Diffractive optical elements for high gain lasers with arbitrary output beam profiles

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Abstract: We introduce a previously unreported laser cavity configuration, using a diffractive optical element (DOE) in place of the output coupler. Such a configuration allows the DOE to work both in reflection, as a mode shaping element, and in transmission as a beam shaper. Employing dual wavelength DOE optimization techniques and phase delays greater than 2π, allows the two functions to be designed independently. Thus, an arbitrary output beam profile can be combined with a mode shape which maximizes energy extraction from the gain medium. Devices are designed and their performance modeled for a 1m cavity with 5mm diameter mirrors and a wavelength of 632.8nm. An element with 32 quantization levels and a maximum phase delay of 8π in transmission produces high quality results.

OCIS codes: (050.1970) Diffractive Optics; (140.3300) Laser beam shaping; (140.3410) Laser resonators

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1. Introduction

It is often desirable to alter the fundamental mode associated with a laser cavity. Two common reasons for doing this are; to generate a more desirable output beam profile, matched to the laser application, or to make most efficient use of the gain medium. The optical devices which have been used to achieve this include variable phase mirrors[1], spatial filters[2] and diffractive optical elements (DOEs)[3]. It is a DOE configuration which we consider in this paper.

DOEs are lightweight optical components with a wide range of applications, including laser beam shaping [4], optical interconnection [5] and color separation[6]. Incorporating DOEs into a laser cavity allows optimization of the dominant mode by using an arbitrary phase profile to alter the field, such devices are referred to as mode selecting elements (MSEs). MSEs are very flexible in the outputs they can generate and are very efficient. Both reflective MSEs [7], where the diffractive device replaces the 100% reflective end mirror and transmissive MSEs [8], which are placed within the cavity have been demonstrated. The latter example introduces greater design complexity but offers a higher damage threshold in high power applications.

Previous MSE designs have not had the flexibility to perform arbitrary mode shaping while simultaneously generating an independent, arbitrary output beam profile. In this paper, we introduce a previously unreported cavity configuration, which uses a single device to perform both of these tasks independently. The cavity layout is illustrated in figure 1. The output coupler, rather than the fully reflective mirror, is replaced by a DOE, in this configuration the DOE operates as a MSE in reflection and as a beam shaping element in transmission. Optimization of the element for both applications is made possible by exploiting the different phase delays produced by DOEs operating in transmission compared to those operating in reflection, and utilizing phase delays greater than 2π. The design process is carried out in a similar fashion to that employed for dual wavelength, far-field DOEs which also use phase delays beyond 2π to give the required degree of freedom in the design[9, 10].

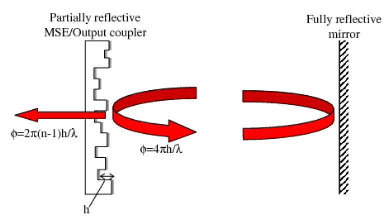

Fig. 1. Schematic of proposed cavity configuration.

2. Method

The desired, unquantized phase profiles for the two operations are first designed independently.

2.1. MSE design

When an end mirror is replaced by a MSE to optimize the use of the gain material, specific phase conjugation can be employed to analytically determine the desired phase profile of the element [7]. To carry out this operation the desired field, U(x,y), is considered at the plane mirror. The angular spectrum of the field is then considered via a Fourier transform. Multiplication by

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$$exp[ikl(L-(\lambda u)^2-(\lambda v)^2)^{1/2}], \tag{1}$$

where k is the wavenumber, L the cavity length and u and v are spatial frequencies, followed by the inverse Fourier transform, models the effect of propagating along the cavity. The MSE simply alters the phase of the field, if this phase profile is chosen to be

$$\phi_R(x',y') = A^*(x',y')/A(x',y') \tag{2}$$

where $A(x',y')$ is the field at the MSE and * indicates the complex conjugate, then the original field is reproduced by propagating back to the plane mirror.

2.2. *Beam shaper design*

The use of DOEs for beam shaping is common and many techniques exist for optimizing the phase profile of the element to produce a desired output. We employ the symmetrical iterative transform algorithm, introduced by Liu et al. [11]. The field generated by multiple passes within the cavity using the MSE is taken as the input to the beam shaping element. A diffractive lens function can be added to the optimized phase profile to generate the desired output at a specific distance from the laser. The optimized, unquantized phase profile from the beam shaper design process is $\phi_T(x',y')$.

2.3. *Designing the multifunction quantized element*

Having optimized the two unquantized profiles independently a quantized structure which acts as a MSE in reflection and a beam shaper in transmission is required. This is achieved using a 'best-fit' quantization approach, previously employed for dual wavelength DOEs[10]. As indicated in the figure 1 the phase delay, ϕ, is different for the two modes of operation. This property, together with phase delays greater than 2π, gives the required degree of freedom to design the element for two functions. When operating in transmission the etch depth, h_1, required to give a phase delay ϕ_T is given by

$$h_1 = \frac{\phi_T \lambda}{2\pi(n-1)} \tag{3}$$

where n is the refractive index of the substrate material, and λ is the wavelength. Similarly, in reflection the etch depth required to give phase delay ϕ_2 is given by

$$h_2 = \frac{\phi_R \lambda}{4\pi} \tag{4}$$

In both cases it is assumed the surrounding material is air, with a refractive index equal to 1. Setting the phase values ϕ_T and ϕ_R equal to 2π gives the etch depths h_1' and h_2', which have have no affect on the transmitted and reflected field respectively.

The quantization process for a single pixel is illustrated in figure 2. h_1 represents the etch depth which produces the phase delay required for the beam shaper, adding multiples of h_1' will give equally valid etch depths. Similarly, h_2 represents the etch depth which produces the phase delay required for the MSE to which multiples of h_2' can be added. Dividing the maximum etch by the number of quantization levels (8 in the example shown) gives the available etch depths. Δ_1 and Δ_2 are the quantization error for the beam shaper profile and the MSE profile respectively. The available quantization level which minimizes both Δ_1 and Δ_2 is selected. This process is repeated for all the pixels in the design to produce the quantized dual function element. It should be noted that further optimization, via depth bias and phase bias, has been demonstrated for dual wavelength elements [12]. These techniques are not employed here.

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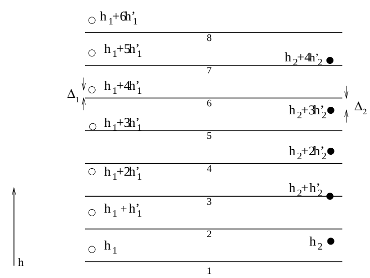

Fig. 2. Illustration of the quantization process.

3. Modeling

To examine the performance of the type of element discussed in this paper a number of designs have been carried out and their results modeled. For the examples presented a cavity of length 1m with 5mm diameter mirrors and a design wavelength of 632.8nm is used. The element is assumed to be fabricated in fused silica. The desired intracavity mode is described by the super-gaussian function

$$U(x,y) = e^{-(\frac{x}{\omega_0})^{20}-(\frac{y}{\omega_0})^{20}} \tag{5}$$

where $\omega_0 = 2.5mm$. The desired output beam profile is a ring, generated at 500mm from the laser and with internal radius of 0.8mm and external radius of 1.9mm. The super-gaussian is a good approximation of a top hat, which enhances energy extraction from the gain medium, while the ring geometry is chosen as a distinctive beam profile, allowing easy verification of the methods success. The variables considered in the design process are the number of quantization levels and the maximum phase delay and the elements are designed with 512x512 pixels.

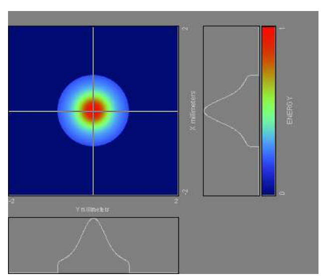

Fig. 3. Fundamental mode generated by the bare cavity.

Fox-Li analysis [13] of the cavity using 2 plane mirrors produces the fundamental mode seen in figure 3, as expected the beam has a Gaussian profile. Repeating the analysis after introducing an unquantized MSE, designed using the phase conjugation method, produces the fundamental mode seen in figure 4(a). This analysis produces a mode which is much closer to the top-hat shape of a super-gaussian profile. The field from the cavity analysis is used as the input for design of the beam shaping DOE. The modeled output from the the resulting unquantized profile is shown in figure 4(b) and shows the ring geometry to be successfully recreated with sharp edges and little zeroth order energy.

Having demonstrated the suitability of the two, independent, unquantized profiles for intra-cavity mode shaping and output beam shaping it is necessary to combine them to generate a quantized profile which performs both operations. The best fit quantization method, described

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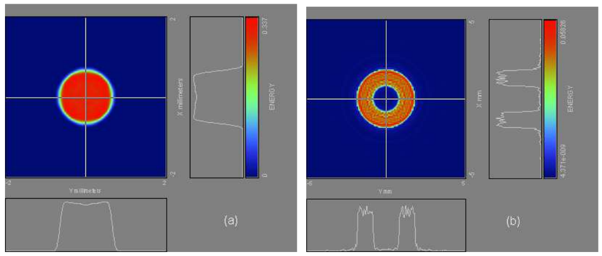

Fig. 4. (a) Fundamental mode generated by unquantized MSE and (b) output at 500mm using unquantized beam shaping DOE.

earlier is used to generate profiles with 16, 32 and 64 quantization levels. For the 16 level structure a maximum phase of 2π in transmission is used, for the 32 level structure two optimizations are run with maximum phase values of 4π and 8π and a maximum phase of 8π is also used for the 64 level structure. Firstly the cavity analysis was carried out using the quantized profiles. The resulting mode shapes for each of the four MSEs are shown in figure 5.

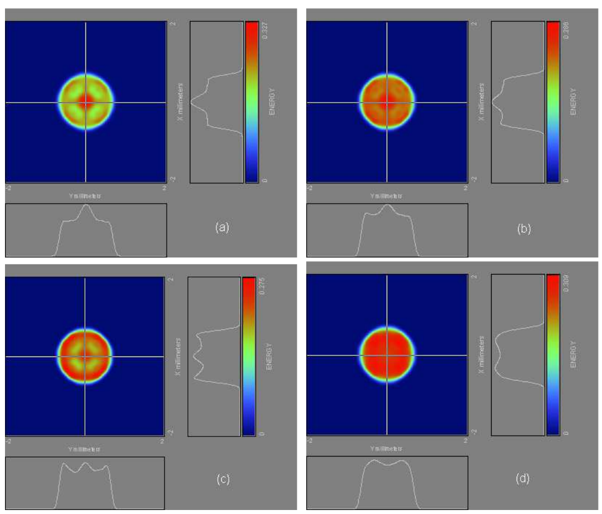

Fig. 5. Fundamental mode generated by elements quantized to (a) 16 levels with a maximum phase in transmission of 2π, (b) 32 levels with a maximum phase in transmission of 4π, (c) 32 levels with a maximum phase in transmission of 8π and (d) 64 levels with a maximum phase in transmission of 8π.

As might be expected, the profile with the largest number of quantization levels gives the best approximation to a super gaussian mode shape. The designs with fewer quantization levels exhibit higher intensities in the central area of the profile, this is undesirable as it will reduce the overall gain achieved. This observation is perhaps unsurprising as etch depth errors in DOEs have been shown to manifest themselves in greater zeroth order energy [14], the best fit nature of the quantization process in effect produces slight errors in the phase profile. The profiles in figure 5 demonstrate that the fewer levels are available the more pronounced this error is.

The modeled fields produced during the intracavity analysis are used as the incident field onto the quantized element operating in transmission, to analyze the performance of the beam shaping part of the element. The modeled outputs at 500mm are shown in figure 6.

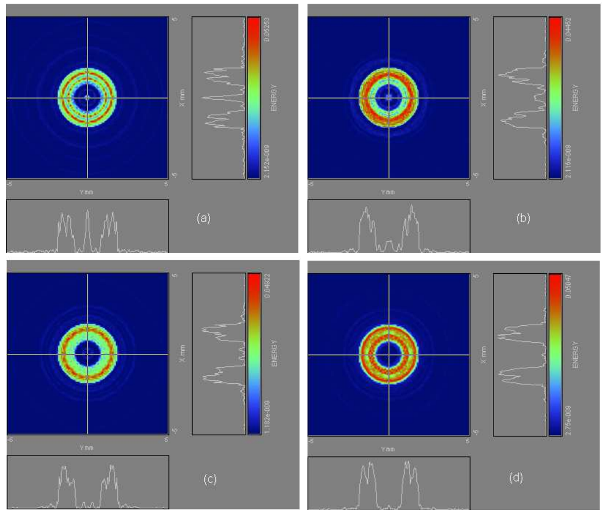

Fig. 6. Resulting output beam shape generated by elements quantized to (a) 16 levels with a maximum phase in transmission of 2π, (b) 32 levels with a maximum phase in transmission of 4π, (c) 32 levels with a maximum phase in transmission of 8π and (d) 64 levels with a maximum phase in transmission of 8π.

The modeled beam profiles demonstrate that again the structures with more quantization levels are more closely matched to the desired output. In particular the 16 level structure produces a high level of zeroth order energy. There is significant zeroth order energy for the element with 32 levels and a maximum phase of 4π, this is improved by increasing the maximum phase value. Allowing 64 levels improves the sharpness of the edges in the beam profile and reduces variation in intensity. The approximations made to the profile have a twofold impact in the case of the beam-shaper. As for the MSE the phase profile will differ from the optimized, unquantized profile, in addition we have seen that the cavity mode resulting from the MSE differs from the profile in figure 4(a), which was used during the optimization process.

4. Conclusion

A new configuration for DOEs within laser cavities has been introduced and its performance modeled. The modeling analysis demonstrates that such a device can successfully optimise the fundamental mode within the cavity to maximize energy extraction from the gain material, while simultaneously generating an arbitrary output beam shape. Modeling indicates that the performance of the element is significantly affected by the choice of both maximum etch depth and number of quantization levels. Satisfactory performance is observed when using 32 or more quantization levels and a maximum etch depth equivalent to a phase delay of 8π in transmission. Employing further optimization techniques, such as those used in dual wavelength DOE design, is likely to enable the number of levels and the maximum etch to be reduced. This is desirable, as reducing these parameters tends to reduce the impact of fabrication errors. The next stage in this work is to fabricate a working device for a laser system to verify the modeled performance experimentally. Should this prove successful we feel this device will provide a significant tool in laser system optimization.

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