Paint stripping with high power Flattened Gaussian Beams

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ABSTRACT

In this paper we present results on improved paint stripping performance with an intra-cavity generated Flattened Gaussian Beam (FGB). A resonator with suitable diffractive optical elements was designed in order to produce a single mode flat–top like laser beam as the output. The design was implemented in a TEA CO_2 laser outputting more than 5 J per pulse in the desired mode. The FGB showed improved performance in a paint stripping application due to its uniformity of intensity, and high energy extraction from the cavity.

Keywords: Flat–top beams, resonator modes, diffractive optics, TEA CO_2 lasers, paint stripping

1. INTRODUCTION

There are many applications in which a laser beam with a flat–top intensity profile would be ideal, as compared to a laser beam with a non–uniform energy distribution. Laser based paint stripping is an example of such an application that can benefit from a laser beam with a flat top intensity profile. Standard stable optical resonators will unfortunately not generate such a laser beam as the oscillating mode. Single–mode oscillation would typically be Gaussian in profile, while multimode oscillation might deliver a beam with an averaged flat–like profile in the near field, but would diverge very quickly due to the higher order modes. In addition, if the modes are coherently coupled, then large intensity oscillations could be expected across the beam. Techniques exist to generate flat–top beams external to the cavity, but this is usually at the expense of energy, and almost always requires very precise input beam parameters. A traditional laser resonator configuration consists of a gain medium inside an optical cavity which is supplied with energy. Usually the cavity consists of two mirrors aligned such that the light passes through the gain medium several times, while traveling between the two mirrors. One of the two mirrors is made partially transparent, and the laser beam is emitted through this mirror (henceforth referred to as the output coupler). If the phase profile of this element is chosen so as to differ from spherical curvature, then it is possible to select transverse modes other than the conventional Helmholtz–Gauss and Laguerre–Gauss modes. Since the laser beam intensity and phase is selected inside the laser by the DOE, this is often referred to as intracavity laser beam shaping. While it is well known that transverse modes may be selected by amplitude means, even for very complex mode patterns[1], this has disadvantages in that the round trip loss increases thus restricting such solutions to high gain lasers. Contrary to this, it has been shown that it is possible to use a DOE to select the resonant mode by means of phase rather than amplitude[2,3], with the potential for greatly reduced losses in the medium. DOEs manipulate light by diffraction rather than reflection or refraction, and thus have feature sizes of the order of the wavelength of the light; this complicates fabrication and may lead to errors in the desired surface profile. If the surface structure of the element is of a kinoform nature (continuous relief surface), then the DOE acts as a phase–only element, without any additional diffraction losses.

2. THEORY

In this section we outline how the phase profile of the intracavity DOE is determined, and how this relates to the choice of the resonant mode inside the cavity. The method of using DOEs inside laser resonators was first proposed by Belanger and Pare[2,3], and which we outline briefly here for the convenience of the reader. Consider some arbitrary field that may be written in the form:

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$$u(x) = \psi(x)\exp[-ik\phi(x)] \ , \tag{1}$$

where $k = 2\pi/\lambda$ is the wavenumber of the laser beam, λ is the wavelength, and $\psi(x)$ and $\phi(x)$ are the amplitude and phase of the electric field respectively. The action of a DOE in the form of a phase–only micro–optical mirror (as depicted in Fig. 1) is to transform the phase $\phi_1(x)$ of an incoming field to a new phase $\phi_2(x)$ of an outgoing field according to:

$$\phi_2(x) = \phi_1(x) - 2\phi_{DOE}(x) \ . \tag{2}$$

The salient point here is that this transformation takes place in a lossless manner, i.e., the outgoing amplitude $\psi_2(x)$ is unchanged. In particular, one can show[2] that if the phase mirror is not spherical, then the change in phase also depends on the incoming field distribution $\psi_1(x)$. Thus it is expected that a phase–only mirror will discriminate against those modes that do not have the correct distribution $\psi_1(x)$. By invoking the requirement that the mode must reproduce itself after one round trip one can easily show that the resulting restrictions on the phase of the DOE mirror is given by:

$$\int_{-\infty}^{\infty} x\left(\frac{\partial\phi_1}{\partial x}\right)\psi_1^2(x)dx = \int_{-\infty}^{\infty} x\left(\frac{\partial\phi_{DOE}}{\partial x}\right)\psi_1^2(x)dx \ , \tag{3}$$

from which we conclude that phase of the resonator eigenmode is the same as the phase of the DOE mirror, apart from a constant:

$$\phi_{DOE}(x) = \phi_1(x) - \phi_1(0) \ . \tag{4}$$

Combining Eqs. (2) and (4), and ignoring the constant phase offset, we see that

$$\phi_2(x) = -\phi_1(x) \ . \tag{5}$$

Therefore the reflected beam $u_2(x)$ is the phase–conjugate of the incoming beam, $u_2(x) = u_1^*(x)$ (note that the wavevector is also inverted in this design due to the normal incidence operation). In this resonator only a particular beam distribution is phase conjugated by the DOE mirror, so that the eigenmode of the resonator satisfies the criteria that its wavefront matches the phase of each mirror in the cavity.

If we describe the desired field at the output coupler as u_{OC}, then reverse propagating the field to the DOE mirror using the Kirchhoff–Fresnel diffraction equation yields the field at the mirror as

$$u_{DOE}(\rho, L) = -i^{n+1}(k/L)\exp(ikL)\exp\left(\frac{ik}{2L}\rho^2\right)\int_0^{\infty} u_{OC}(r)J_n\left(\frac{k\rho r}{L}\right)\exp\left(\frac{ik}{2L}r^2\right)rdr \ , \tag{6}$$

where we have assumed that the resonator is rotationally symmetric and of optical path length L. If after reflection off the DOE the field u_{DOE} is to reproduce u_{OC} at the output coupler, then the required phase for DOE mirror must be given by

$$\phi_{DOE} = Arg[u_{DOE}^*(\rho, L)] \ , \tag{7}$$

with optical transfer function

$$t_{DOE} = \frac{u_{DOE}^*}{u_{DOE}} \ . \tag{8}$$

This is the basis by which custom resonators may be designed.

2.1 Flattened Gaussian Beams (FGBs)

An often used distribution of flat-top-like beams is that of the so–called Flattened Gaussian Beam (FGB)[4]:

$$u_{FGB}(r,z) = A\frac{w_{0N}}{w_N(z)}\exp(i[kz - \Phi_N(z)])\exp\left[\left(\frac{ik}{2R_N(z)} - \frac{1}{w_N^2(z)}\right)r^2\right]\sum_{n=0}^{N} c_n L_n\left(\frac{2r^2}{w_N^2(z)}\right)\exp[-2in\Phi_N(z)] \tag{9}$$

Here the intensity of the beam is given by $I_{FGB}(r,z) = |u_{FGB}(r,z)|^2$ with beam parameters of new waist size, Rayleigh range, beam size, radius of curvature and Gouy phase shift given by:

$$w_{0N} = w_0 / \sqrt{N}$$

$$z_r = k w_{0N}^2 / 2$$

$$w_N(z) = w_{0N} \sqrt{1 + (z / z_r)^2}$$

$$R(z) = z + z_r^2 / z$$

$$\Phi(z) = \tan^{-1}(z / z_r)$$

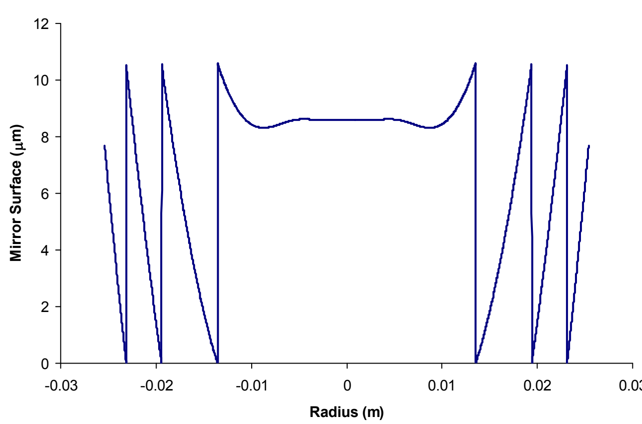
The summation is over a weighted set of Laguerre polynomials, where the weighting of factor c_n of the nth Laguerre polynomial, L_n, is given by

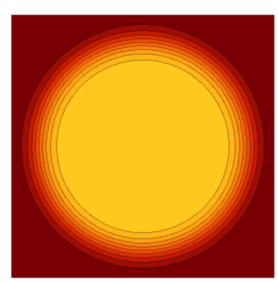
$$c_n = (-1)^n \sum_{m=n}^{N} \binom{m}{n} \frac{1}{2^m}$$

The advantage of this profile over others is that Eq. (9) offers a simple analytical expression for its profile at any propagation distance z. Once again there is an order parameter associated with the field, given by the summation index N.

2.2 Resonator Design and Analysis

This paper sees the culmination of several theoretical and experimental studies over the past few years for the generation and application of intra-cavity flat-top beams[5-8]. A designed axisymmetric DOE mirror is shown in Fig. 1(a), with associate output intensity given by Fig. 1(b). The element was designed for a CO_2 laser cavity of length L = 1.772 m, operating at a wavelength of λ = 10.6 µm. The DOE was designed so that a circular FGB of order N = 10 is generated at the output coupler, with w_0 = 10 mm; the phase at the output coupler was set to 'flat', i.e., $R(0) = \infty$, with the DOE mirror placed well within the Rayleigh range of the beam, $L/z_r \sim 0.6$. Note that the surface height is modulated every 10.6 µm in height, or one complete wavelength, corresponding to a 2π phase shift of the light. An intracavity aperture was added to the resonator in the form of a 15 mm radius circular aperture placed at the DOE mirror in order to mimic the limited spatial extent of the electrodes of the CO_2 laser.





(a) (b)

Fig. 1. Example of a DOE for outputting a FGB of order N = 10: (a) DOE mirror surface, and (b) contour plot of the expected beam intensity at the output coupler, showing a uniform intensity central region and steep edges.

Calculations of the mode were performed using the Fox–Li method, starting from spontaneous emission (background noise). The field at the output coupler was computed for each complete round trip, and the losses for the *i*th round trip were calculated as:

$$Loss = 1 - \frac{\gamma_i}{\gamma_{i-1}} \tag{10}$$

where γ is the energy contained in the field. The modal build–up was computed starting from a background noise signal. After approximately 250 round trips the losses of the field stabilized, indicating that a stable mode had formed. The final loss of the stable mode per round trip was found to be 0.2%, which is close the theoretically predicted 0% loss for this conjugating resonator.

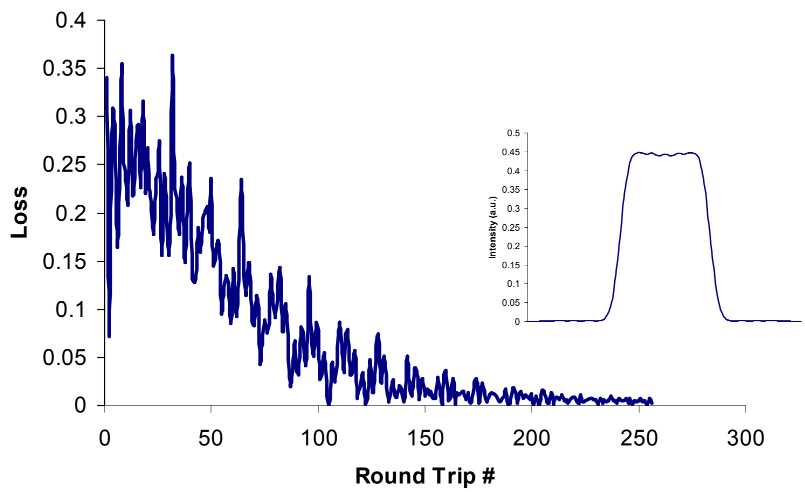


Fig. 2. Round trip loss starting from noise (high loss) finally converging to low loss after ~250 round trips. The inset shows the final stabilized field, and is clearly the desired FGB.

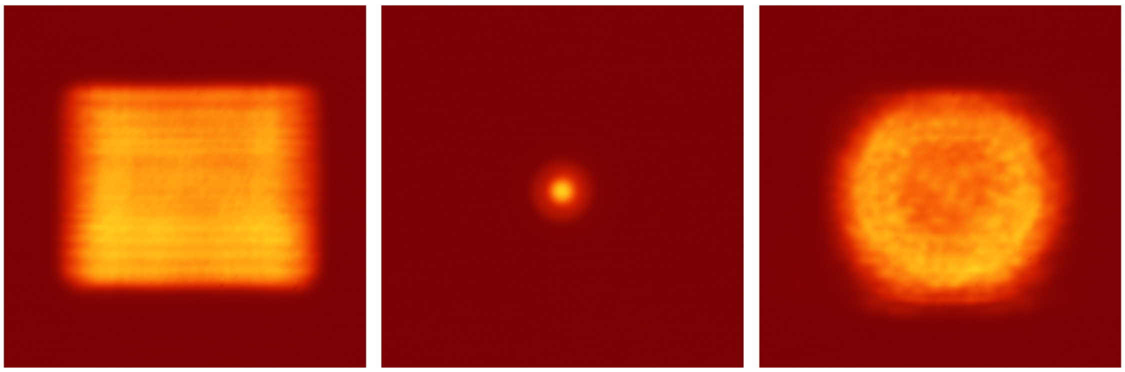
At convergence, the wavefronts on both mirrors match that of the oscillating beam, as expected, and the output field is the desired FGB, as shown in the inset of Fig. 2. However, a small error in the phase of the mirror has a significant influence on the output mode from the resonator and thus one expects that fabrication errors are an important likely contributor in determining the stable mode of the cavity. We have therefore proposed a DOE mirror with a static phase that can be adjusted with the aid of a deformable mirror to compensate for such problems[7].

3. EXPERIMENTAL RESULTS

The above mentioned DOE mirror was manufactured and installed in a TEA CO_2 laser[8]. The laser was designed to yield nominal pulse energy of 5 J and an average power of 1500 W at a repetition rate of 300 Hz. The multimode and single mode Gaussian beam propagation characteristics of the laser were measured as a baseline. Hereafter, the propagation properties of the FGB were determined. Table 1 summarizes the beam propagation parameters for the various laser beams. From Table 1 it can be seen that the multimode beam produces the highest pulse energy but also has the highest divergence and M^2 values. The single mode Gaussian beam in contrast has low divergence and M^2 values which is ideal for beam propagation but however only contains approximately 4% of the energy that is available in the multimode beam. The FGB exhibits divergence and M^2 values that are lower than for multimode case but not as low as for the single mode Gaussian beam. The FGB however has 85% of the energy that is contained in the multimode beam. When the beam area of the multimode beam and the FGB are compared it is found that the area of the FGB beam is approximately 70% of the area of the multimode beam. Taking into account the fact that the energy in the FGB is 85% of the energy that is contained in the multimode beam it can be concluded that the FGB resonator design yields a better energy extraction than in the multimode case. The FGB will therefore be quite suitable for applications where a flat–top beam with high pulse energy and favorable beam propagation parameters are required.

Parameter	Multimode	TEM_{00}	FGB
M^2 x-axis	21.3	1.06	9.2
M^2 y-axis	28.7	1.08	9.4
Pulse energy	6.3 J	250 mJ	5.3 J

Table 1. Measured beam propagation parameters for various TEA CO_2 laser output modes.



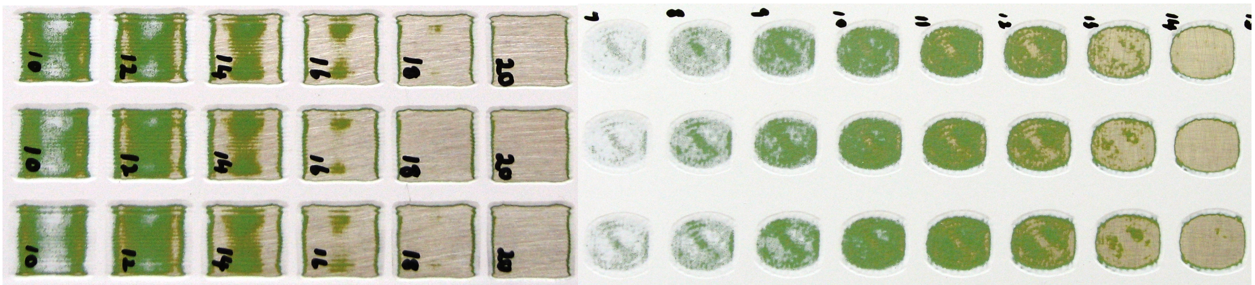
(a) (b) (c)

Fig. 3. Measured output beam profiles showing: (a) multimode operation, (b) Gaussian operation, and (c) a FGB output using an intra-cavity DOE.

Figure 3 shows that with the presence of the DOE in the cavity the laser yielded a near single mode FGB; this has been confirmed by observing an unchanging temporal pulse across the beam profile. The FGB is not completely flat but shows some high intensity peaks, with a "dip" in the centre. This could potentially be attributed to non–uniformities that exist in the laser gain over the gain volume area, as well as some contribution from the second mode of the cavity.

The FGB could ideally be used in a laser based paint stripping application. For laser based paint stripping with a TEA CO_2 laser, high pulse energy, good beam propagation characteristics and a uniform energy distribution in the beam are desirable to deliver the laser beam to the target and to uniformly ablate the target surface. The single mode Gaussian beam has favorable propagation characteristics but does not contain enough energy to do the paint stripping. The multimode beam is more ideal as it has high pulse energy and an almost flat–top like profile but the propagation parameters are not ideal. The multimode beam also exhibits the modes that it is made up of, and this can be seen as intensity fluctuations in the beam while it is used in the paint stripping application.

Figure 4 shows the application of a multimode beam for paint stripping. The results shown in Fig. 4 were recorded by keeping the paint stripping target stationary at a position and applying a number pulses to the target. The target was then moved to a new position and the number of laser pulses increased. This process was repeated until the substrate was exposed. The higher intensities in the multimode beam are clearly visible in Fig. 4(a) during the paint stripping process and one can see that in some areas paint is already removed from the substrate, while in other areas of the beam the top coat is still visible. The horizontally aligned intensities are due to the mode structure of the beam and the vertical intensities due to non–uniformity of the gain in the gain area. The application of the FGB is shown in Fig. 4(b). It is evident that the top coat of paint and primer are more evenly ablated with the FGB. The FGB therefore poses distinct advantages over the multimode and single mode Gaussian beams in the application of paint stripping.



(a) (b)

Fig. 4. Examples of the application of (a) multimode and (b) FGBs used in laser based paint stripping.

4. CONCLUSION

We have outlined the design approach for an optical resonator that produces as the stable transverse mode a flat–top–like laser beam, by making use of an intra–cavity phase–only diffractive mirror as the mode selective device. A diffractive mirror for the resonator was designed, fabricated and then verified in a TEA CO_2 laser. Furthermore, the propagation of the FGB was compared to the propagation for the multimode and single mode Gaussian beams for the particular laser under study. The generated FGB was also used in a paint stripping application to demonstrate the advantages that a FGB holds for such an application.

5. ACKNOWLEDGEMENTS

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