Optik 122 (2011) 914–918

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

First-order layout of a two-lens varifocal objective focusing a CO_2 laser beam in a post-objective three-axis scanner

Vincenzo Greco*, Luciana Bertoncini

Consiglio Nazionale delle Ricerche – Istituto Nazionale di Ottica Applicata, Largo Enrico Fermi 6, I-50125 Firenze, Italy

ARTICLE INFO

Article history:
Received 16 November 2009
Accepted 10 June 2010

Keywords:
Laser beam shaping
First-order optics

ABSTRACT

In this paper we describe a procedure to work out the first-order layout of a two-lens varifocal objective for a post-objective three-axis scanner. In particular, the two lenses are considered thin, the laser beam is propagated paraxially (ABCD law) and the focal lengths of the two lenses and the maximum value of the distance between them are worked out in accordance with the specifications of the objective. Finally, the plots of the dimension and the position of the focused light spot versus the distance between the two lenses are evaluated.

1. Introduction

Post-objective three-axis scanners [1] are used in many industrial applications. In particular, they are used in marking, cutting, drilling on a variety of materials including glass, wood, textiles, metals, tiles, stone, paper and others. Fig. 1 shows a schematic representation of the post-objective three-axis scanner considered in this paper. It is composed by a two-dimensional scanning mechanism, made up of two galvanometers with reflective mirrors attached, placed after a two-lens focusing objective. The input CO_2 laser beam is, first, expanded by the negative lens L_1, subsequently focused by the positive lens L_2 and, finally, directed to the desired position on the working plane by the two galvanometers. To keep the laser beam always focused, while the galvanometers move the light spot on the working plane, it is necessary to adjust in real time the distance between the two lenses. As shown in Fig. 1, this task is performed by mounting the negative lens L_1 in a linear translator.

In general, when the system designer defines the whole structure of a post-objective three-axis scanner so that it will meet the customer's requirements, he assigns the specifications of the focusing objective by setting the parameters shown in Fig. 2: ϕ_2, the clear diameter of the positive lens L_2, δ, the travel range of the negative lens L_1, Δ, the corresponding travel range of the focused light spot, and $t_{2\,\mathrm{min}}$, the minimum value assumed by the working distance t_2, that is the distance between L_2 and the focused light spot. In this paper we describe a procedure to work out the first-order layout of the two-lens varifocal objective that meets the specifications mentioned above. For this purpose, L_1 and L_2 are considered thin lenses and the CO_2 laser beam is propagated paraxially [2] from the source to the working plane. The focal lengths of the two lenses and $t_{1\mathrm{max}}$, the maximum value assumed by the distance t_1 between L_1 and L_2, are worked out, in accordance with the specifications above mentioned, by minimizing the dimension of the focused light spot for $t_2 = t_{2\,\mathrm{min}}$ and $t_2 = t_{2\,\mathrm{min}} + \Delta$. Moreover, particular attention is paid to set at zero the clipping of the beam produced by L_2, because power losses of the focused light spot or edge diffraction effects are not tolerated in a post-objective three-axis scanner. Finally, the plots of the dimension and the position of the focused light spot versus the distance between the two lenses are evaluated.

2. Preliminaries

The various industrial applications, where a post-objective three-axis scanner is used successfully, demand that the dimension of the focused light spot be as small as possible depending on the clear diameter ϕ_2 and the working distance t_2. For this reason, generally, the input CO_2 laser beam of a post-objective three-axis scanner is supposed to be a TEM_{00} Gaussian beam. The distribution of irradiance (W/m^2) in a TEM_{00} Gaussian beam [2] is described by Eq. (1):

$$I(r) = I_0 \exp\left(-\frac{2r^2}{w^2}\right) \tag{1}$$

where $I(r)$ is the beam irradiance at a distance r from the beam axis, I_0 is the irradiance on the axis and w, referred to as the beam width, is the radial distance at which the irradiance falls to I_0/e^2. By integration of Eq. (1), it is easy to show that the circle of diameter $2w$ encompasses 86.5% of the beam power. The term πw is referred to as the full beam diameter of the Gaussian beam because the circle of diameter πw encompasses 99% of the beam power. A Gaussian

* Corresponding author. Tel.: +39 055 2308271; fax: +39 055 2337755.
E-mail address: vincenzo.greco@inoa.it (V. Greco).

0030-4026/$ – see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2010.06.017

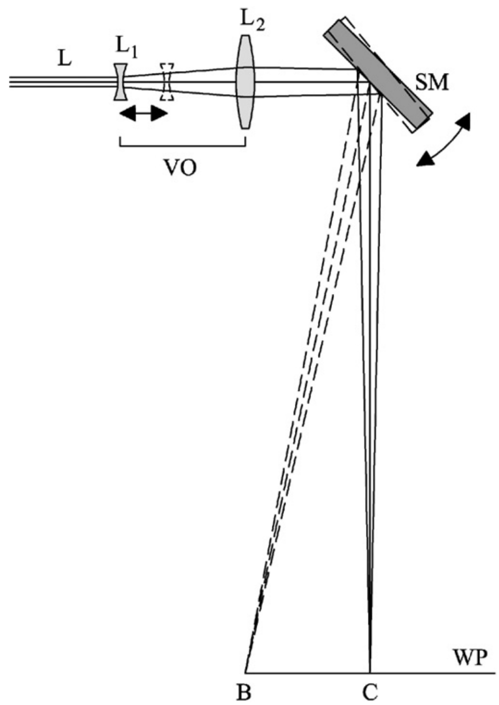

Fig. 1. Schematic representation of a post-objective three-axis scanner: L, laser beam; VO, two-lens varifocal objective; SM, two-dimensional scanning mechanism; WP, working plane; C and B, center and border of the working area respectively.

beam has a narrowest width at some point, which is called the waist. At the waist the wave front of the beam is exactly plane. Moving from the waist, the beam width and the wave front radius vary according to the following equations [2]:

$$w^2(z) = w_0^2\left[1+\left(\frac{\lambda z}{\pi n w_0^2}\right)^2\right]$$
$$\rho(z) = -z\left[1+\left(\frac{\pi n w_0^2}{\lambda z}\right)^2\right] \tag{2}$$

where $w(z)$ is the beam width at a axial distance z from the waist, w_0 is the beam width at the waist, λ the vacuum wavelength of the beam, n is the refractive index of the medium where the laser beam propagates and $\rho(z)$ is the radius of curvature of the wave front. Unlike Ref. [2], in this paper we use, for the sign of wave front radius, the convention generally used in lens design, that is for a diverging beam ρ is negative. The Eq. (2) controls the free propagation of a Gaussian beam in a medium: from the knowledge of w_0 and the position of the waist it is possible to know the beam width and the wave front radius at every axial distance from the waist. From the treatment reported in Ref. [2] it is possible to work out a set of two equations, for the free propagation of Gaussian beam, a little more general than Eq. (2). If P_1 is a generic point on the beam axis where the beam width is w_1 and the wave front radius is ρ_1, we can calculate the beam width $w(d)$ and the wave front radius $\rho(d)$ at a axial distance d from P_1 with the following equations:

$$x(d) = x_1\left(1-\frac{d}{\rho_1}\right)^2 + \frac{d^2}{x_1} \tag{3}$$

and

$$\rho(d) = \frac{x_1^2(\rho_1-d)^2+\rho_1^2 d^2}{x_1^2(\rho_1-d)-\rho_1^2 d} \tag{4}$$

where $x_1 = \pi\, n\, w_1^2/\lambda$ and $x(d) = \pi n w^2(d)/\lambda$.

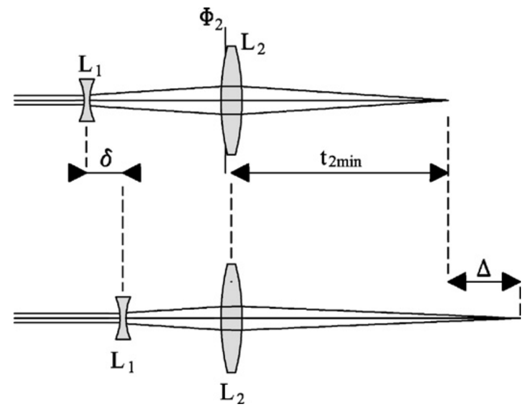

Fig. 2. Parameters used to assign the specifications of the focusing objective: ϕ_2, clear diameter of L_2, δ, travel range of L_1, Δ, corresponding travel range of the light spot, and $t_{2\,\mathrm{min}}$, the minimum distance between L_2 and the light spot.

In the paraxial approximation, when a Gaussian beam strikes a thin lens in air, the refracted beam is still a Gaussian beam. The beam width w' and the wave front radius ρ' on the thin lens immediately after the refraction can be derived with the following equations [2]:

$$w' = w \tag{5}$$

and

$$\rho' = \frac{\rho}{1+(\rho/f)} \tag{6}$$

where w and ρ are the beam width and the wave front radius on the thin lens immediately before the refraction and f is the focal length of the thin lens. By applying Eqs. (3)–(6) recursively, it is possible to carry out, in the paraxial approximation, the propagation of the input TEM_{00} Gaussian beam through the post-objective three-axis scanner: from the waist of the input beam to the working plane through the focusing objective.

The paraxial approximation defines the application range of the paraxial beam propagation in above mentioned (Eqs. (3)–(6)). In particular, we can know immediately that this cannot completely model the propagation of the laser beam through the focusing objective. In fact, while on L_1 the full beam diameter is generally very small, on L_2 the full beam diameter is approximately equal to the clear diameter of the lens, and L_2, in general, will introduce spherical aberration on the laser beam. In that case, in the subsequent bending of L_2 the paraxial beam propagation is not usable, and the propagation of the laser beam through L_2 has to be performed by diffraction-based beam propagation techniques [3–11]. On the other hand, the value of the paraxial beam propagation lies in the fact that for a well-corrected focusing objective the dimension and the position of the focused light spot coincide almost exactly with like quantities calculated paraxially, and also that the dimension and the position of the focused light spot evaluated paraxially provide a convenient reference from which to measure departures from the diffraction limited condition.

3. First-order considerations

Fig. 3 shows the first-order layout of the two-lens varifocal objective focusing the minimal light spot at the minimum ($t_{2\,\mathrm{min}}$) and at the maximum ($t_{2\,\mathrm{min}}+\Delta$) working distance. w_0 indicate the beam width at the waist of the input Gaussian beam and t_0 the distance of the waist from L_2. We suppose that the quantities w_0, t_0, λ, the vacuum wavelength of the laser considered and the quantities Φ_2, $t_{2\,\mathrm{min}}$, δ and Δ defined in Fig. 2 are known. As an example Table 1 shows typical values for all these quantities. It is our aim