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Research Article

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Distributed Focusing of Laser Radiation and Applications Possibility

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Abstract
A new type of focusing is reported. For the first time, the lenses necessary to obtain the distributed focusing are described. The approximate calculation shows that this type of focusing can be useful in surgery, industry and information technology. There is only one type of distributed focusing at this moment, that is Bessel beam. In this type of beams, energy flux, excurrenting out of axicon, is distributed by a line segment. Power distribution by the line segment can be changed by varying the intensity profile of the incoming beam. Another way is presented in the paper. There are two types of laser scalpels (contact and non-contact ones), but this type of focusing can be used as a base for creating new types of laser scalpels with fundamentally new characteristics. Also this focusing can be applied to creation of more efficient laser cutters.

Keywords: Distributed Focusing, Fresnel Lens, Optical Inhomogeneity, Gradient Lens, Aspheric Lens, Axicon

Introduction

There are two types of laser scalpels at this moment: contact and non-contact ones. Contact laser scalpels heat the cutting tip of the optical fiber. These scalpels need the contact of the optical fiber tip and the patient's tissue to cut it. Non-contact laser scalpel uses a focused beam [1]. It means that precise control of the distance between the focusing lens and the cut tissues is required. Non-contact scalpels don't allow deep cut. In some cases, laser scalpels should be able to cut tissues in some small segment of few centimeters in size like metal scalpels. In addition, in industry, there is necessity to control the distance between focusing lens and cut material precisely [2]. This distance can be easily set if the beam is able to cut some segments. Then the deviation from the optimal distance between the focusing lens and the cut material results in better slice quality than the use of a dot focusing lens. New lenses allowing creation of these types of scalpels and cutters are first described in the present work.

Laser cutting requires proper account for the effect of ejected melt on the quality of slice and the speed of cutting [3]. New type of lenses can decrease the volume of melted metal during cutting. This fact provides a possibility of reduction of the power of laser cutters or an increase in the cutting speed.

It is shown in this work that a new type of lenses can increase the efficiency of laser cutters.

Here a question is also discussed, how to make the lenses with distributed focusing. There are three types of lens constructions, except the spherical one: Fresnel lens, optically inhomogeneous plate (gradient lens) and aspheric lens.

A lenses, which focus a light beam into a dot, is just a model approximation. But we make attempts very often to make these lenses closer to this ideal model to be used as objectives, laser scalpels, cutters, gravers, scanners except laser tweezers, where Bessel beam is used. Bessel beam is an example of the distributed focusing.

The Bessel beam is made by passing Gaussian beam thorough an axicon (Figure 1) [4]. This beam is used like an optical tweezers [5]. There is an idea to use this beam for creating a laser induced plasma canal [4].

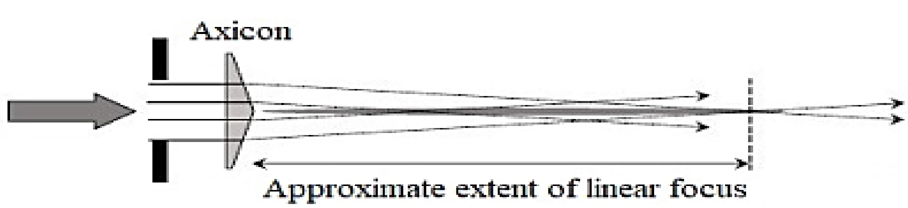

Fig. 1: Mechanism of Bessel beam formation [4].

The present work reports more general description of the lenses with distributing focusing.

Within the framework of the considered model, the beams become of cylindrical symmetry after passing these lenses through, as Bessel beams.

The term "distributed focusing" has been introduced because the existing nearest term, except Bessel beam, is spherical aberration, which is not a useful phenomenon, not worth of special generation.

The work is aimed to description of the lenses with distributed focusing and comparison of the efficiency of distributed focusing lens and classic lens using geometrical optics in laser cutting.

Analytical Part

Three types of lenses are described here: an analog of the Fresnel lens (focusing in a line segment, not into a dot), analog of aspheric lens and optical inhomogeneous plate.

In this type of lenses, the focal distance of the radial segment depends on the radius of the segment.

First of all, we should analyze common details of these three types of lenses.

Let x_o and x_1 will be the ends of the segment for focusing of a laser beam (further we will call it "blade"), P_0 is the laser beam power, *dP* is the beam power falling on segment *dx, R* is the radius of the lens and the beam, *d* is the thickness of the lens (Figure 3).

Let *f(x)* to be a function, which describes the distribution of power on blade.

$$f(x) = \frac{dP}{dx} \qquad (1)$$

The lenses with minimum one planar side are considered here. Axis OX of the coordinate system is normal to the lens planar surface and aligned with the main optical axis. Axis OY is located in the plane of the planar side of the lens. Let us select an element of the lens surface with radius *y* and width *dy*. Then the energy flow, which passes through this segment of the lens with the area $2\pi y dy$ will be focused at distance x on segment dx. Then we have:

$$f(x) = \pm 2\pi W(y) y \frac{dy}{dx} \qquad (2)$$

where *W(y)* is the function, which describes the dependence of intensity on the value of coordinate y (intensity profile).

Therefore, if we have a uniform intensity profile, then

$$W(y) = \frac{P_0}{\pi R^2} \qquad (3)$$

and (1) is transformed as:

$$f(x) = \pm \frac{2P_0}{R^2} y \frac{dy}{dx} \qquad (4)$$

As it was said before, the focal distance of this lens, which focuses a beam in blade, is not the same over the whole lens. This lens is of cylindrical symmetry and different elementary rings of this lens have different focal distances. The sign in (2) can be found as follows: if the radius of an elementary ring increases with an increase of focal distance of this ring, then the sign "+" is applied, if an increase in the radius of an elementary ring is associated with a decrease of the focal distance of this ring, then sign "–" is used (see Figure 2).

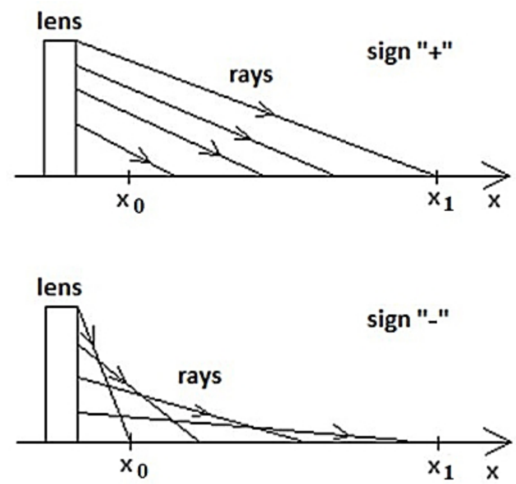

Fig. 2: Two different types of distributed focusing.

The result of solution of (2) is function *x(y)=Ψ(y)*. This function describes the dependence of the focal distance and the radius of an elementary ring of the lens.

1. Analog of Fresnel lens

In order to avoid light diffraction through the Fresnel lens, the width of the lens rings should be significantly larger than the wavelength of light. The same condition is applied here.

After of the coordinate system is selected, we have the following scheme (Figure 3).

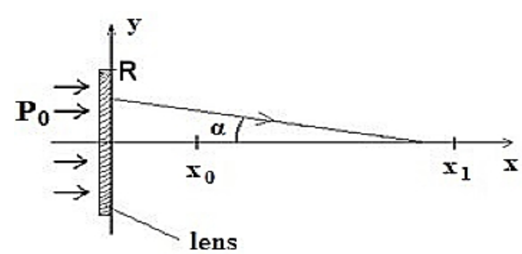

Fig. 3: Schematic image of the lens with distributed focusing.

Let us look at one segment of the lens, where the laser beam comes out of the lens (Figure 4).

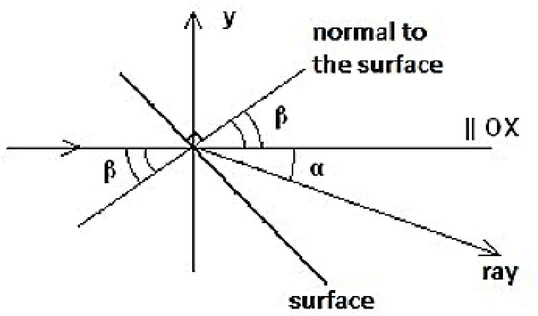

Fig. 4: Rays near a small part of Fresnel lens surface.

As we can see in Figure.4:

$$n = \frac{\sin(\alpha+\beta)}{\sin(\beta)} \tag{5}$$

Using function *Ψ(y)*,we have

$$\beta(y) = arcctg\left(n\sqrt{1+\left(\frac{\psi(y)}{y}\right)^2} - \frac{\psi(y)}{y}\right) \tag{6}$$

This equation describes the angle between the normal to lens surface and axis OX. In a real lens, function β(y) will be not a smooth function, but a partly smooth one.

There are some limits for x_0 and x_1. Any material can decline a beam no more than at some maximum angle.

In Figure 3, we see that the minimal focal distance of the ring segment of radius y can be found with using max(α), where 0≤α+β≤π/2.Then, the minimum at x_1 exists for sign "+" in (2) and finite radius of lens. Sign "–" is associated with the minimum at x_0 .

2. Optically inhomogeneous plate

Schematic picture is the same as in Figure 3.

Before finding parameters of this lens with distributed focusing, it is necessary to look at a simpler question. Laser beam is normally falling on a plate, and going out at an angle α through its previous direction (Figure 5).

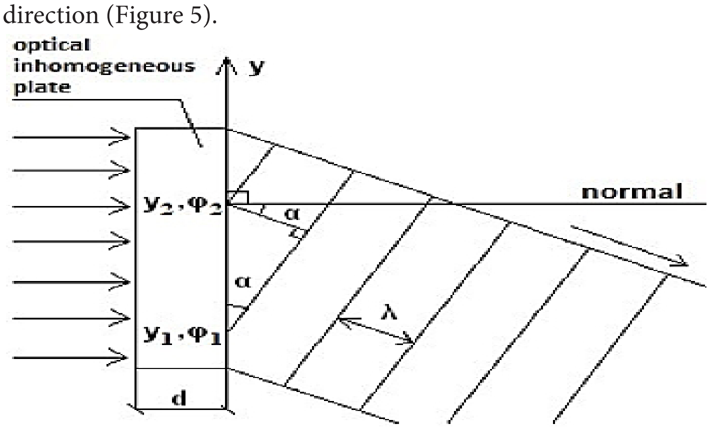

Fig. 5: Phase surfaces near the surface of an optically inhomogeneous plate.

Here φ_1 and φ_2 are the phases of phase surfaces, $y_1$and y_2 are coordinates of the tangency of these surfaces to optical inhomogeneous plate, λ is the wavelength of the light.

In Figure 5 we can see:

$$\varphi_1 = 2\pi\frac{n(y_1)d}{\lambda} + \varphi_0 \tag{7}$$

$$\varphi_2 = 2\pi\frac{n(y_2)d}{\lambda} + \varphi_0 \tag{8}$$

Here is φ_0 the phase on the left-hand side of the lens surface (not pictured), *n(y)* is the refractive index of the plate as a function of coordinate *y*.

φ_1 and φ_2 are chosen in order to satisfy the equality φ_2-φ_1=-2π , and it is possible when *d*>>λ . In this case a small difference between *n*(y_1) and n(y_2) provides the requires difference of optical ways and phases. Using these conclusions in segment [y_1,y_2], we can make our calculations with monotonic continuous function *n(y)*. Then, with φ_1 and φ_2 as described above, we have

$$y_2 - y_1 = \frac{\lambda}{\sin(\alpha)} \tag{9}$$

As we can see in Figure 5, φ(*y*) is a linear function of *y*. According to monotonicity of *n(y)* within [y_1,y_2], with taking into account the fact that φ_2 - φ_1= -2π and equation (9), we can write down this differential equation as

$$\frac{dn}{dy} = -\frac{\sin(\alpha)}{d} \tag{10}$$

Now we come back to the general question that is creation of a distributing focusing lens.

Using function Ψ(*Y*) , we get

$$\frac{dn}{dy} = \frac{-y}{d\sqrt{\psi^2(y)+y^2}} \tag{11}$$

or

$$n(y) = \int_{y_1}^{y} \frac{-y_2}{d\sqrt{\psi^2(y_2)+y_2{}^2}}dy_2 \tag{12}$$

But equations (11) and (12) have some limitations. During calculations, it is possible to find a refractive index value that we cannot produce. For example, we can find that the value of the refractive index, that we cannot achieve by variation of the concentration or the type of admixtures in a certain material of the lens by the existing technologies. In this case, we need to create function *n(y)* with a jump discontinuity, which should be deployed where *n(y)* becomes critical. For example, *n(y)* decreases with below the minimal value we can produce. Before the critical value is reached, a jump discontinuity should be introduced and *n(y)* should be set at the minimal value we can produce. But we can do this in an ideal model. In reality, it will be a lens with a very high gradient of the refractive index in the area in the vicinity of the "jump discontinuity". In these areas (rings), the light will disperse from the blade. The wider these rings are, the less power is scattered.

In the end of this work, calculation of different types of the lenses are presented.

3. Aspheric lens

Here the schematic picture is different from the previous types, because this "plate" is of different thickness with different y (Figure 6).

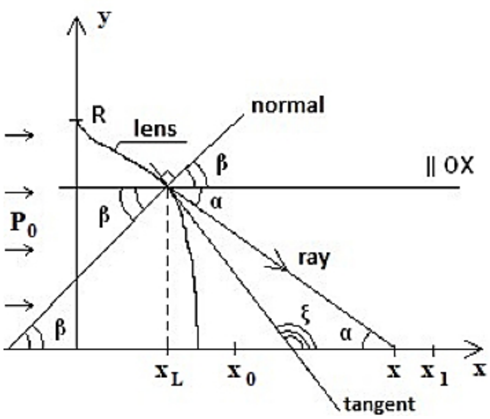

Fig. 6: Schematic image of the rays and an aspherical lens with distributed focusing.

We can see in this figure, that

$$\beta = arcctg\left(\frac{n-\cos(\alpha)}{\sin(\alpha)}\right) \quad (13)$$

That is similar to a Fresnel lens analog.

In aspherical lens type, it is necessary to find a function that describes the form of the surface of this lens, namely, function $y(x_L)$. There is only one function, because only Plano-convex lenses are described here, so a beam is normally falling on the planar side.

Using function *Ψ (y)*, we get

$$\frac{dy(x_L)}{dx_L} = \frac{\psi(y)-x_L}{y} - n\sqrt{1+\left(\frac{\psi(y)-x_L}{y}\right)^2} \quad (14)$$

Solving this differential equation, we find the form of the lens.

Analyzing of Efficiency

If these types of lens will be used in laser cutters or scalpels, it is necessary to calculate a possible increase of efficiency. In this work, the efficiency is described as the energy flux density in the cutting area and the volume of deleted material, for example, melted metal, to be compared with the ideal lens where the focal distance at the far side of cutting material.

Further we suppose that the cutting is made by an analog of the Fresnel lens type, an optically inhomogeneous plate (minus is used in equation (2)).

First of all, it is necessary to find the cutting area for a lens with distributed focusing. Let us find the external surface of the interference area, i.e. the caustic surface. Here the caustic surface is the external surface of the area of crossing of the rays spreading from different parts of the lens surface. As the problem is of cylindrical symmetry, the generatrix of this surface is required.

In order to find the generatrix, let us look at crossing of two rays coming from two neighbor ring segments (Figure 7):

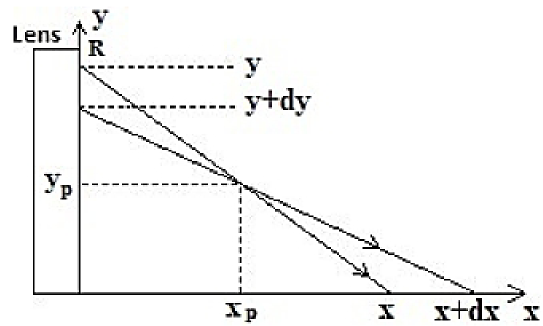

Fig. 7: Crossing of the rays from the nearest circular segments of the lens surface.

All points (x_p, y_p) should be found.

Using Figure 7, we write down a system of equations:

$$\begin{cases} \dfrac{y_p - y}{y} = -\dfrac{x_p}{x} \\ \dfrac{y_p - y - dy}{y+dy} = -\dfrac{x_p}{x+dx} \end{cases} \quad (15)$$

After some transformations, the system of equations describes the generatrix:

$$\begin{cases} y_p = \dfrac{y^2 \dfrac{\partial\psi(y)}{\partial y}}{y\dfrac{\partial\psi(y)}{\partial y} - \psi(y)} \\ x_p = \psi(y)\left(1 - \dfrac{y\dfrac{\partial\psi(y)}{\partial y}}{y\dfrac{\partial\psi(y)}{\partial y} - \psi(y)}\right) \end{cases} \quad (16)$$

The resulting system of equations describes the shape of the external caustic surface.

An example of a caustic surface is shown in Figure 8. In this example, radius of lens is 0.5 cm, the blade length is 30 cm, and the nearest to the lens end of blade is at x_0=32 cm.

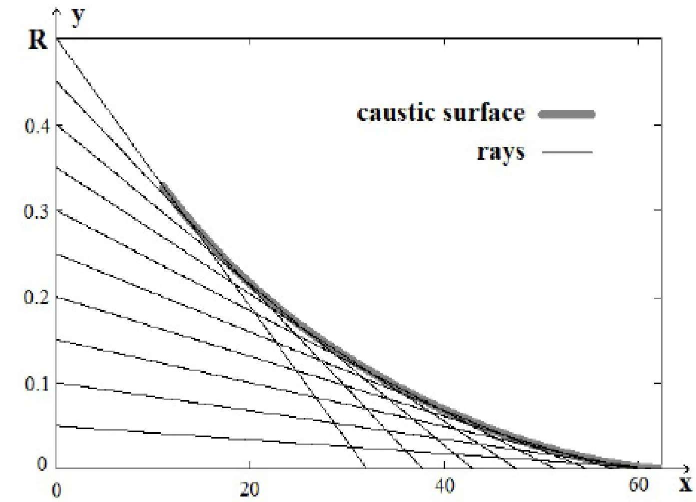

Fig. 8: Crossing of rays from different circular segments of lens surface creates caustic surface.

Let us suppose that the cutting area is the volume between the blade and the caustic surface included. The reasons are described below.

Now it is necessary to find the density of the energy flux through the circle normal to OX with coordinate x_a and radius y_a. But this circle with radius y_a and width dy_a can accumulate the rays from few rings with radius y, as pictured in Figure 9.

$$\begin{cases} \dfrac{y_r - y}{y} = -\dfrac{x_r}{x} \\ \dfrac{y_r - y}{y - y_a} = -\dfrac{x_r}{x_a} \end{cases} \tag{17}$$

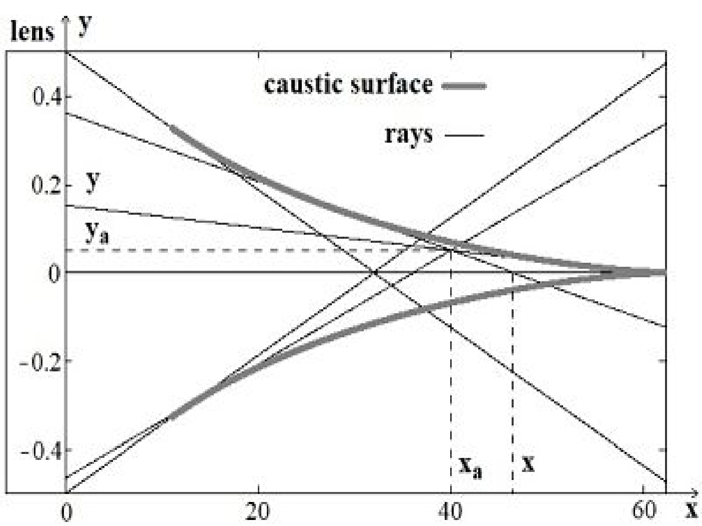

Fig. 9: Rays crossing in the interference area.

Solving the system of equations (17), we can find

$$(y - y_a)\psi(y) - yx_a = 0 \tag{18}$$

The number of all solutions y of (18) with Im(y)=0 and $|y| \le R$ is the number of all radiuses of the lens segments where the rays fall on the ring at distance x_a and radius y_a. In geometrical optics approximation, the power of radiation passing these rings is focused on the ring of radius y_a. Then we have:

$$\sum_i 2\pi y_i W(y_i) dy_i = 2\pi y_a W_a(x_a, y_a) dy_a \tag{19}$$

or

$$\frac{dP_a}{dy_a} = \sum_i 2\pi y_i W(y_i) \frac{dy_i}{dy_a} \tag{20}$$

Here y_i are the roots of equation (18), $W_a(y_a)$ is the light intensity on the ring of radius y_a, P_a is the total energy flux through the circle at the distance to the lens x_a and radius y_a.

Using (18) we can see:

$$\frac{dP_a}{dy_a} = \sum_i \frac{2\pi y_i W(y_i)\psi^2(y_i)}{\psi^2(y_i) - x_a\left(\psi(y_i) - y_i\left(\left.\dfrac{d\psi(y)}{dy}\right|_{y_i}\right)\right)} \tag{21}$$

If we calculate the deleted material volume as the volume of the area under the caustic surface, we get

$$P_a(x_a) = \int_0^{y_p} \frac{dP_a}{dy_a} dy_a \tag{22}$$

Now we consider the example described above with $x_0 = 32$ cm.

The scheme of the rays and the caustic surface for this example is presented in Figure 10.

In Figure 11, we can see an ideal model of the lens with dot focusing and the focal distance x_1 (pictured to be compared with distributed focusing).

In Figure 12, the intensity profiles are shown in plane $x_a = 47$ cm from the lens with distributed focusing $W_a(x_a, y_a)$ (the middle of the blade) and dot focusing with the focal distance equal to 62 cm. Powers of both beams falling to the lenses are equal to unity and their intensity profiles are of top-hat shape. In Figure 12, we can see that the use of the lens with distributed focusing provides the cutting area confined by the blade and the external caustic surface.

The intensity in this area is higher than that related to the dot-focusing lens.

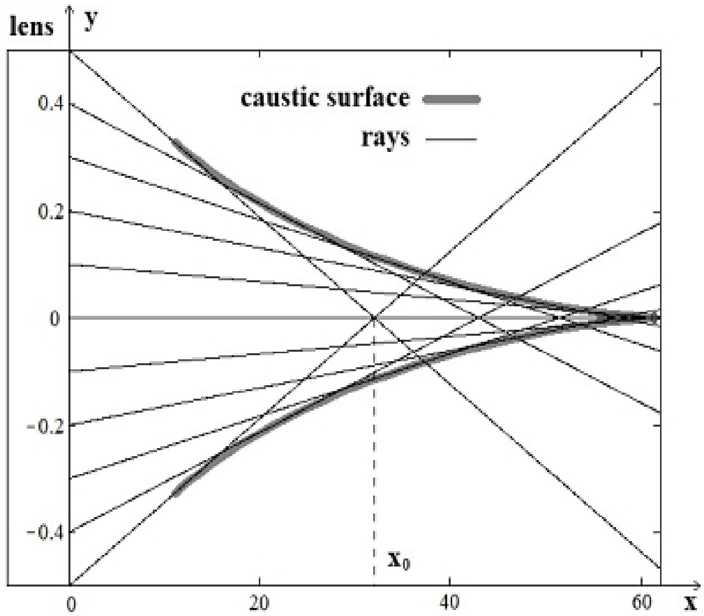

Fig. 10: Schematic image of the rays spreading from the lens with distributed focusing.

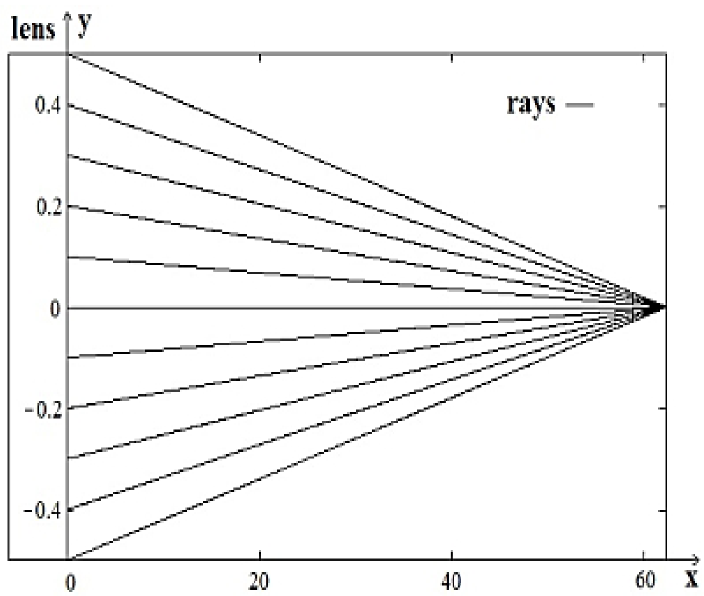

Fig. 11: Scheme of the rays, spreading from the ideal lens with dot focusing and focal distance at x_1

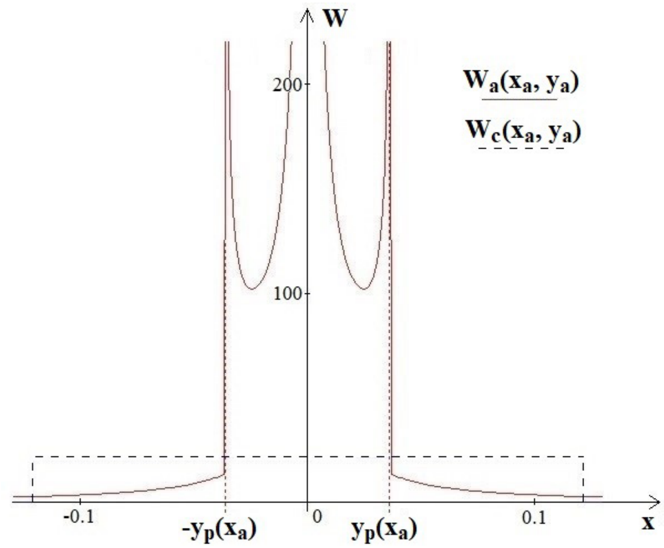

Fig. 12: Intensity profiles in plane x_a=47cm when using the lens with distributed focusing $W_a(x_a,y_a)$ and the dot-focusing one $W_c(x_a,y_a)$.

By comparing Figure 10 and Figure 11, we can see that the volume under the caustic surface is smaller than the volume of the deleted material that is cut by the lens with focusing in dot.

After calculating the volumes of the deleted material for dot focusing and distributed focusing lenses, we can see that the cutter with distributed focusing lens deleted material less by 64.5% and the beam power can be decreased by 77.5%.

Of course, this is just a theoretical estimate and experimental confirmation is needed.

Conclusions

A lens with distributed focusing is described and the efficiency of laser cutting by a distributed focusing lens and a classic lens is compared by using geometrical optics.

Three types of lenses with distributed focusing are analyzed.

The calculations are provided for any radial symmetric intensity profile of falling beam and any power distribution on blade.

Theoretical calculation of the efficiency of laser cutting shows that the use of the lens of 0.5 cm in radius and the ends of the blade at the distance of 32 cm and 62 cm results in decreasing of the volume of the deleted material during cutting by 64.5 % and decreasing of necessary beam power by 77.5 %, as compared to a classic lens of the same radius and the focal distance of 62 cm.

To increase the accuracy of the efficiency calculation, it is necessary to consider thermal conductivity, light scattering etc. In order to describe a lens with distributed focusing and blades in microscale, the wave properties of light should be taken into account. It's also important to consider the results of falling of a dissent beam on the lens, and falling of a beam at an angle.

This method of description of a lens can be a useful tool for simplifying the calculations of lens structures, creating, using laser beam, any interference pattern to provide a beam of any possible properties.

The lens with distributed focusing can be useful, because these lenses could decrease the losses of constructive materials during cutting. Working by laser scalpels with distributed focusing lens could be similar to working by common steel scalpel that has an extensive blade and advantages of laser scalpels.

Besides, the laser blades could be useful for creating laser inducted plasma canals. Opposite to [4], it is not necessary to make power distribution in blade like in Bessel beam or to change it by modification of the intensity profile of the falling beam, but just by changing the distributed focusing lens. It means that different plasma canals with different properties can be created.

The results of this work can be used in laser cutting, engraving, surgery, information technologies, laser induced plasma canals etc.

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