

# Coloring linens with excimer lasers to simulate the body image of the Turin Shroud

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The body image of the Turin Shroud has not yet been explained by traditional science; so a great interest in a possible mechanism of image formation still exists. We present preliminary results of excimer laser irradiation (wavelength of 308 nm) of a raw linen fabric and of a linen cloth. The permanent coloration of both linens is a threshold effect of the laser beam intensity, and it can be achieved only in a narrow range of irradiation parameters, which are strongly dependent on the pulse width and time sequence of laser shots. We also obtained the first direct evidence of latent images impressed on linen that appear in a relatively long period (one year) after laser irradiation that at first did not generate a clear image. The results are compared with the characteristics of the Turin Shroud, reflecting the possibility that a burst of directional ultraviolet radiation may have played a role in the formation of the Shroud image. © 2008 Optical Society of America

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## 1. Introduction

The Turin Shroud is one of the most studied and investigated objects worldwide, both for scientific and religious purposes, and the results of these studies have been and still are widely debated by international groups of different disciplines [1–15]. The Turin Shroud (the Shroud from now on) is a herringbone linen fabric 4.4 m long and 1.1 m wide; each linen yarn is made by ~100 fibers, each one about 15  $\mu\text{m}$  in diameter. The Shroud appears to show frontal and dorsal images of a man crowned with thorns, scourged, and crucified, which some Christians interpret as being the body of Jesus Christ dead on the Cross.

The most interesting features of the Shroud are the two faint body images that have peculiar characteristics [5]. The extensive chemical and physical measurements made in the frame of the Shroud of Turin Research Project (STURP, 1980) [5,11] show

that these body images are not painted, printed, singed by a heated bas-relief, or rubbed on a sculpture. More recent studies [10,12–15] show that a source of energy (either heat or light) may account for the main image characteristics. Reference [5] listed, among others, 42 chemical and physical features of the Shroud body images, and to date all attempts to reproduce an image on linens having these characteristics have been unsuccessful. Many authors obtained images having a similar macroscopic aspect, but none of them matches the microscopic features of the Shroud images. In this respect, the origin of the body images is still unknown, although recent experimental results show that the corona discharge caused by a very high electric field between the body and the cloth that also generated ultraviolet (UV) radiation may have played a role in the formation of the Shroud image [14].

In the recent past, the Excimer Laser Laboratory at Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA) Frascati obtained a permanent coloration of cotton and wool fabrics [16] and syn-

thetic textiles [17] with XeCl (emission wavelength  $\lambda = 0.308 \mu\text{m}$ ) excimer laser irradiation. At the same time [18,19], some attempts to obtain a body image irradiating linen by a CO<sub>2</sub> laser ( $\lambda = 10.6 \mu\text{m}$ ) failed, mainly because the infrared laser radiation did not allow a very thin surface layer coloration of the fibers ( $0.1 \mu\text{m}$ – $0.5 \mu\text{m}$ ) as in the case of the Shroud images [5]. On the contrary, UV radiation has a short penetration depth in the fibers, thus allowing in principle a surface layer coloration close to that of the body images in the Shroud. To the best of our knowledge, the coloration of linen by using excimer laser irradiation was never reported in the literature. In agreement with the hypothesis of the UV radiation generated by corona discharge to explain the Shroud image, we used our XeCl UV excimer laser pulses to perform a linen coloration.

## 2. Experiment Plan

In order to test the capability of UV radiation to obtain Shroud-like images, we decided to irradiate linen fabrics by a sequence of laser pulses corresponding to the hypothetical burst of energy correlated to the Shroud image. The experiments discussed in this paper are therefore addressed to determine the necessary conditions (number and duration of laser pulses, intensity, and time interval between consecutive laser pulses) to image linen fabrics similar in bleaching and sizing to that of the Shroud. Moreover, to test the hypothesis of Shroud images that appear in a relatively long period (a few years) after the irradiation of an energy source that at the moment did not generate a clear image [7], we tested the effects of both natural aging and artificial aging obtained by heating the irradiated samples on latent images.

The paper is organized as follows. Section 3 details the results of the experimental tests on two different samples of fabric to find the optimum laser parameters to achieve linen coloration. Section 4 describes the aging effect on nonimaged samples to unveil if a latent image could be impressed on linen. In Sections 5 and 6 we compare the characteristics of colored fibers with those of the Shroud image. The

results and perspectives are summarized in Section 7.

## 3. Irradiation Experiments

We used two XeCl ( $\lambda = 0.308 \mu\text{m}$ ) laser systems (namely, the laser facility Hercules [20,21] emitting 4 J in a 120 ns pulse width and a Lambda Physik LPX-305 emitting 0.4 J in a 33 ns pulse width) to irradiate a light brown linen fabric (linen F) manufactured recently according to the ancient technology and a white linen cloth (linen B) woven in the first half of the twentieth century and never used before for any purpose.

The experimental setup is schematized in Fig. 1. The energy (power) density on the linen is varied by moving the target along the optical axis of the lens. Both temperature (20 °C) and relative humidity (55%) were constant during each experimental run, as the whole laboratory is air conditioned.

### A. Irradiation: Long Laser Pulse Width Case

Irradiation by the Hercules laser pulses having an energy density on the target in the range of  $0.44$ – $16 \text{ J/cm}^2/\text{pulse}$  (corresponding to an intensity range of  $4$ – $140 \text{ MW/cm}^2/\text{pulse}$ ) did not produce any visible coloration on the linens. Above  $1.5 \text{ J/cm}^2$  we observed a partial ablation of the irradiated yarns, the ablation effect being proportional to the energy density on the linen.

Then, we repeated the irradiation after both linens were immersed in a saturated solution of sugar and water at 50 °C, to create a polysaccharides sheath wrapping the fibers [22]. In this case, when observed by a 20× optical microscope, the irradiated sugared linen F showed a dozen strands of yarn that were colored burnt-sugar-like, as shown in Fig. 2. No effects on sugared linen B were observed.

### B. Irradiation: Short Laser Pulse Width Case

We repeated the irradiation on sugared linens by using the LPX-305 laser. We moved the linen (see Fig. 1) in such a way that the energy density on it was the same as that which produced the burnt-sugar-like yarns using Hercules (see Fig. 2). The results are summarized in Tables 1 (linen F) and 2 (linen B).

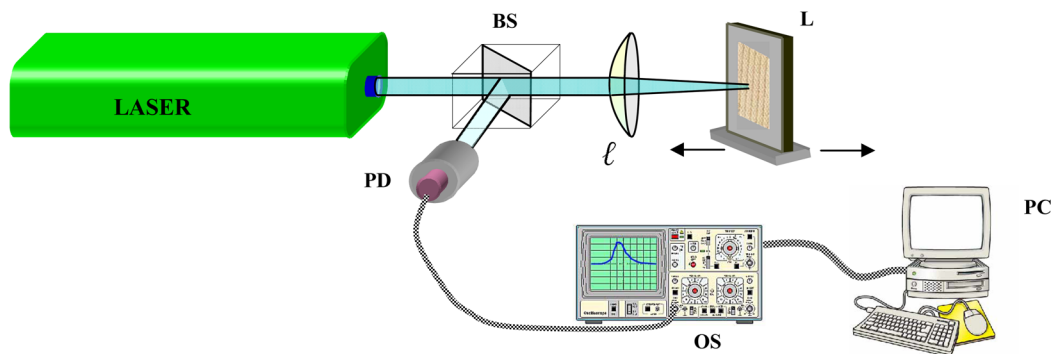


Fig. 1. (Color online) Experimental setup of linens' irradiation. BS, beam splitter;  $\ell = 1 \text{ m}$  focal length lens; L, linen; PD, photodiode; OS, oscilloscope TDS520; PC, computer.

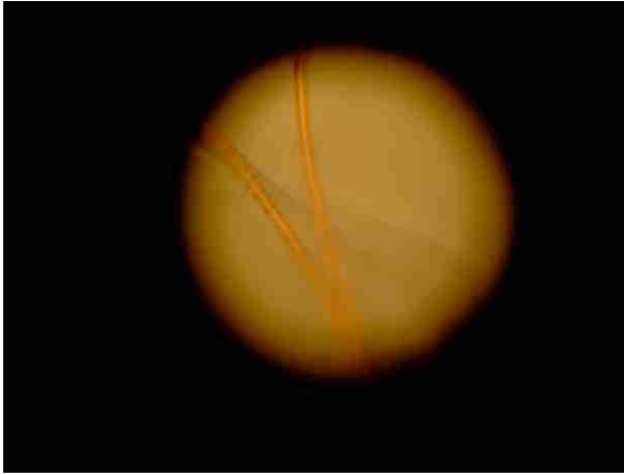


Fig. 2. (Color online) Sugared linen F irradiated by ten pulses of the laser Hercules (energy density  $0.44 \text{ J/cm}^2/\text{pulse}$  and intensity  $3.5 \text{ MW/cm}^2/\text{pulse}$ ). Image size, 1.25 mm.

Tables 1 and 2 show that, when irradiating sugared linens with the same energy density that colored a dozen yarns of sugared linen F (see Fig. 2) but delivered in a time 3.6 times shorter (due to the different pulse widths of the Hercules and the LPX-305), we obtained a brown spot in both linens. Observation with an optical microscope of colored linens did not show morphologic differences between the irradiated and the nonirradiated yarns.

The range of values of laser parameters that produce the macroscopic coloration is very narrow: Tables 1 and 2 show that the same number of laser shots delivered in two different sequences (100 running or  $50 + 50$ ) give different coloration results despite having the same energy density and repetition rate. Moreover, Table 2 shows that the same number and the same sequence of shots can color linen B depending on the repetition rate, i.e., on the length of time between consecutive shots. Last, the changing repetition rate  $f$  and number of shots  $N$ , maintaining their product  $f \times N$  constant, and fixing the energy density give different coloration results; see the second and third rows of Table 1. In summary, Tables 1 and 2 show that we are facing a phenomenon having

unusual behavior with respect to the prevalent laser–fabric interaction rules [16].

To show the influence of the polysaccharides sheath on the coloration effects, we irradiated both nonsugared linens under the same experimental conditions in Tables 1 and 2. The results are summarized in Tables 3 (linen F) and 4 (linen B).

For the same 9 Hz repetition rate the spot is sharper and darker in the nonsugared linens (see the second row of Tables 1 and 3 and of Tables 2 and 4). In general, Tables 3 and 4 confirm the critical dependence of the coloration effects on the repetition rate and on the sequence of laser shots as emphasized in Tables 1 and 2. A comparison of the third and the fifth rows of Table 4 shows that, when fixing the sequence of laser shots and energy density, changing the frequency from 9 to 50 Hz does not change the coloration effects on linen B. Moreover, increasing the energy density by 20%, we obtain almost the same coloration with half pulses (see the second and the third rows of Table 4). Linen F shows a different behavior (see the fourth row of Table 3 and the fifth row of Table 4), probably because the two linens have quite different absorption coefficients of light at the laser wavelength of  $0.308 \mu\text{m}$ .

A further difference between sugared and nonsugared linens is indicated by observation with the optical microscope: in the nonsugared case both linens show a morphologic difference in irradiated and nonirradiated yarns. A  $20\times$  magnification is sufficient to unveil a change in the surface of irradiated fibers of linen F (see Fig. 3). Linen B shows the same behavior (see Fig. 4, magnification  $100\times$ ). In contrast, we did not observe any morphologic differences in irradiated and nonirradiated yarns of sugared linens.

### C. Summary of Irradiation Results

Figure 5 summarizes all the irradiation data in a plot of macroscopic results for different laser intensities and pulse widths. As a first-step approximation we can draw a line between  $10^8 \text{ W/cm}^2$  and 400 ns that divides the figure into two regions. The upper right is a no-coloration region, where the laser intensity is above the ablation–damage threshold. The lower left is a region where linen coloration can be obtained.

Table 1. Parameter Values for Sugared Linen F Irradiated by the LPX-305 Laser and Corresponding Macroscopic Results

Repetition Rate (Hz)	Energy Density ( $\text{J/cm}^2$ )	No. of Shots	Intensity ( $\text{W/cm}^2$ )	Macroscopic Results
9	0.45	$50 + 50$	$13.6 \times 10^6$	None
9	0.45	100	$13.6 \times 10^6$	Brown spot, slightly visible on the back
45	0.45	20	$13.6 \times 10^6$	None

Table 2. Parameter Values for Sugared Linen B Irradiated by the LPX-305 Laser and Corresponding Macroscopic Results

Repetition Rate (Hz)	Energy Density ( $\text{J/cm}^2$ )	No. of Shots	Intensity ( $\text{W/cm}^2$ )	Macroscopic Results
9	0.45	$50 + 50$	$13.6 \times 10^6$	None
9	0.45	100	$13.6 \times 10^6$	Brown spot, slightly visible on the back
1	0.45	100	$13.6 \times 10^6$	None

**Table 3. Parameter Values for Linen F Irradiated by the LPX-305 Laser and Corresponding Macroscopic Results**

Repetition Rate (Hz)	Energy Density (J/cm <sup>2</sup> )	No. of Shots	Intensity (W/cm <sup>2</sup> )	Macroscopic Results
9	0.46	50 + 50	16.1 × 10 <sup>6</sup>	Yellowing
9	0.46	100	16.1 × 10 <sup>6</sup>	Sharp brown spot, visible on the back, too
50	0.39	50	13.9 × 10 <sup>6</sup>	None
50	0.39	50	21.2 × 10 <sup>6</sup>	Holed and burned linen
50	0.59	10	21.2 × 10 <sup>6</sup>	None

**Table 4. Parameter Values for Linen B Irradiated by the LPX-305 Laser and Corresponding Macroscopic Results**

Repetition Rate (Hz)	Energy Density (J/cm <sup>2</sup> )	No. of Shots	Intensity (W/cm <sup>2</sup> )	Macroscopic Results
9	0.46	50 + 50	16.1 × 10 <sup>6</sup>	Slight spot
9	0.46	100	16.1 × 10 <sup>6</sup>	Sharp brown spot, also visible on the back
9	0.59	50	21.2 × 10 <sup>6</sup>	Sharp brown spot
9	0.59	10 + 10 + 10 + 10 + 10	21.2 × 10 <sup>6</sup>	Slight yellowing
50	0.59	50	21.2 × 10 <sup>6</sup>	Sharp, dark brown spot

Indeed, even when no visible results are obtained by UV laser irradiation, a suitable aging technique can color the irradiated yarns, as discussed in Section 4.

Figure 6 focuses on the results in Tables 3 and 4. The intensity-threshold effect is evident: 50 shots at 50 Hz leave the linens unaltered when the intensity is below threshold, but burn them when the intensity is high. This figure also shows a cumulative effect with the number of consecutive shots: 50 consecutive shots at high laser intensity color linen B, while 50 shots divided into 5 bursts at the same intensity do not. Analogously, 100 consecutive shots at medium intensity do color both linens, while 100 shots divided into two bursts are not sufficient to do it.

#### 4. Aging

Aging the irradiated samples was also tested to detect if a latent image could be impressed on linen irradiated by our excimer laser pulses. We cut half of the slight yellow laser spot on linen B corresponding to the fourth row of Table 4. One of the two parts was

heated 15 s by an iron at the temperature of  $190 \pm 10^\circ\text{C}$ , and Fig. 7(a) shows visible coloration of the heated part of the fabric in the area covered by the laser spot. The heating process (which simulates aging) colored the irradiated region.

A very interesting feature is displayed in Fig. 7(b), which shows the same samples of Fig. 7(a) one year later. A coloration appears even in the unheated part of the linen. This means latent images appear on a time scale of a few years after irradiation. To our knowledge, this is the first direct evidence of aging effects on latent images in linen fabrics irradiated by laser light.

#### 5. Other Experimental Analyses

Two single yarns of linens F and B are shown in Fig. 8. Both yarns are colored in the area exposed to the laser pulses and not in the region covered by other warp yarns. This means the UV laser radiation cannot pass through the single yarn. Figure 9

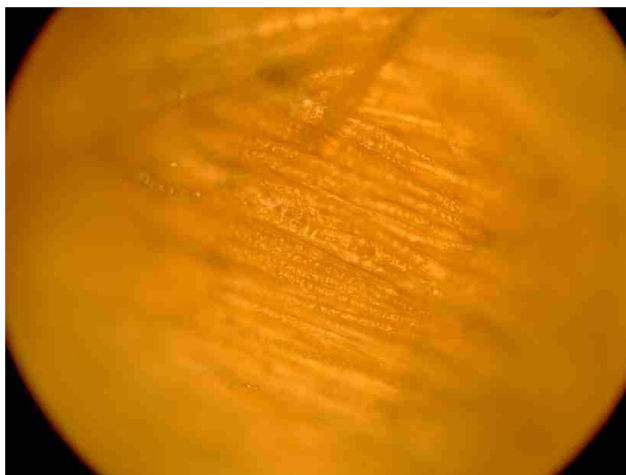


Fig. 3. (Color online) Linen F irradiated by 100 LPX laser pulses (energy density 0.46 J/cm<sup>2</sup>/pulse and intensity 16.1 MW/cm<sup>2</sup>/pulse); see the second row of Table 3. Image size, 1.25 mm.

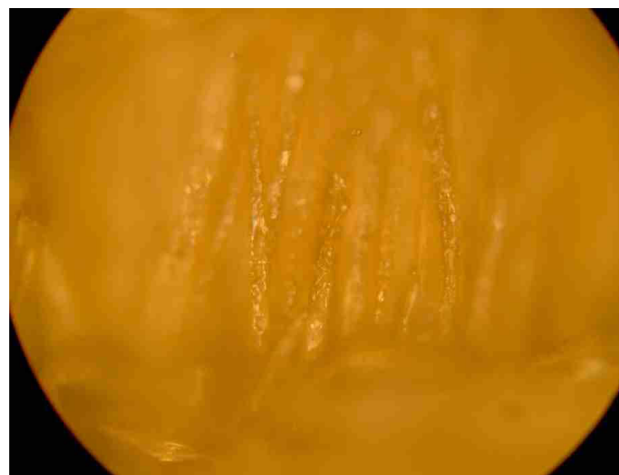


Fig. 4. (Color online) Linen B irradiated by 100 LPX laser pulses (energy density 0.46 J/cm<sup>2</sup>/pulse and intensity 16.1 MW/cm<sup>2</sup>/pulse); see the second row of Table 4. Image size, 0.25 mm.



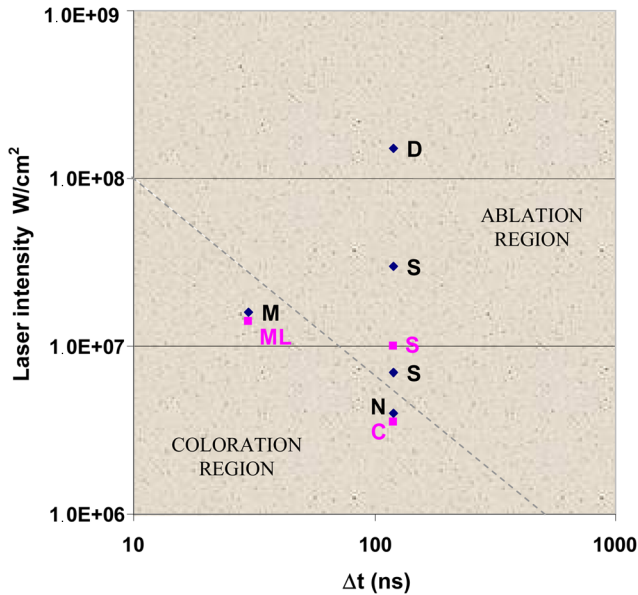


Fig. 5. (Color online) Linen irradiation results for different light intensities using the lasers LPX (pulse width 33 ns) and Hercules (pulse width 120 ns) lasers. Diamond, nonsugared linen, square, sugared linen; M, sharp brown spot, showing morphologic changes; ML, brown spot, without morphologic changes; D, damaged yarns; S, ablated yarns; N, no visible results; C, some burnt-sugar-like yarns.

shows that about 25% of the yarn of linen B is colored. The percentage of yarn section colored depends on many factors, including the number of laser shots, the mutual distance of fibers in each yarn, and the light absorption coefficients of linens (linen F absorbs much more energy than linen B at 0.308  $\mu\text{m}$ ). Most important, the absorption coefficient of light increases during irradiation, as the last laser pulses interact with fibers colored by previous laser shots.

Figure 10 shows a partially colored fiber of linen B immersed in oil observed in cross polarization to

identify the stress characteristics of the fiber. The nonirradiated region has the usual aspect of a recently made linen. In contrast, the irradiated region of the fiber displays stressed areas coupled with high-fragility regions with cracks. The dehydration of the fiber cellulose is in fact associated with an increment of the fiber fractures (pointed out by birefringence at the location of the defects). Also the Shroud image fibers, even if their cellulose is not colored, show a multicolored aspect like that shown in Fig. 10 when seen in cross-polarized light because their external layer is overstressed and crackled [11].

## 6. Comments and Remarks

Both F and B linen fabrics show a permanent coloration after excimer laser pulse irradiation. This coloration is a threshold effect: that is, linens are never colored when irradiated below the threshold intensity value, independent of the number of laser shots. In our experiments, we observed that the two irradiated linens show different intensity thresholds because they have different absorption coefficients at the laser wavelength of 0.308  $\mu\text{m}$ .

The range of laser parameters allowing coloration is very narrow: in fact, a shift of the sequence of laser shots, the repetition rate, the number of shots, and/or of the laser pulse width may change the coloration effect. In particular, the laser pulse width plays a fundamental role in the coloring effect (see Fig. 5).

As the Shroud fibers are covered by a thin ( $\sim 2 \mu\text{m}$ ) polysaccharides layer, the coloration effect has been tested in both sugared and nonsugared linens (see Fig. 5). The coloration of the nonsugared linen is darker than the sugared one, and the microscope observation reveals that only nonsugared linens, when colored, show a morphologic change of the surface of irradiated fibers (see Figs. 3 and 4).

Figures 8 and 9 show that UV laser radiation cannot pass through the single yarn, and in the case of

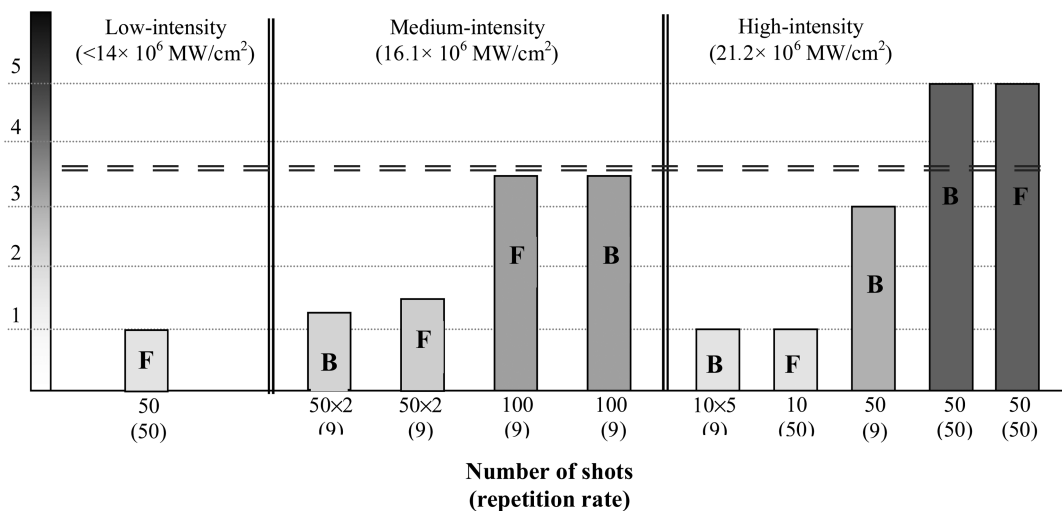


Fig. 6. Histogram of the results of Tables 3 and 4. Vertical, coloration effect on linens (arbitrary units). Horizontal, number of shots and repetition rate. B, linen B; F, linen F. Vertical lines divide the histogram into three regions: low laser intensity (left) medium intensity (middle), and high intensity (right). The horizontal dashed line corresponds to the boundary between coloration and damage.

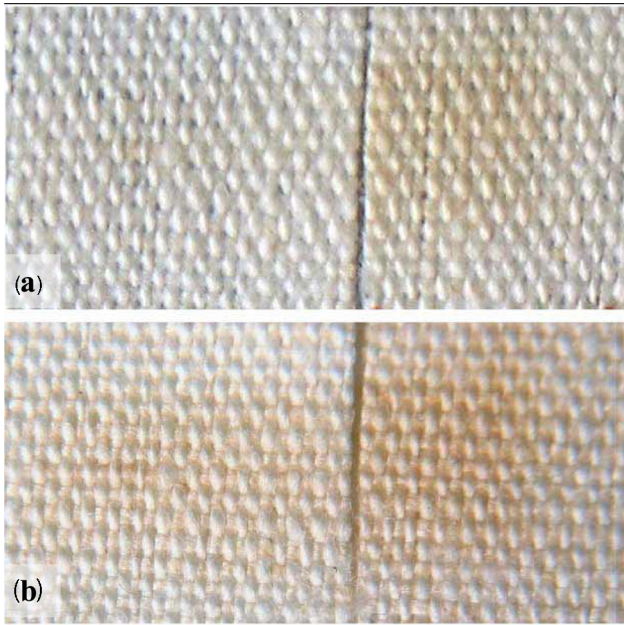


Fig. 7. (Color online) Linen B irradiated in the conditions of the fourth row of Table 4. (a) Left: irradiated part. Right: irradiated part heated 15 s by an iron at 190 °C. The heating process (which simulates aging) colored the region corresponding to the laser spot. (b) The same samples of (a) one year later.

linen B about 25% of the yarn section is colored. This means that a relatively large number of laser shots when delivered in a short time may cause a secondary thermal diffusion that contributes to color the internal fibers. A progressive thermal gradient effect may also explain the different coloration results achieved using the same number of laser shots delivered in two different sequences (100 running or two bursts of 50, as well as 50 running or five bursts of 10) as shown in Fig. 6. A substantial reduction of the thickness of colored yarns (thus improving the simi-

larity with the Shroud images) can be obtained by reducing the laser wavelength: in fact, the smaller the wavelength, the smaller the penetration depth and the higher the energy per unit volume deposited into the linen. As a consequence, a smaller number of laser shots is required to obtain surface coloration, and, also, residual thermal spread is greatly reduced. The best would be a coloration obtained in single shot, to make direct reference to the hypothesized burst of energy that may have generated the Shroud images [2,10].

The results in Table 4 suggest that a substantial reduction in the number of laser pulses necessary to color the linen can also be obtained by increasing the laser peak power. It is convenient to increase the peak power by shortening the laser pulse width to further increase the photochemical effects, reducing the thermal ones.

In agreement with Fig. 10, the colored fibers are more discontinuous and fractured with respect to the nonirradiated fibers. This UV-induced fragility is analogous to that observed in the image fibers of the Shroud.

Artificial aging by heating at 190 °C causes a visible coloration of the irradiated spot on linen B, as shown in Fig. 7(a). Although at this working point (corresponding to the fourth row of Table 4) the number of laser shots with this time sequence was not able to color the linen [see the left side of Fig. 7(a)], the irradiation did in fact change the cellulose structure, allowing the latent image to develop later either under heating, which simulates aging [Fig. 7(a)] or after natural aging [namely, one year after irradiation; see Fig. 7(b)]. This interesting result is consistent with the hypothesis that Shroud images might appear after a relatively long period (a few years) after irradiation by an energy source that at first did not generate a visible image [7].



Fig. 8. (Color online) Single yarn of linen F (above) and linen B (below) after irradiation.

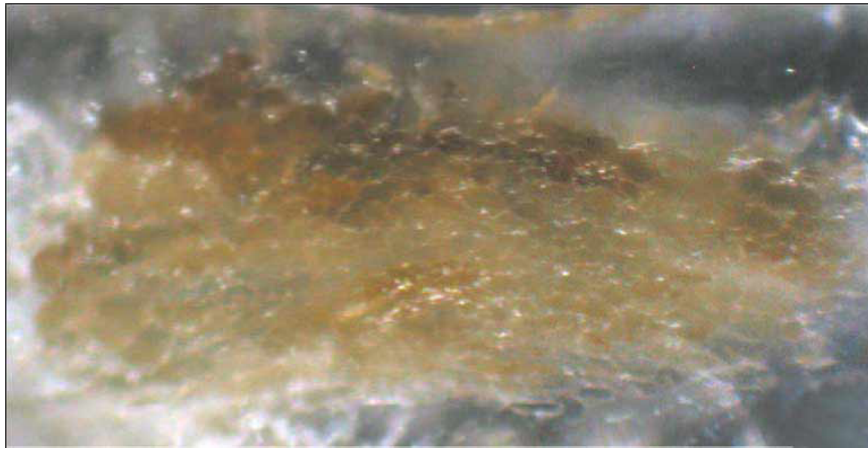


Fig. 9. (Color online) Cross section of a colored yarn of linen B let into the paraffin wax.

## 7. Conclusions

We irradiated two linen fabrics with XeCl excimer laser pulses ( $\lambda = 0.308 \mu\text{m}$ ) having different pulse widths to evaluate the possibility that a burst of directional UV radiation might have played a role in the formation of the Shroud image.

We have obtained a permanent macroscopic coloration of the linen. The coloration is the result of a threshold effect, and the range of UV radiation parameters suitable to generate linen coloration is surprisingly narrow (see Tables 1–4 and Figs. 5 and 6). The microscopic characteristics of irradiated yarns and fibers show analogies to those observed in the Shroud images, for instance, color distribution, appearance in cross-polarized light, and fragility (see Figs. 7, 8, and 10), while other characteristics still do not fit those of the Shroud, for instance, the depth of coloration (see Fig. 9). Also, the morphologic change that appears in the nonsugared linen fibers (see Figs. 3 and 4) disappears when the colored fibers are covered with a thin sugar layer, as in the Shroud fibers.

Following these results, we have identified the main changes of the laser irradiation parameters for improving the similarity between the characteristics of yarns colored by laser and the Shroud images. Namely, a shorter wavelength down to the deep UV and vacuum ultraviolet (VUV), a shorter pulse width, and a higher intensity together should allow a substantial reduction (down to one) of the number of laser shots necessary to give a very short depth of coloration of linen fibers. In this respect, these experimental results have a large margin for improvement and encourage us to carry on further UV laser irradiations, including artificial aging effects. These results are compatible with the hypothesis of body image formation due to corona discharge, as corona discharges generate UV radiation [14].

In conclusion, the results presented in this paper do not exclude the possibility that the body image on the Shroud was generated by a burst of UV or VUV radiation, in agreement with the Jackson theory of image formation [10]. However, more investigations are still necessary to unveil the origin of the body

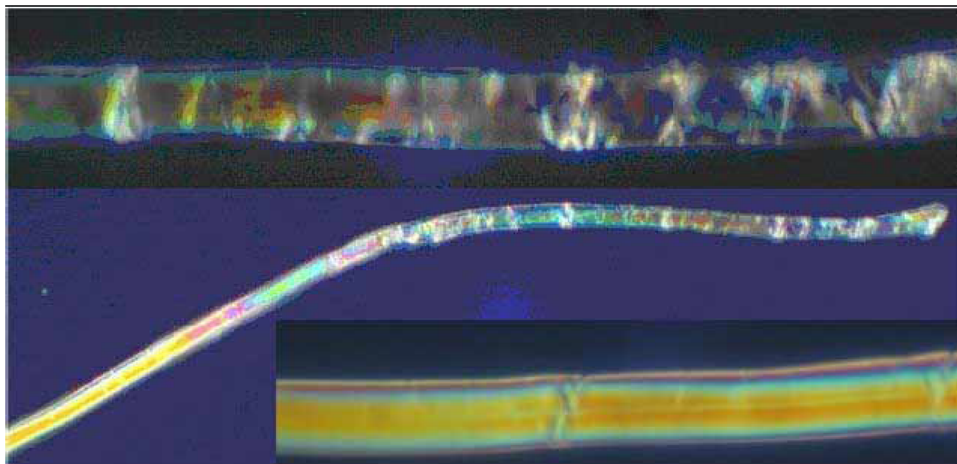


Fig. 10. (Color online) In the middle is a partly colored fiber of linen B in oil 1.515 between crossed polarizers to detect stress characteristics. On the left of the fiber is the nonirradiated region, enlarged in the inset below. On the right is the irradiated region, enlarged in the inset above.



image on the Shroud, which still represents a “challenge to the intelligence” [23].

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22. The presence of the polysaccharides layer that wraps linen fibers of the Turin Shroud yarns is presented in [5], p. 4, points A3, A4, A7, and A10. This layer was discovered by R. Rogers and communicated to the Shroud Science Group, a 100-expert private group study (G. Fanti, chairman) that discusses the scientific aspects of the Turin Shroud. The presence of this layer was successively confirmed by G. Fanti.
23. “La Sindone è provocazione all’intelligenza,” (The Turin Shroud is a challenge to the intelligence), said Pope John Paul II visiting Turin on 24 May, 1998, adding that “The Church entrusts scientists the task to go on with research.”