Two-faceted mirror for active integration of coherent high-power laser beams

J. Armengol, F. Vega, N. Lupon, and F. Laguarta

A new integration method suited for spatially coherent high-power laser beams is demonstrated. The integrator system is based on a mirror with two facets, one of which can vibrate under the action of a piezoelectric translator. After reflection in the faceted mirror, the beam intensity distribution is modified to obtain greater uniformity. However, because of the coherence of the reflected beamlets, this distribution is affected by an interference pattern. The active integration consists of a periodic displacement of the moving facet that causes the interference pattern to vibrate, and its contribution to the intensity profile therefore averages out (fringe visibility within a 5% range). The combination of a faceted mirror and a simple imaging system results in an intensity profile with good uniformity over large spot sizes. Both simulated and experimental results are presented, the latter showing that a final uniformity within a 10% range can be achieved and it is limited mainly by diffraction at the edges of the facets.

Key words: Laser beam integration, laser material processing.

1. Introduction

Many applications in laser material processing require a uniform beam intensity distribution at the sample plane. Various methods to obtain flattopped intensity profiles from nonuniform (mainly Gaussian) beams have been proposed in recent years. Among others, multifaceted integrating mirrors,[1,2] amplitude and phase diffractive elements,[3–5] and absorbing filters[6] have been widely used. When dealing with high-power laser applications, one carries out beam shaping by means of multifaceted laser beam integrators,[1,2] the integrated intensity being affected by diffraction at the edges of the facets. Moreover, most of the industrial applications are commonly driven by unstable cavity laser sources that provide nearly pure transverse monomode beams with a large spatial coherence. Integration of these beams results in an intensity profile that shows a sharp contrast because of the interferential effects produced by the superposition of the beamlets reflected from different facets. This nonuniformity in the laser beam intensity translates into a nonuniform temperature distribution with high transverse thermal gradients on the sample surface. Thus, laser treatments with spatially coherent integrated beams are traditionally restricted to materials with a high thermal conductivity such as metals, because in this case the lateral heat flow rapidly minimizes the temperature gradients on the sample surface. In laser applications involving materials with a low thermal conductivity such as glass,[7] a laser-induced nonuniform temperature distribution would last for a period long enough to induce irregular thermal treatment and/or undesirable effects such as permanent macroscopic surface deformations.

In this paper we present a new active laser beam integrator that is suitable for spatially coherent high-power lasers. The integration system is based on a two-faceted mirror. The faceted mirror divides the incoming beam into two beamlets that are forced to overlap partially in order to obtain a redistribution of the beam intensity for greater uniformity. However, the interferential effects mentioned above produce large intensity variations. By displacing one of the facets periodically, one can establish a periodic phase shift between the two reflected beamlets. As a consequence the interference pattern at the sample plane vibrates at the same frequency as the facet, and its contribution to the intensity distribution averages out.

Results showing beam integration of spatially coherent high-power $TEM_{01}{}^{*}$ CO_2 laser beams ($\lambda = 10.6\ \mu m$) are presented. With close control of both the amplitude and the frequency of the facet motion

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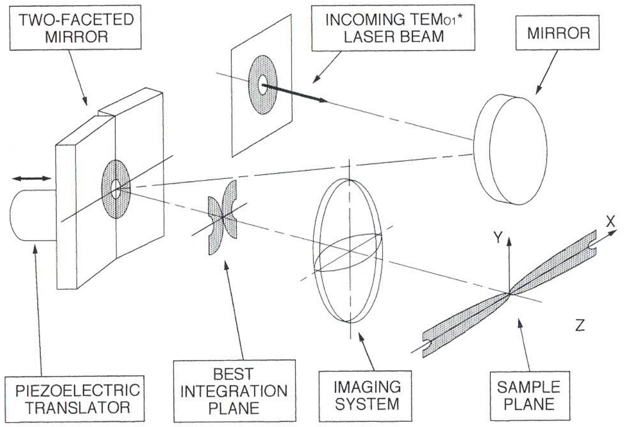

Fig. 1. Diagram of the experimental setup used for the active beam integration. After reflection in the faceted mirror an imaging system allows a strip beam to be obtained at the sample plane.

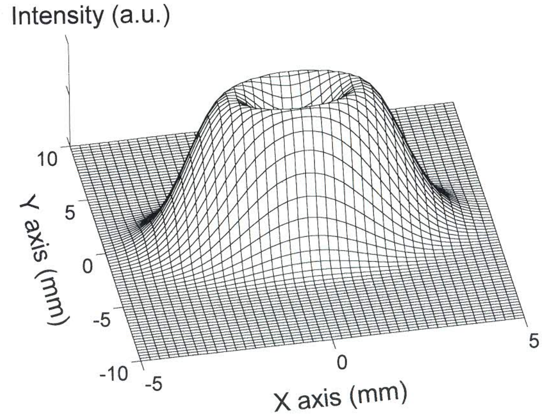

Fig. 2. Simulated intensity distribution corresponding to an incoming TEM_{01}* beam.

the contribution of the interference pattern to the intensity distribution is effectively minimized (fringe visibility ≈5%). When scanning this actively integrated intensity distribution over a sample, one obtains a uniform intensity profile. The final uniformity achievable, which is within a 10% range, is limited mainly by diffraction at the edges of the facets.

2. Active Integration System

The experimental setup used for active integration is shown in Fig. 1. It consists of a high-quality 2-in. (5-cm) gold-coated infrared mirror formed by two separate facets. Since each facet of the mirror is mounted in its own holder, we have micrometric control of its separation (i.e., the edge width) along the X direction in Fig. 1. Tilt alignment of each facet is also independent. A fast piezoelectric translator is coupled to one facet in order to provide it with a periodic displacement along the Z direction. One can externally control both the amplitude and the frequency of the facet motion by using a high-voltage amplifier and a pulse generator, respectively. The piezoelectric translator is driven with a triangular voltage signal that induces displacements of amplitude equal to or slightly higher than $\lambda/2$, whereas typical frequencies range from 55 to 90 Hz.

In comparison with multifaceted integrator mirrors the proposed two-faceted mirror presents certain advantages owing to its simple design:

(1) No beam expansion over the faceted mirror is required to obtain good integration of the laser beam. Therefore small tilt angles between the facets are enough to separate the incoming beam from the reflected beam and, as a consequence, a low image distortion at the sample plane is expected.

(2) The cross section of the reflected beam is not the geometric projection of one facet and thus the beam size is not limited to the facet size. In addition, an expansion of the incoming beam directly induces a magnification of the integrated one at the image plane without requiring additional optics. It is also worth noting that the particular shape of the facets (circular, square, rectangular, etc.) does not affect the shape of the integrated beam, the latter providing great flexibility to adapt the integrating mirror to any particular application.

(3) Since the two-faceted mirror does not have a fixed focal length, an optimum integrated distribution can always be obtained for any practical work distance if one simply modifies the tilt angle between the two facets. Moreover, since both facets are flat and their relative tilt is always very small (≈0.5°), they induce the same magnification and so no rolloff edge at the integrated image is expected.[1]

(4) The diffraction ripples are generated by only one edge and are therefore smaller than those produced by the coherent addition of the contribution of many edges as occurs in multifaceted mirrors. Because of this, significant variations in the intensity associated with the diffractive effects are restricted to the outer part of the intensity distribution.

For any laser application, an imaging system is commonly used to obtain a laser beam spot of the required size and shape at the sample plane. In our case, following reflection in the faceted mirror, a two-lens system gives a strip beam at the sample plane, a situation that is common in laser scan applications.

3. Results and Discussion

Integration was achieved using a high-power TEM_{01}* CO_2 laser (Fig. 2) as a collimated near on-axis incoming beam on the faceted mirror. After reflection, the TEM_{01}* intensity distribution is divided into two symmetric distributions. The effect of the redistribution of the beam intensity as the reflected beamlets spatially overlap is shown in Fig. 3. When the superposition between the beamlets is too small, a dip occurs at the resultant intensity distribution [Fig. 3(a)]. Too large a superposition, on the other hand, leads to a hill-shaped intensity distribution [Fig. 3(c)]. A nearly optimum overlap condition corresponds then to Fig. 3(b). Although it is obvious from

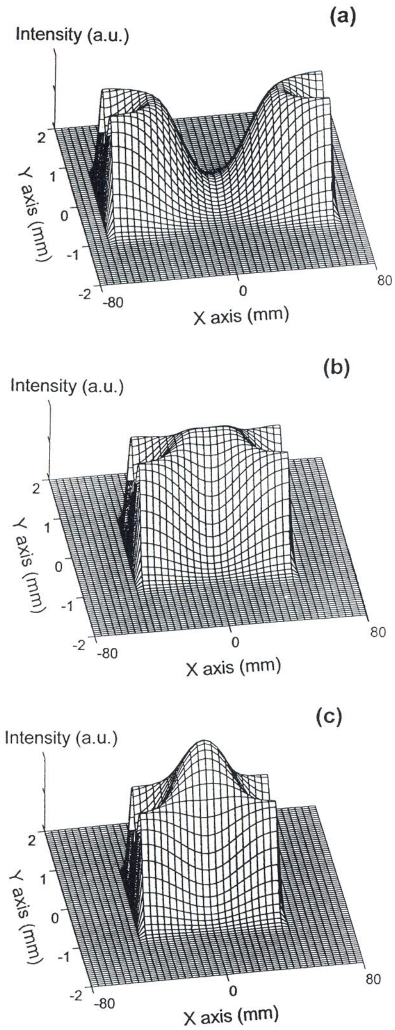

Fig. 3. Simulated intensity distributions obtained at the sample plane as the two reflected beamlets spatially overlap: (a) small, (b) optimum, (c) too large overlapping. Neither diffraction nor interferential effects are included.

Fig. 3(b) that this intensity distribution is not flat-topped, it results in a uniform intensity profile over a sample surface after it has been scanned along the Y direction (see Fig. 1). However, as has been pointed out above, this intensity profile must exhibit spatial variations because of the existence of interferential and diffraction effects. We have studied both phenomena separately.

Figure 4 shows the intensity profiles corresponding to experimental intensity distributions obtained under overlapping conditions that are similar to those simulated in Fig. 3. Since they were recorded using a 1.0-mm slit positioned in front of a pyroelectric detector, these intensity profiles correspond to those obtained when one scans the intensity distributions along the Y direction. As mentioned above, only for accurate overlapping conditions in the intensity distribution [Fig. 3(b)] does the intensity profile achieved [Fig. 4(b)] show neither a dip nor a hill shape. However, in all cases [Figs. 4(a)–4(c)] the profiles are clearly disturbed by interference ripples, the visibility of the fringes increase as the overlap of the beamlets grows. It can be deduced from Fig. 4(b) that the distance between two interference fringes at the sample plane is large ($\approx$5 mm). Then, in laser applications focused on materials of a low thermal conductivity, the material cannot average out the interference pattern contribution because there is no way to combine a realistic irradiation time with the thermal conductivity of the material to obtain a thermal diffusivity length of the order of the fringe separation. Our alternative is to integrate the interference fringes by means of an active integration method applied to the laser beam. If one facet is forced by the piezoelectric translator to make a periodic motion along the Z direction, a phase shift between the reflected beamlets can be established. Since the spatial location of maxima (minima) at the interference pattern depends on the particular phase difference between these beamlets, the induced peri-

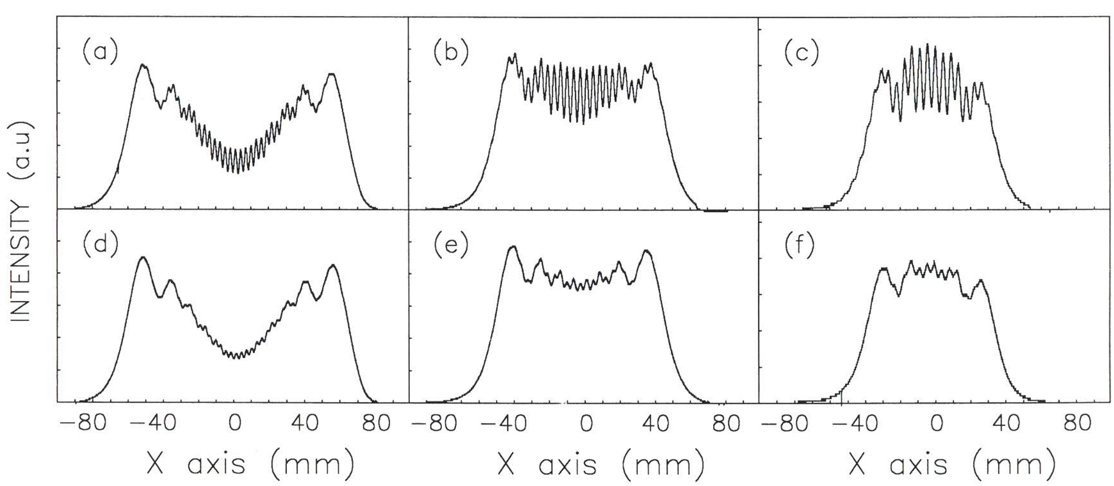

Fig. 4. Experimental intensity profiles obtained along the X direction for three overlapping degrees between the reflected beamlets: (a) small; (b) near optimum; (c) too large; (d), (e), (f) the same profiles under active integration. A CO_2 laser beam of 150 W was used as the incoming beam.

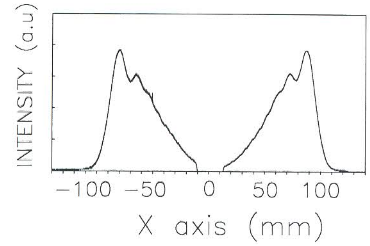

Fig. 5. Experimental intensity profiles of the reflected beamlets showing the diffractive effects of an edge. The results were obtained after spatial separation of the beamlets. A CO_2 laser beam of 150 W was used as the incoming beam.

odic phase shift translates to a periodic variation (along the X direction) of the maxima (minima) location. The result is that the interference pattern vibrates at the sample plane, which effectively minimizes its contribution. Figures 4(d)–4(f) show the intensity profiles under active integration. Optimum integration of the interference pattern depends on the amplitude of the facet displacement, its velocity, and frequency. An amplitude of $\lambda/2$ produces a phase shift between the reflected beams of 2 πrad, a situation for which a maximum (minimum) in the interference pattern moves to the position of the nearest one and thus a good integration should occur. Additionally, the periodic displacement of the facet (and consequently the displacement of the interference pattern) has to be performed at uniform velocity, since otherwise the integrated intensity will present nonuniformities associated with the convolution between the interference pattern and the nonuniform displacement pattern. Active integration carried out at frequencies in the 55–80-Hz range produces optimal intensity profiles except for a few frequencies that are mechanically coupled to the holder system.

Figure 4(e) corresponds, then, to nearly optimal integration conditions both for the superposition of the two beamlets and for averaging out the interference pattern. The active integration leads to a reduction of the visibility of the interference fringes of as much as 5%. It is worth noting that such good uniformity can be achieved over large spot sizes ($\approx$60 mm). The remanent interference fringes are likely to be related to the fact that the high-voltage amplifier has a relatively low cutoff frequency (200 Hz) and therefore cannot provide the piezoelectric translator with a pure triangular voltage signal.

A different mechanism explains the nonuniformities that basically affect the queues of the integrated intensity profiles. They originated because of the diffractive effects at the edge of the two facets, as is clearly seen in Fig. 5, where the two reflected beamlets are spatially separated. The intensity profiles are quite symmetric, thus proving that the incoming beam energy is equally distributed between them. The individual profiles represented show ripples that correspond to a Fresnel diffraction pattern of an edge. Taking this effect into account, a visibility of $\approx$10% can be achieved over the whole intensity profile (Fig. 4).

4. Conclusions

A new active integration method for high-power nonuniform laser beams has been presented. The method is specially suited to laser scan applications with highly spatial coherent beams. The integrator is basically formed by a mirror with two facets, one of which can vibrate under the control of a piezoelectric translator. The system is versatile in the sense that an intensity distribution that leads to uniform intensity profiles can be easily achieved at any practical work distance. The active integration method is based on the periodic displacement of one of the facets of the mirror, which strongly reduces the contribution of the interference pattern to the intensity profile (fringe visibility within a 5% range). The combination of a two-faceted mirror with an imaging system allows intensity profiles of good uniformity to be obtained over large spot sizes, the final achievable uniformity being within a 10% range because of the diffraction at the edges of the facets.

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