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Design of laser beam expander for LWIR spectrum range

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Abstract: The paper presents the outcomes from designing laser beam expanders for LWIR spectrum range. Specifics of laser beam radiation have been given proper observation and a reference optical diagram selected. Three different materials such as ZnSe, Si and Ge have been used. The optical design has been carried out by means of primary synthesis, analysis and optimization. Two kinds of optimization have been effected with resultant expanders of diffraction-limited quality of the outgoing beam.

I. Introduction

Laser radiation features specific properties such as coherence, high, monochromatism, low divergence; high spectrum and surface power density. These properties allow the development of highly effective devices and equipment that display superior quality as compared to devices and equipment using thermal source of radiation. Rational utilization of lasers as radiation sources entails development of optical systems for laser beam conversion. One feasible method of laser beams conversion is by way of collimation. In itself collimation is reduction of laser beams divergence. Laser beams collimation finds its application in the following cases [1]-[8]:

- The outgoing laser beam is of small cross-section. Some applications demand larger laser beams. This can be accomplished in two possible ways. The first one includes the use of scanning system which complicates the overall design of the device and lowers its reliability. The second one involves utilization of laser beam expander;
- With technical lasers it is necessary to focus the laser beam into a spot which is of far smaller dimensions as compared to the laser itself. The use of focal optical systems is not quite productive in most of the cases. In order to obtain a spot of minimal dimensions, the laser beams are first to be expanded and then focused;
- in instances when powerful lasers are used, it is necessary to reduce radiation surface density to prevent from destruction the samples being tested or the photodetector used. This can be achieved by way of laser beam expansion;
- In some applications of lasers the task is to obtain small spots at a long distance. It is done by decreasing the laser beam angular divergence which is preceded by expansion.

CO₂ lasers find a wide range of application in technology systems for materials treatment. Lasers are used for marking, etching, cutting, welding and boring of holes. However, this type of lasers feature specific properties which distinguish them from the other types of lasers. These features are the comparatively large wave length (LWIR spectrum range) and the high density of the generated radiation power density. Accordingly, beam expanders for CO₂ lasers feature specific optical design which differs from the one used with lasers operating in the visible and close infrared range.

The aim of this work is to develop optical systems for expansion of laser beams operating within LWIR spectrum range (8÷12) μm.

II. Selection of principal optical scheme

In designing optical systems for conversion of laser radiation due consideration is to be given to the properties of laser radiation, the laws concerning its dissemination in space as well as its interaction with optical media. Also account is to be taken of some undesirable effects whose possible occurrence should not be allowed

- A laser beam (particularly the CO₂ laser) is a powerful source of coherent radiation. Under its influence it is possible for some non-linear effects, which are related to the resultant large concentrations of energy in certain points of space, to occur. To prevent the occurrence of such effects, there should be selected optical designs which do not allow the formation of intermediate real image.
- Interference effects may result in the distortion of the spatial structure of the beam. The impact of these effects may be reduced by precise selection of the thickness of optical elements, and by not using, if possible, joint components. Joint optical components are particularly undesirable when operating with powerful CO₂ lasers.
- Powerful laser radiation may result in destruction of optical components, therefore it is advisable to use optical materials which are able to withstand high power radiation.

Laser beam expanders are afocal telescope systems. Depending on the spectrum range of radiation and the requirements for beam structure transformation, expanders are refractive, reflective and catadioptric afocal attachments.

As the case is, telescope systems shape images which are observed by approximation coefficient equal to the magnifying power (MP). With this there is an angular field expansion which is proportional to angular magnification m_α ($MP = m_\alpha$).

If the telescope system is turned at 180° , this will result in a device which decreases angular field (in proportion with angular magnification m_α) and expanding the breadth of axial beam (inversely proportional to angular magnification m_α). Therefore, an inverted telescope system can be used as laser beams expander. It is also possible to use the notion "expander magnification" M which can be defined as

$$M = \frac{1}{m_\alpha} = \frac{1}{MP}$$

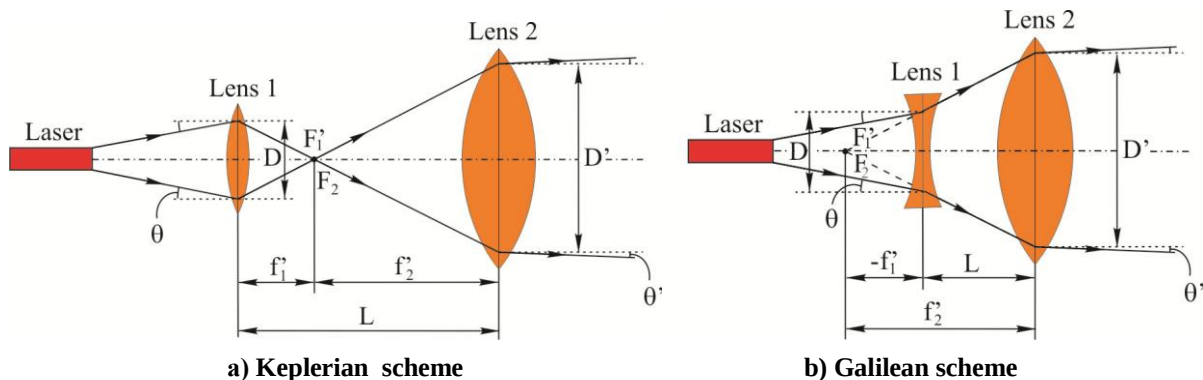
Telescope systems are refractive, reflective and catadioptric afocal attachments [9]-[13].

In [14], [15] there is presented reflective afocal system composed of 2 extra-axial parabolic mirrors which generate aberration-free wave front. Such systems are available in industrial applications, however, they are of very large overall dimensions and high cost.

In [14], [15] there is presented catadioptric system composed of extra-axial parabolic mirror and negative refractive component which allows to design a diffractive expander of minimum aberrations. The optical and geometrical axes of such system misalign which sophisticates its assembly and adjustment.

Refractive systems can operate only within predetermined spectrum range which is limited by the transmission factor of the used optical materials. There are two optical designs whereby refractive expanders can be developed: those of Galileo and Kepler.

Figure 1 Optical schemes of afocal attachments



In response to the outcomes of the analysis made, an inverted refractive system was selected as primary design of laser beams expander.

Telescope systems operate in a very small angular field, therefore it is reasonable to assume that spherical type of aberration is the prevalent one. Likewise it may readily be assumed that optical components are made of identical material. Our preliminary assumption will be that both components consist of one element. Due to the spherical aberration the outgoing rays form beams which are not strictly parallel but display some angular divergence θ' whose value may be defined by the expression [16]

$$\theta' = \frac{n(4n-1)}{64(n-1)^2(n+2)(F/\#)^3} \cdot \frac{M-1}{M} \quad (1)$$

where:

- n is the index of refraction for the material of which lenses are made;
- $F/\#$ is the expander focal number.

Expander magnification can be rendered as

$$M = \frac{D'}{D} = \frac{\theta}{\theta'} = -\frac{f'_2}{f'_1}$$

where:

- D and D' are the diameters of input and output beam;
- θ and θ' are the angular divergences of input and output beam;
- f'_1 and f'_2 are the focal distances of the first and second element of the afocal system.

The expander focal number can be expressed as

$$F/\# = \frac{f'_1}{D} = \frac{f'_2}{D'}$$

It should be noted that Galilean system gives upright image and has positive magnification whereas Keplerian system renders inverted images and produces negative magnification respectively. From expression (1) it follows that with all other parameters being equal, the divergence of rays in Galilean system will be smaller as compared to Keplerian system. In addition, unlike Keplerian system in Galilean system there is no real intermediate image which helps to avoid generation of high power densities in laser radiation. Accordingly, the reverse telescope system of Galileo can be regarded as the right selection of optical design for laser beam expander.

III. Development of the optical design for laser beam expander

Expander's optical design development implies well defined design parameters of the optical system. These include the radii r of optical surfaces curves; the distances between them t , and the refraction indices n of optical materials. Development includes the following stages: primary synthesis, analysis and optimization of optical design. Specialized ZEMAX software has been used in developing this design.

A. Primary synthesis of the laser beam expander optical design

The aim of this synthesis is to determine the initial design parameters of the optical system. Different methods are employed to determine the initial points of a certain optical design. Our paper makes use of the primary synthesis method which is based on the third order aberrations theory. The laser beams expander consists of two components: the first is negative and the second is positive. Second (positive) component L_2 is selected so that its shape should correspond to the minimum spherical aberration [4], [11]. This shape depends only on the focal distance of component L_2 and the material refraction index n . Then the radii of its refraction surfaces r_{21} and r_{22} will be determined by the expressions

$$r_{21} = -\frac{2(n_2 + 2)(n_2 - 1)}{n_2(2n_2 - 1) - 4} \cdot f'_2 \quad \text{and} \quad r_{22} = -\frac{2(n_2 + 2)(n_2 - 1)}{n_2(2n_2 + 1)} \cdot f'_2 \quad (2)$$

The design parameters of the first (negative) component of the expander L_1 are determined in such a way whereby its spherical aberration $SA3(L_1)$ makes up for the spherical aberration of the second component $SA3(L_2)$, viz.

$$SA3(L_1) = -SA3(L_2) \quad (3)$$

It is shown in [16] that formula (3) will be fulfilled when the shape factor of the first component K_1 is determined as solution of the equation

$$\frac{(n+2)}{n} K_1 - (2n+1)K_1 + n^2 - \frac{n(4n-1)}{4(n+2)} \cdot M = 0 \quad (4)$$

The shape factor K of randomly selected lens is defined as

$$K = \frac{c_1}{c_1 - c_2}, \quad \text{where } c_1 \text{ and } c_2 \text{ are the curves of the first and second refractive surfaces.}$$

Therefore, the relationship between the shape factor of the first element and its radii is

$$K_1 = \frac{r_{11}r_{12}}{r_{11}r_{12} - r_{11}^2} \quad (5)$$

Both joint solution of expressions (4), (5) and taking into account the lensmaker's equation for a thin lens, lead to the following expressions concerning the radii of the first component.

$$r_{11} = \frac{n-1}{K_1} \cdot f'_1 \quad \text{and} \quad r_{12} = \frac{n-1}{K_1 - 1} \cdot f'_1 \quad (6)$$

In making the original synthesis of the optical design, it will be assumed that

$$f'_2 = 100\text{mm}, \quad F/\# = 2 \quad \text{and} \quad M = 10^X \quad (7)$$

Refractive surfaces' radii in expressions (2) and (6) are determined for the so called „thin lenses”. Transition to “thick lenses” brings to a change in the magnification power and distance between elements which is why design parameters should be modified so as to meet requirements (7).

B. Analysis of laser beam expander optical design

The aim of this analysis is to check laser beam characteristics at the expander output. Rays have been traced and SPOT diagram plus the wave front of the originally synthesized optical design have been analyzed. If analysis results do not meet all quality criteria for the output beam, the entire optical design should be optimized.

C. Optimization of laser beam expander optical design

Optimization aims at modifying optical design and generating output laser beam of higher quality.

In this work optimization has been carried out by the method of damped least square and the root mean square of the wave front aberration W_{RMS} . has been selected as optimization criterion [17]-[19].

IV. Results

Laser beam expanders have been designed for LWIR spectrum range by using various materials - *ZnSe*, *Si* and *Ge*. Here follow the criteria which have been employed to assess the optical system quality:

$$\left. \begin{array}{l} \bullet \text{ Rayleigh criterion} \\ \bullet \text{ Marechal criterion} \\ \bullet \text{ Airy disc criterion} \end{array} \right\} \begin{array}{l} W_{P-V} < \frac{\lambda}{4} \\ W_{RMS} < \frac{\lambda}{14} \\ \beta_{RMS} \ll \beta_{Airy} \end{array} \quad (8)$$

Two kinds of optimization have been implemented. With the first kind the radii of the first surfaces of lenses (r_{11} and r_{21}) are selected as variables as well as the distance between lenses. Here the radii of the second surfaces (r_{12} and r_{22}) are used to sustain the values of focal distance $f'_1 = -10mm$ and $f'_2 = 100mm$. With the second kind, radii (r_{11} , r_{12} and r_{21}) are selected as variables as well as the distance between lenses. Here the radius of the second surface of the second lens r_{22} is used to retain the value of its focal distance $f'_2 = 100mm$. Table 1 shows the following rated output characteristics of non-optimized and optimized beam expanders for LWIR spectrum range: Peak-to-Valley aberration of the wave front W_{P-V} , root mean square of the wavefront aberration W_{RMS} , mean quadratic angular dimension of the spot radius β_{RMS} , and angular dimension of the radius according to Airy's disk criterion β_{Airy} . Fig. 2 presents the SPOT diagrams for non-optimized and optimized laser beam expander *Ge*, which has undergone optimization of the second kind. Fig.3 presents the wavefronts for non-optimized and optimized beam expander made from *Ge*. Values contained in Table 1 and Fig.3 refer to maximum angular field which corresponds to the angular divergence of the input laser beam ($2mrad$).

Table I Output characteristics of non-optimized and optimized laser beam expanders

Optical material	W_{P-V} , waves	W_{RMS} , waves	β_{RMS} , mrad	β_{Airy} , mrad
Non-optimized laser beam expander				
ZnSe	1.3753	0,2589	0,925	0,312
Si	0.6846	0,1313	0,522	0,2873
Ge	0,5346	0,1025	0,423	0,281
Optimization – first option				
ZnSe	1.0914	0,2022	0,758	0,3015
Si	0.6768	0,1276	0,514	0,2865
Ge	0.5331	0,1015	0,421	0,281
Optimization –second option				
ZnSe	0,1278	0,0147	0,084	0,2822
Si	0.0437	0,0058	0,021	0,269
Ge	0.0289	0,0039	0,012	0,2658

Figure 2 SPOT diagrams for laser beam expander made from Ge

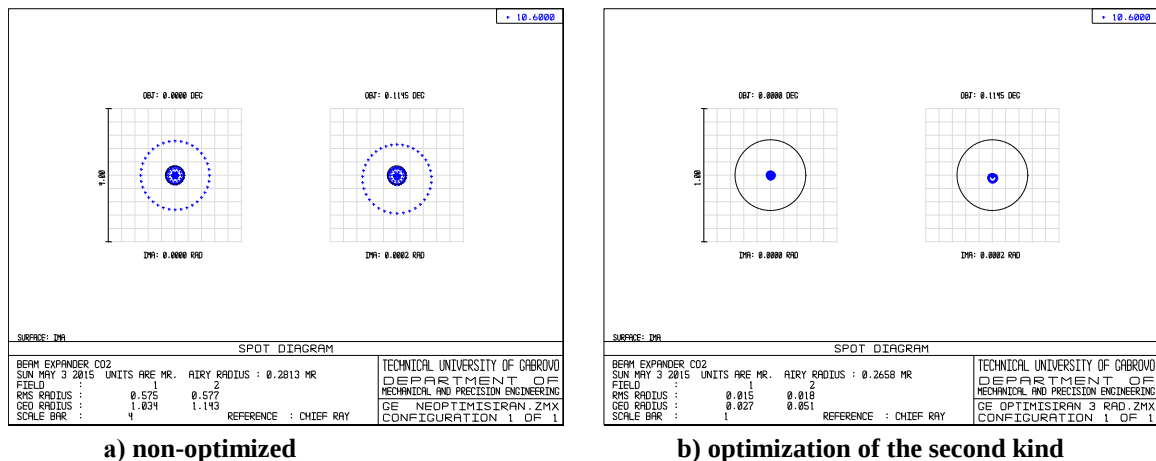
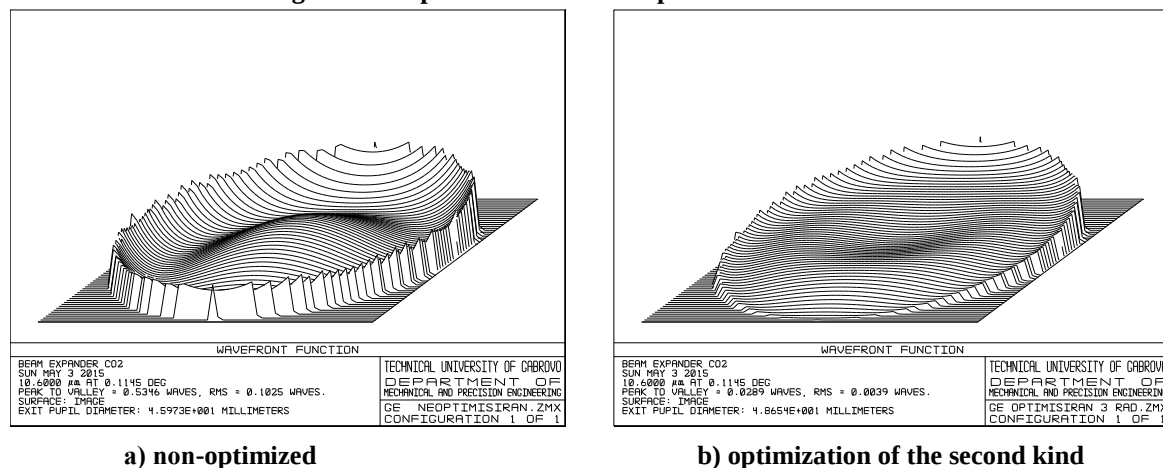


Figure 3 Output wave front for expander made from Ge



V. Conclusion

Laser beam expanders for LWIR spectrum range have been developed and designed from three different materials: *ZnSe*, *Si*, *Ge* and ensuing optimization of two kinds has been made.

There is a negligible difference in the output characteristics of laser beams in conventional expanders and in expanders which have had optimization of the first kind. In this particular case none of the criteria (8) is met and the outgoing beam quality is limited in terms of aberration.

In making optimization of the second kind all three criteria (8) are met and therefore, the quality of laser beam in this case is limited in terms of refraction.

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