How effective is using of laser beam?

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Abstract

An analysis of efficiency of TEM_{00} laser beam usage on the base of geometrical consideration is done; laser beams of circular symmetry and laser diode beams are considered separately. It is shown that losses of laser energy in some types of material processing technologies can reach very high level, up to 63%; in general usage of laser diode energy is more efficient. The efficiency of laser beams usage in some laser technologies could be increased substantially with applying beam shaping optics to provide homogeneous intensity distribution.

Keywords

Laser, Material processing, Beam shaping, Flattop beam

Introduction

Laser radiation is widely used for material processing that is why there is a great importance to evaluate which part of energy of laser beam has an effect upon a material under processing, i.e. what is an efficiency of using laser radiation in a particular laser technology. Let's make such evaluation for so called single mode (or TEM_{00}) laser beam, as is well known this kind of laser beam is often used since it provides largest energy concentration. Of course, for various lasers and materials a nature of interaction of laser radiation with a material is different and depends on many features, it is impossible to give a common description of all processes. However, because of the nature any single mode laser beam has a certain, so called Gauss, intensity distribution. Therefore, as a first approach of the efficiency evaluation it is enough to consider geometrical features of Gauss function only, without taking into account effects accompanying laser treatment of materials like burning, etc.

A special consideration should be done for radiation of laser diodes since these laser sources have features of intensity distribution.

Theory and calculations

The intensity distribution $I(r)$ of single mode laser beam is described by well-known relationship:

$$I(r) = I_{max}\, e^{-2\frac{r^2}{\omega_o^2}} = \frac{2}{\pi\omega_o^2}\, e^{-2\frac{r^2}{\omega_o^2}} \qquad (1)$$

where ω_o - waste radius of laser beam,
r – current radius.

The maximum intensity value I_{max} is chosen in such a way that total energy of beam is 1, see Fig.1.

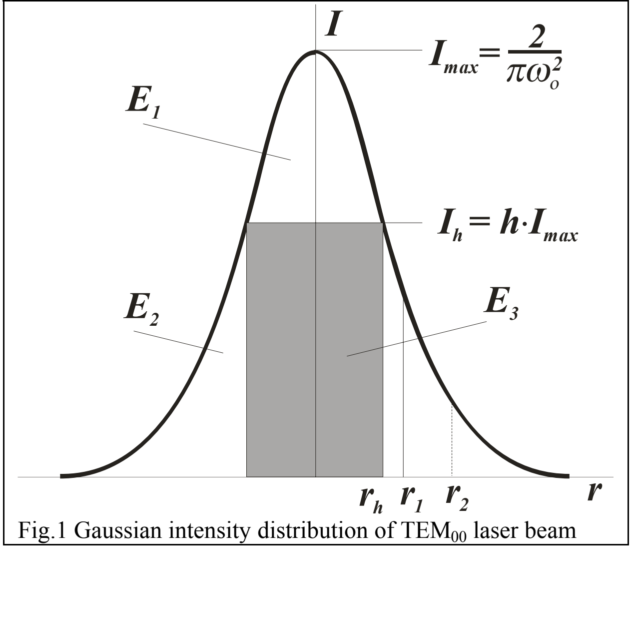

Fig.1 Gaussian intensity distribution of TEM_{00} laser beam

A purport of most of laser technologies is to transfer a certain amount of laser energy to the material under processing, therefore in further efficiency evaluation we will use energy specifications of laser beam. For convenience of further consideration let's consider that all processes of laser radiation propagation occur within interval of time being equal to 1, and let's find an energy amount concentrated within the ring part of laser beam bounded by circles of radii r_1 and r_2.

The ring part of energy E_{r1-r2} can be found by integration of intensity function $I(r)$ [1]:

$$E_{r1-r2} = 2\pi \int_{r_1}^{r_2} I(r)\, r\, dr \qquad (2)$$

By substituting of function of intensity distribution (1) to formula (2) and making integration we get a formula to calculate the ring part of laser beam energy:

$$E_{r1-r2} = e^{-2\frac{r_1^2}{\omega_o^2}} - e^{-2\frac{r_2^2}{\omega_o^2}} \qquad (3)$$

Let's suppose that in a laser technology the material treatment occurs when applying of beam intensity of a certain level I_h, Fig.1. For convenience of further considerations let's input a variable h:

$$h = I_h / I_{max}$$

Thus, h is a "working" level of laser beam, a range of values of h is from 0 to 1.

Now, let's consider a three-dimension geometrical figure bounded by a horizontal plane and a surface of two-dimensional Gauss function $I(r)$ defined in polar coordinates. The volume of this figure has physical sense of energy of a laser beam; under the normalization conditions adopted earlier a value of this energy is 1. Let's denominate by variables E_1, E_2 and E_3 different parts of the figure; these parts could be interpreted as parts of beam energy:

- E_1- an "apex" of Gauss function is an excess of energy over the working level h, in some cases it is a loss of energy, for example, when processing thin films of a certain material,
- E_2 - "tails" of Gauss that almost always are losses of energy or lead to bad effects of laser treatment like overheating [2], and
- E_3 - effective "cylinder" of energy.

With using the relationship (3) it is not difficult to define formulae to calculate values of "parts of energy":

$$\begin{aligned} E_1 &= 1 - h + \ln h \cdot h \\ E_2 &= h \\ E_3 &= -\ln h \cdot h \\ E_1 + E_2 &= 1 + \ln h \cdot h \end{aligned} \qquad (4)$$

The sum E_1+E_2 is given for evaluation of losses when processing thin films of a certain material. Results of calculations using these formulae are presented at Fig.2.

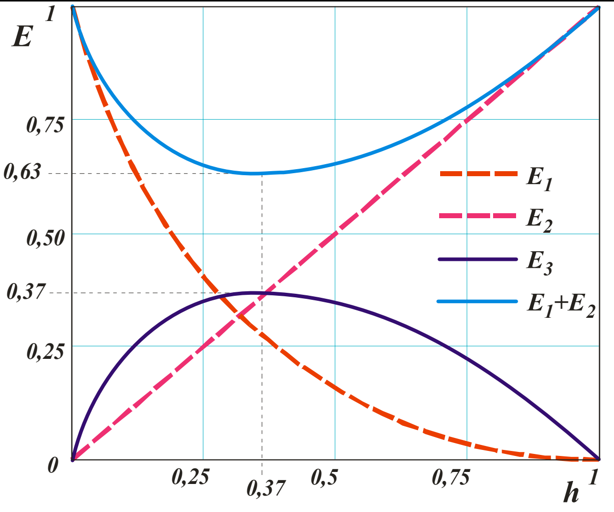

Fig.2 Variation of parts of laser beam energy:
E_1- "apex", E_2- "tails", E_3- "effective cylinder"

The above consideration relates to laser beams of circular symmetry, for example, fiber lasers, Nd:YAG or CO_2 lasers. Unlike these laser sources intensity distribution of high power laser diodes has rather a symmetry about plane – the radiation is multi-mode alongside a stripe emitter (so called slow-axis) and a single mode one in perpendicular direction (so called fast-axis). Therefore, analysis of laser diode radiation should be done specially. As a geometrical model of energy distribution one can use a simplified "energy figure" bounded by horizontal plane and a cylinder which generating line is the Gauss function. Thus, we assume that intensity distribution in the slow-axis direction is homogeneous; in that case it is enough to analyze a section of "energy figure" in fast-axis direction only, i.e. to analyze the Gauss function that is shown at Fig.3.

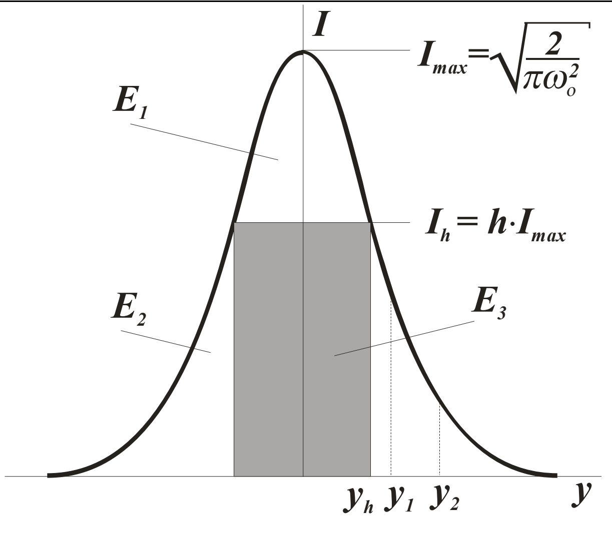

Fig.3 Intensity distribution in fast-axis of a laser diode

As before we will use a normalized intensity function assuming that width of "energy figure" in slow-axis direction is 1, and the maximum intensity value I_{max} is chosen in such a way that total energy of beam is 1. In that case the intensity in fast-axis direction could be described by relationship:

$$I(y)=\sqrt{\frac{2}{\pi\omega_o^2}}\; e^{-2\frac{y^2}{\omega_o^2}} \tag{5}$$

here y – coordinate in fast-axis direction,
the rest variables have the same sense like in previous consideration.

Then by integration one can get a formula for calculation of energy part within the coordinate range y_1-y_2:

$$E_{y1\text{-}y2}=erf\left(\frac{\sqrt{2}}{\omega_o}y_2\right) - erf\left(\frac{\sqrt{2}}{\omega_o}y_1\right) \tag{6}$$

Using the formula (6) it is not difficult to get relationships for calculation of "parts of energy": "apex" E_1, "tails" E_2 and effective rectangle E_3, analogous to ones analyzed for TEM_{00} beams.

$$\begin{aligned} E_1 &= erf(\sqrt{-\ln h}) - \frac{2h\sqrt{-\ln h}}{\sqrt{\pi}} \\ E_2 &= 1 - erf(\sqrt{-\ln h}) \\ E_3 &= \frac{2h\sqrt{-\ln h}}{\sqrt{\pi}} \\ E_1+E_2 &= 1 - \frac{2h\sqrt{-\ln h}}{\sqrt{\pi}} \end{aligned} \tag{7}$$

Results of calculations using these formulae are presented in graphic form at Fig.4.

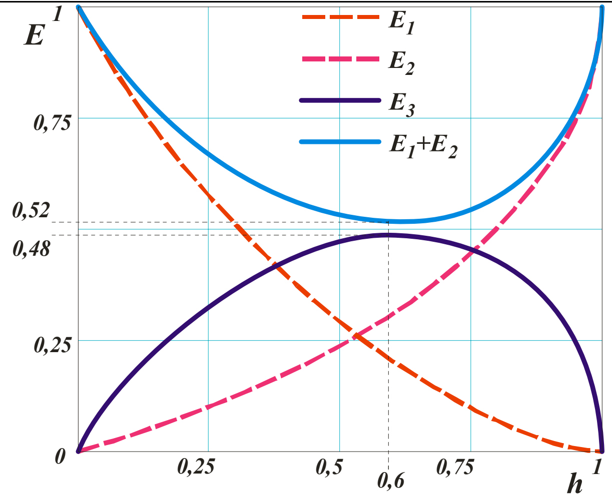

Fig.4 Variation of parts of laser beam energy:
E_1- "apex", E_2- "tails", E_3- "effective rectangle"

Discussion

The results of calculations obtained for the pure TEM_{00} laser beam and the beam of laser diode are of a great interest from the point of view of efficiency of using the laser radiation.

For TEM_{00} beams the unconditional energy loss E_2, "tails", can reach very high level, for example, if a working energy level is a half of maximum, h=0,5 (very often just this level is considered as a working one) the energy losses are 50% of full laser beam energy!

In case of laser technologies of treatment of a thin layer of a material, for example, thin films, the energy part E_1, "apex of Gauss", is also considered as a loss of energy since this part exceeds the working energy level I_h, thus both energy parts E_1 and E_2 are losses. Sum of losses E_1+E_2 is shown as a graph at the diagram as well; minimum of this function is 0,63. In other words, when treating of thin film or layer of a material in the best case "only" 63% of energy is lost and only 37% is effective! Of course, this conclusion is based on the simplified geometrical interpretation, however this approach makes it possible to evaluate amount of losses of laser radiation, they could reach, sometimes, a half of total laser energy!

In case of laser diodes the behavior of losses is similar to one of the pure TEM_{00} beam, while the efficiency is higher. This is a logic result since under the assumption adopted the radiation function is homogeneous in slow-axis direction.

No doubt, these results show very good how important is to take a care for more efficient use of laser energy. In any laser technology just a laser plays a "central" role and determines most important specification of a particular technology including the productivity and the costs, and these important features are in strong dependence on how efficient is using the laser energy.

There is no a universal method how to increase the efficiency. However, for some types of applications, like laser annealing, welding, illumination of objects in holography, etc., the efficiency can be increased substantially by converting the shape of the beam intensity distribution from Gauss-function to a homogeneous one. Very often such homogeneous distribution is called as a flattop or a top-hat one, its sections is close to a rectangle, thus the efficiency of using reshaped beam could reach almost 100%!

This intensity conversion, or beam shaping, could be provided by specially designed optical systems, so called Homogenizers. There are several methods of designing these systems, [2,3], and several types suggested by various manufacturers, thus today it is possible to find an optimum solution for a particular laser technology.

Conclusion

In spite of the feature of TEM_{00} laser beam to provide very high concentration of energy the intensity distribution within the laser beam isn't an optimum one for many laser applications. Due to inhomogeneous intensity distribution (well known Gauss-function) the amount of unused or improper used energy could reach very high level – for some applications more than a half of source energy. Therefore, the task of optimizing the energy usage is very important for modern laser technology, especially in materials processing where efficiency of using the laser beam influences directly on the productivity and expenses of a particular laser technology.

One of the ways to increase substantially the efficiency of using the laser beam is applying so called Homogenizers – special optical systems converting the source Gauss-function of intensity distribution to homogeneous one, in other words to flattop or top-hat distribution.

References

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