

Implementation of intra-cavity beam shaping technique to enhance pump efficiency

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In this work we propose an implementation of a new intra-cavity beam shaping technique to vary the intensity distribution of the fundamental mode in a resonator cavity while maintaining a constant intensity distribution at the output. This method can be useful for fitting a transversal intensity profile of the required mode with a pump beam profile in the region of the active medium to increase mode discrimination.

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1. Introduction

In several laser application processes, a laser beam of single mode laser radiation is preferable. To achieve this effortlessly, good mode discrimination of the required mode is a necessity. There are two prevalent techniques to obtain the required mode discrimination, namely, increasing diffraction losses of the undesired modes [1] or fitting of the transversal intensity profile of the required mode with the pump beam profile (spatial mode-pump matching) in the region of the active medium [2]. In general, the discrimination of the required mode is a combination of both techniques mentioned above.

The implementation of intra-cavity beam shaping [3] allows for the control of the required mode volume and spatial mode-pump matching with no degradation in quality of the transversal intensity and phase distributions of the output mode. We are thus able to vary the intra-cavity mode-pump matching with no variation in intensity and phase of the output transversal beam distribution.

In the following work we will construct a resonator system where we are able to tune the intra-cavity transversal field distribution of the fundamental mode to fit the transversal intensity distribution of the pump beam to produce a Flat-Top (FT) beam with constant intensity distribution at the output for all variations within the resonator. The selection of a given resonator system is not random and a laser with a FT intensity distribution at the output is ideal for several branches of laser materials processing, medicine and science [4].

2. Resonator concept

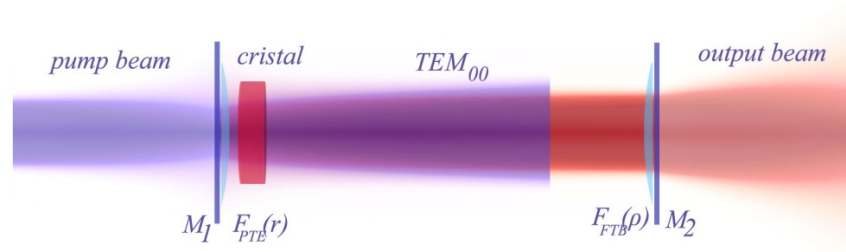


Fig.1. A schematic of the resonator concept. M_1 and M_2 are flat mirrors; F_{PTE} and F_{FTB} are the lossless phase transformation elements at mirror M_1 and M_2 respectively.

To solve a given problem we must solve the problem of transforming a Super-Gaussian (SG) beam into FT beam in the cavity. We consider a system consisting of a lens with focal length f and a lossless phase transformation element $\varphi(r)$ on the plane of mirror M_1 which are positioned as a doublet (see fig. 1) [5]. The field at the focal plane of the lens (mirror M_2 (see fig. 1)) $u(\rho)$,

can be found by following the Hankel transformation for the initial field $\varphi(r)$ at the doublet plane:

$$u(\rho) = h(\rho) \int_0^\infty g(r) \exp(i\varphi(r)) J_0\left(\frac{k\rho r}{f}\right) r dr, \quad (1)$$

where $h(\rho) = -\exp(ik(f + \rho^2/2f))ik/f$, $k = 2\pi/\lambda$, λ is wavelength.

We may apply the method of stationary phase to find an analytical solution for the phase transformation function $\varphi(r)$, such that the field $u(\rho)$ is a perfect FT beam, of width R and the view of initial field is SG function of order n namely $g(r) = \exp(-r^n/2w^n)$:

$$\varphi(r) = \beta \frac{\sqrt{2\pi}}{2} \int_0^{r/w} \sqrt{A_n - \Gamma\left(\frac{2}{n}, l^n\right) n^{-1}} dl \quad (2)$$

$$A_n \equiv \lim_{l \rightarrow 0} \left(\Gamma\left(\frac{2}{n}, l^n\right) n^{-1} \right)$$

where a dimensionless parameter β has been defined as $\beta \equiv 2\pi R w / f \lambda$ (the parameter shows how well the geometrical optics approximation holds) [5] and $\Gamma(k, m)$ is the incomplete gamma function.

Equation 2 fits an equation obtained by Romero et al [5] for the particular case of a Gaussian initial field ($n=2$) and presents the general case of the transformation element equation for any power of SG initial field.

Due to the generation of the FT beam at the Fourier plane of the lens, the effective phase profile of the lossless phase transformation element (PTE) with a Fourier transformation lens is given by:

$$F_{PTE}(r) = \varphi(r) - \frac{kr^2}{2f}. \quad (3)$$

It is possible to use the stationary phase method to extract a closed form solution for the phase of FT beam $u(r)$ at the Fourier plane as well:

$$F_{FTB}(\rho) = \frac{k\rho^2}{2f} + F_{PTE}(r(\rho)) - \frac{\beta r(\rho)\rho}{Rw}, \quad (4)$$

where from the stationary phase condition $\rho/R = \partial F_{PTE}(r)/\partial(r/w)$ we may find the unknown function $r(\rho)$ for any specific integer n . As an example we will find $r(\rho)$ for $n=2$ (see Eq. 5a) and $n=4$ (see Eq. 5b):

$$r(\rho) = w \sqrt{-1 \left(1 - \left(\frac{2\rho}{\sqrt{\pi}R} \right)^2 \right)} \text{ for } n = 2, \quad (5a)$$

$$r(\rho) = w \sqrt{\text{Erfc}^{-1} \left(1 - \frac{4\rho^2}{\sqrt{\pi}R^2} \right)} \text{ for } n = 4. \quad (5b)$$

Equation (5a) fits an equation presented by Litvin et al [6] for the particular case of $n=2$ namely the FT–Gaussian resonator.

If we know the equation for the phase of the PTE which transforms the SG beam into a FT beam and the phase of the FT beam at the Fourier plane, we are able to therefore construct a resonator system with an intensity of the fundamental mode which transforms from a FT transversal intensity distribution into a SG intensity distribution for a single pass from mirror M_1 to mirror M_2 . The reverse propagation technique [7] can be used to obtain the shape of the reflecting or transmitting lossless diffractive optical element (DOE) at mirror M_2 and the matrix Fox–Li method [3] to determine the profile of the transversal intensity distribution of the oscillating fundamental mode of the obtained resonator system.

We present in figure 2 the intensity profiles of the obtained field on both mirrors for different values of n under the assumption that output FT beam is constant. The intensity distributions of the first competing modes on the same mirrors for a parameter of $n=4$ which were obtained by matrix Fox–Li method are also presented.

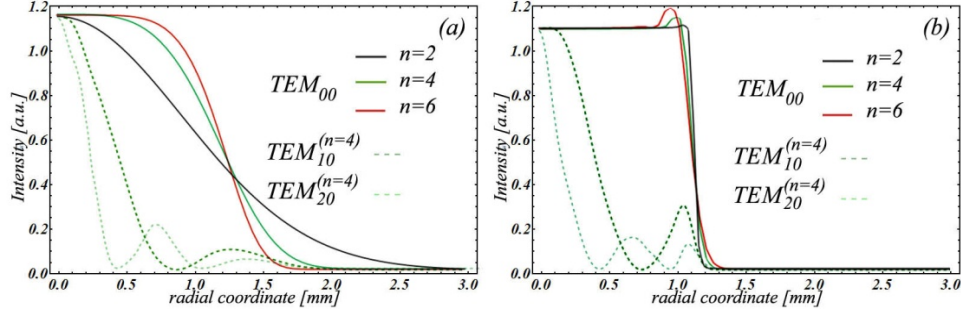


Fig. 2. The obtained field intensity distribution of fundamental mode and nearest competing modes on mirror M_1 (a) and mirror M_2 (b) for different parameter n of SG beam for the following parameters of resonator system: radii of mirrors M_1 and M_2 are equal and 4 mm; radii of FT (R) and SG (w) beams are equal and 1.5 mm; wavelength is 1064 nm; distance between mirrors is 200 mm; the corresponding Fresnel number and β parameter are 75 and 66 respectively.

As indicated in fig. 2, the resulting FT beam at mirror M_2 loses the quality upon increasing the SG beam power n . This behavior is a result of the use of the stationary phase approximation. The requirement for the stationary phase approximation is the presence of two functions at the integrand, namely one which is a relatively slowly varying function and the other which is a generally large and rapidly varying function. In our case the function $g(r)$ presents the slowly varying part of integrand which increases the derivative with a rise in n and consequently decreases the stationary phase requirement. Therefore to keep the quality of FT beam constant we must increase both the β parameter and the power of the SG beam n simultaneously.

Based on the method described above we are able construct a resonator system which can tune the spatial fundamental mode distribution to match a pump beam and the same time hold a spatial intensity distribution of an output beam to increase pump efficiency.

2.1. Example of real pump

To illustrate the method we consider an example of a real pump beam which is obtained from a multi-mode fiber coupled diode. The experimental image of the intensity distribution of the pump is presented in the fig. 3. This was obtained by imaging the output plane of the multimode radiation of the optical fiber onto a CCD camera. As presented in fig.3, we can approximate the transversal intensity distribution of the pump beam at a given plane with high accuracy using a 4th order SG intensity distribution (see incept of fig. 3).

We assume the use of a thin crystal (see fig.1), thus the transversal intensity distribution of the required mode and pump beam does not change significantly while passing through the crystal. We are therefore able to calculate a spatial mode-pump matching of the required fundamental mode [2] (the overlapping integral of the required mode and pump beam) and compare it with nearest competing modes.

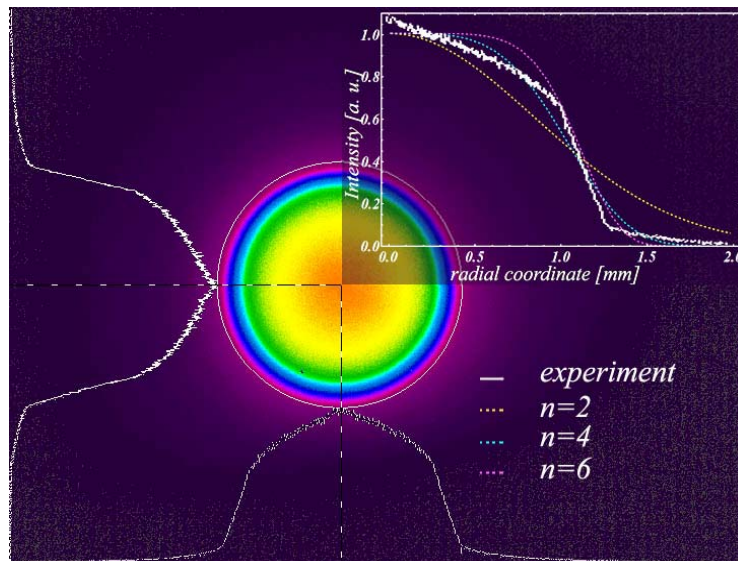


Fig. 3. An image of the spatial profile of a fiber coupled diode pump and examples of Super-Gaussian fits for different parameters of n (incept).

For this particular case of pump and assuming a thin crystal which is located close to mirror M_1 (see fig.1), the overlapping integral for the SG fundamental modes of orders 2, 4 and 6

with the pump beam gives a value which is approximately 91.9, 99.6 and 90.8 percent respectively. Thus a fundamental mode must have a super-Gaussian intensity distribution of 4th order at mirror M_I for optimal pumping.

We can determine the difference in diffraction losses of the nearest competing modes for a given Fresnel number of the system and fundamental mode parameters ($n=4$) using the matrix Fox–Li method (see fig. 2).

The difference in diffraction losses for the first and the sixth competing mode is less than one percent. At the same time a comparison between the mode to pump fitting value of the fundamental mode with other higher order modes presents a significant difference, namely $TEM_{00}=99.6\%$ $TEM_{10}=77.2\%$ $TEM_{20}=58.3\%$ (see fig. 2) for the similar parameters of the fundamental mode. Therefore the diffraction losses are insignificant in the process of the selection of output modes. The major difference in the overlapping value of the fundamental mode and the pump beam in comparison to the nearest competing modes (which was obtained by intra–cavity fundamental mode shaping) is the dramatic increase in mode discrimination.

3. Conclusion

In this work we have shown one of the ways of varying the intensity distribution of the fundamental mode in a cavity while maintaining a constant intensity distribution at the output. We have successfully presented a technique for a cavity which produces a Flat–Top intensity distribution at output. The intra–cavity variation of the intensity distribution of the fundamental mode can be applied to increase a spatial mode–pump matching and therefore to enhance pump efficiency.

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