3,6 %	13%	5,8%
C2x		4,3%	13,7%	-

Important experiment was to study the dependence on the illuminating wavelength. Using our laser, we obtained for the two wavelengths – 1.06 μm and 1.36 μm [3] no change of K_1. This is the case for all considered in the work blackened tracing papers. The example for the paper type A3x is shown in Fig.8; (spots at 1.06 μm and 1.36 μm for 1.1 J and 0.5 J illuminating energy and pulses duration 250 μs respectively). This can be expected for general reasons (thermal and ablation effect). The present results concern the investigation of the illumination with pulse length in the range 100 – 3000 μs. This is very common case of laser use – e.g. solid-state lasers in regime of free generation. The effect of bleaching arises from combination of material burning and ablation processes. The two effects are evident – the burning from the microscope photographs with shown typical case in Fig. 2. The ablation is evident in the experiments by formation of cloud after the shots of the laser pulse. It can be noted that, for cw light illumination, the effects on the studied material are quite different and not suitable for the discussed treatment.

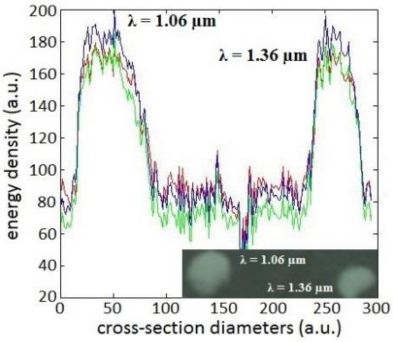

Fig. 8. The 2D computer processing graphs of two spots -at 1.06 and 1.36 μm. The spots (in the inset) are marked on the blackened tracing paper A3x type

SUMARISING THE EXPERIMENTAL RESULTS AND DISCUSSION

Summarizing the experimental results gives:

In summary, Xerox treated tracing paper in combination with standard computer treatment can be a base of development of advantageous techniques for laser beam profile registration:

- this material has been selected experimentally among a number of potential materials as most suitable; this study gives optimal conditions how to prepare and use the samples;

– applicability is shown for correct registration in a large energy density and pulse lengths range of the illuminated beam (0.3- 4 J/cm^2 ; 100-3000 us), that is typical for the widely used laser -Nd:YAG, ND:Glass; Ruby, Ho:YAG, Er:YAG; the typical error is within the limits of 4-5 %, with maximal value for a single case of ~ 13 % (for the shown in the work optimal treatment tracing paper, as it is shown in Table 1);

- the experiments confirm the expected no dependence on the wavelength of the laser beam under investigation;

- no noticeable dependence on the prepared samples when using different standard and widely accessible Xerox-type machine and tracing papers;

In addition, the prepared simples are very cheap and accessible.

CONCLUSION

We presented in the work original technique for laser beam-profiling and found a very suitable material for its application. The technique is competitive with the electronic beam-profiler with the proposed and positively characterized by us material for registration – the simplest suitably Xerox-blackened tracing paper. As additional advantage the technique is non-wavelength sensible, also cannot be disturbed by electromagnetic noise.

We have shown its real and correct applicability as a beam profiler for the laser pulses that is typical for the widely used lasers, such as Nd:YAG, generating at different wavelengths, including the case of two-wavelength operation [3], Nd:Glass, the Yb:YAG, Ho:YAG, Er:YAG, flash lamp pumped Dye, semiconductors etc. Except more important possibility for energy distribution, the shown dependence additionally gives also the approach to determine the laser beam energy using comparison of the calculated spot volume with this of a given etalon spot on the same paper.

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КСЕРОКС ТРЕТИРАН ПАУС КАТО ПОДХОДЯЩ И ДОСТЪПЕН МАТЕРИАЛ ЗА РАЗВИТИЕ НА НОВА ТЕХНИКА ЗА РЕГИСТРАЦИЯ НА ПРОФИЛА НА СЕЧЕНИЕ НА ЛАЗЕРЕН СНОП

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(Резюме)

На базата на систематично изследване, ние въвеждаме като подходящ и достъпен материал за изследване на профила на лазерния сноп подходящо обработена хартия от стандартна ксерокс копирна машина. Както показваме, побеляването на този материал при осветяване с лазер в комбинация с подходяща компютърна обработка може да бъде база за развитие на много конкурентна неелектронна техника за комплексно изследване на енергетичния профил на лазерното петно. Такова побеляване на случайно избран, недефиниран, почернен материал и без някаква количествена обработка, е използвано и преди в литературата и в лабораторната практика, но само за визуално илюстративно маркиране на лазерното петно (също и успешно за илюстрация на интересни случаи). Ние взехме под внимание, че обсъжданото регистриране представя, като потенциал, някои съществени предимства в конкуренция с модерния електронен регистратор на профила на снопа. Разработваната от нас техника е използваема в много широк спектрален диапазон (от УВ до ИЧ – напр. 0.3 - 3 μm и повече), не се влияе от електромагнитните шумове и е изключително евтина и достъпна. Чрез комплексно изследване, ние разработихме конкурентна техника от отбелязания по-горе вид за реални приложения в лабораторни и практически изследвания на лазерното петно. Като първа важна точка в това развитие, е намерения подходящ, възпроизводим и широко достъпен материал за регистрация на петното, който в определен, достатъчно широк диапазон на параметри на лазерното лъчение предлага възможност чрез използване на стандартна компютърна обработка да се получи добро количествено определяне на енергетичните параметри на петното. Отбелязаните предимства на такъв тип техника са показани в работата.