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A substrate-mode holographic collimating and beam shaping element for laser diodes

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A new type of substrate-mode holographic collimating and beam shaping element for laser diodes is presented. Techniques and design considerations are described. A sample is fabricated and its function is demonstrated. It has many merits, such as easy fabrication, low cost, compactness of monolithic structure, and is easily used. © *1997 American Institute of Physics.* [S0003-6951(97)01608-2]

Owing to its compactness, lightness, and low cost, a laser diode is often used as a light source in many scientific and engineering applications.[1] Because of the characteristics of a laser diode, its light beam is divergent with an elliptical cross section.[2] So some elements, such as conventional refractive optical elements,[3,4] graded-index optical elements,[5] micro-Fresnel lenses,[6] and holographic optical elements,[7] are proposed to obtain a collimated beam with a circular cross section to meet the requirements of many applications. Conventional refractive optical elements with a pair of anamorphic prisms are bulky and expensive. Although other optical elements have small size, it is difficult to fabricate them and align them in an optical system. To solve these problems, a new type of collimating and beam shaping element for laser diodes with substrate-mode holographic structure is proposed. A sample is fabricated and its function is demonstrated. It has many merits such as easy fabrication, low cost, compactness of monolithic structure, and is easily used.

The architecture of this new type of substrate-mode holographic collimating and beam shaping element for laser diodes is depicted in Fig. 1. It consists of two asymmetrical holographic lenses and a monolithic glass substrate. The divergent elliptical light coming from a laser diode with long axis being along the x axis, is incident on the holographic lens H_1. Here, the light component in the meridian plane containing the x axis (x-meridian plane) is diffracted and collimated, and its diffracted angle θ_d is so designed that it is larger than the critical angle of the interface between air and the glass substrate. So the diffracted light is guided in the substrate and propagates along the x axis. On the other hand, the light component in the meridian plane containing the y axis (y-meridian plane) is diffracted by H_1, and becomes more divergent. And its width becomes wider as the light propagates in the substrate. Its propagation distance in the substrate is so designed that its width equals that of the light component in the x-meridian plane. Hence, as the light beam reaches another holographic lens H_2, it has a circular cross section. Because of the diffraction at H_2, the light component in the x-meridian plane changes its direction and passes normally through the substrate, and the light component in the y-meridian plane is collimated. Finally, a light being parallel to the incident light with a circular cross section is obtained.

To easily understand the diffraction properties and geometrical relations of this element, Fig. 1 is redrawn as Fig. 2. In the unfolded configurations in Fig. 2, the direction of the light beam propagates straight without changing its direction being due to reflections. Figures 2(a) and 2(b) represent the light paths in the x- and y-meridian planes, respectively. For convenience, the parameters related to the holographic lenses H_1 and H_2 are denoted by subscripts 1 and 2, those in the x- and y-meridian planes are denoted by superscripts x and y, respectively. Because the recording and the reconstruction waves in both the x- and y-meridian planes originate from or converge to point sources, the general diffraction properties of a holographic lens can be used in these two planes. The relevant coordinates (R_q,β_q) are the positions of the point sources in these two planes; where $R_q(q=o,r,c,i)$ are the distances from the point sources of (object, reference, reconstruction, image) to the center of the hologram, and β_q are the off-axis angles of the waves. Based on the paraxial wave approximation, the relevant readout equations for a holographic lens are given as[8–10]

$$\phi_i=\phi_c\pm(\phi_0-\phi_r), \tag{1}$$

$$\sin\beta_i=\sin\beta_c\pm\mu\,(\sin\beta_0-\sin\beta_r), \tag{2}$$

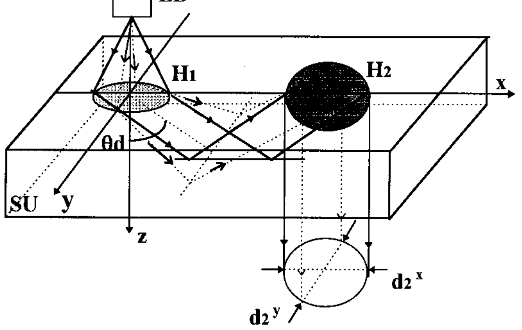

FIG. 1. The architecture of the substrate-mode holographic collimation and beam shaping element for laser diodes; LD: laser diode, H: holographic lens, SU: substrate.

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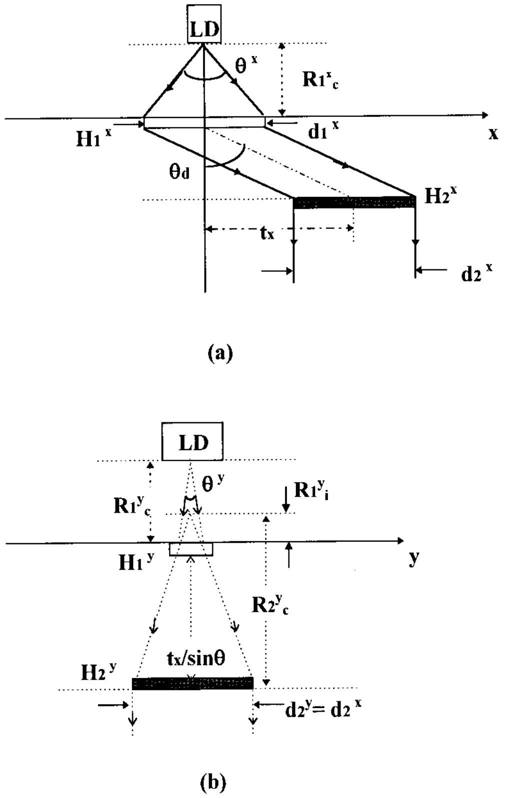

FIG. 2. The unfolded configurations for (a) x- and (b) y-meridian planes, respectively.

$$\frac{1}{R_i^x}=\frac{1}{R_c^x}\pm\mu\left(\frac{1}{R_o^x}-\frac{1}{R_r^x}\right), \tag{3}$$

$$\frac{\cos^2\beta_i}{R_i^y}=\frac{\cos^2\beta_c}{R_c^y}\pm\mu\left(\frac{\cos^2\beta_o}{R_o^y}-\frac{\cos^2\beta_r}{R_r^y}\right); \tag{4}$$

where $\mu=\lambda_c/\lambda_r$ is the ratio between the reconstruction and recording wavelengths. The ± refers to $+1$ and -1 orders of the diffracted images of the holographic lens. Here, only the real image is of interest, and the minus sign is used hereafter instead of ± 1 in the equations. Moreover, the necessary conditions for an efficient aberration-free holographic lens are given as[9–11]

$$\begin{aligned}\beta_o&=\sin^{-1}(a\sin\beta_i+b\sin\beta_c),\\ \beta_r&=\sin^{-1}(a\sin\beta_c+b\sin\beta_i),\end{aligned} \tag{5}$$

TABLE I. The fabrication parameters of the collimation and beam shaping element.

λ^c	672 nm			λ^0	441.6 nm		
R^i_{1x}	∞	β^i_{1x}	42°	R^0_{1x}	111.3 mm	β^0_{1x}	33.67°
R^c_{1x}	20 mm	β^c_{1x}	0	R^r_{1x}	23.9 mm	β^r_{1x}	6.58°
R^i_{1y}	18.5 mm	β^i_{1y}	42°	R^0_{1y}	19.3 mm	β^0_{1y}	33.67°
R^c_{1y}	20 mm	β^c_{1y}	0	R^r_{1y}	17.3 mm	β^r_{1y}	6.58°
R^i_{2x}	∞	β^i_{2x}	0	R^0_{2x}	∞	β^0_{2x}	6.58°
R^c_{2x}	∞	β^c_{2x}	42°	R^r_{2x}	∞	β^r_{2x}	33.67°
R^i_{2y}	∞	β^i_{2y}	0	R^0_{2y}	638.7 mm	β^0_{2y}	6.58°
R^c_{2y}	82.5 mm	β^c_{2y}	42°	R^r_{2y}	92.8 mm	β^r_{2y}	33.67°

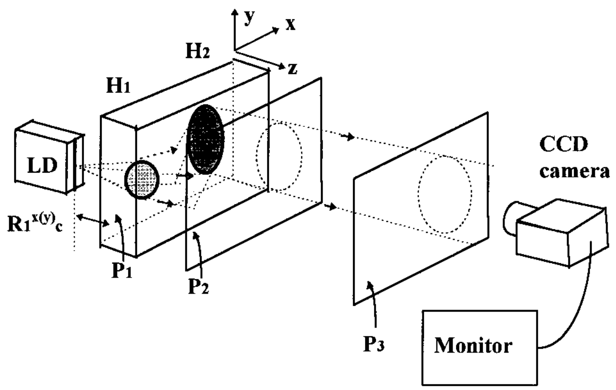

FIG. 3. Optical setup for demonstrating the performances of this element.

$$\left.\begin{aligned}R_o^x&=\left(\frac{a}{R_i^x}+\frac{b}{R_c^x}\right)^{-1},\\ R_r^x&=\left(\frac{a}{R_c^x}+\frac{b}{R_i^x}\right)^{-1},\end{aligned}\right\}\quad\text{(in the x-meridian plane)}, \tag{6}$$

and

$$\left.\begin{aligned}R_o^y&=\cos^2\beta_o\Bigg/\left(\frac{a\cos^2\beta_i}{R_i^y}+\frac{b\cos^2\beta_c}{R_c^y}\right),\\ R_r^y&=\cos^2\beta_r\Bigg/\left(\frac{a\cos^2\beta_c}{R_c^y}+\frac{b\cos^2\beta_i}{R_i^y}\right),\end{aligned}\right\} \tag{7}$$

$$\text{(in the y-meridian plane)},$$

where $a\equiv(\mu+1)/2\mu+\Delta$, $b\equiv(\mu-1)/2\mu+\Delta$, $\Delta=(\mu^2-1)\sin^2\beta_i/(16n^2\mu^2)+(\sin^4\beta_i)/(32n^4)$, and n is the refractive index of the recording material. Furthermore, to assure that the diffracted wave can be guided in the glass substrate by total internal reflection, $\beta_i(=\theta_d)$ must satisfy the relation

$$n_g\sin\beta_i\geqslant 1, \tag{8}$$

where n_g is the refractive index of the glass substrate. And for beam shaping shown in Fig. 2, the beam widths at H_1 and H_2 in the x- and y-meridian planes should satisfy the following conditions:

$$d_2^x=d_2^y=d_1^x=2R_{1c}^x\tan\theta^x, \tag{9}$$

$$\frac{R_{1i}^y(=R_{2c}^y-t_x/\sin\theta_d)}{R_{2c}^y}=\frac{d_1^y}{d_1^x}, \tag{10}$$

and

$$t_x>2d_1^x, \tag{11}$$

where θ^x is the divergent angle of the laser diode in the x-meridian plane, and t_x is the lateral propagation distance between H_1 and H_2.

In order to demonstrate its feasibility, a substrate-mode holographic collimating and beam shaping element for a laser diode (TOLD 9215), manufactured by Toshiba America Electronic Components, Ltd., is designed and fabricated. This element is fabricated with self-made dichromated gelatin and a He–Cd laser of wavelength 441.6 nm. The thickness of this emulsion layer after fixing is 12 μm, and its refractive index is 1.52. Its output wavelength is 672 nm

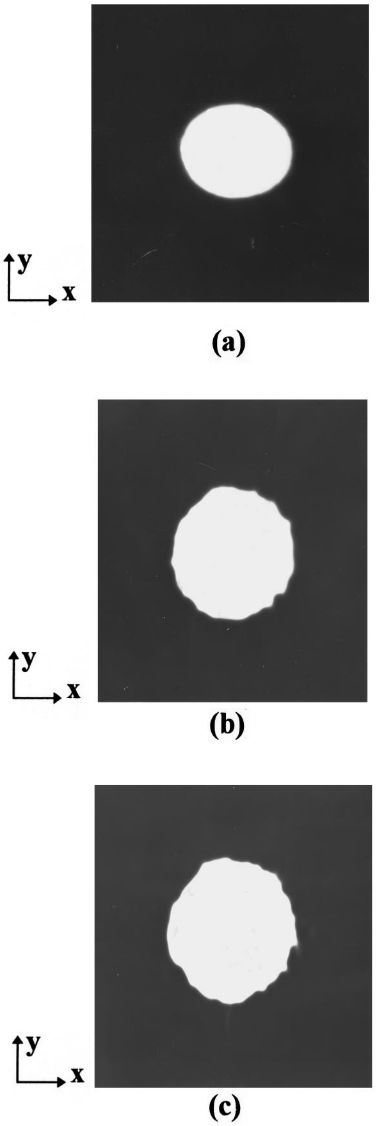

FIG. 4. The photographs of the laser beam shapes of (a) the incident light at H_1, and the output light at (b) 100 mm and (c) 500 mm, after the element, respectively.

under the conditions of temperature 20 °C and current source 35 mA. And its divergent angles θ^x and θ^y in the x- and y-meridian planes are 47° and 12°, respectively. Let the working distance from the laser diode to H_1 to be 20 mm, then the fabrication parameters can be calculated based on the above Eqs. (5)–(11) and are summarized in Table I. And the cylindrical lenses are used to generate the desired point sources in the x- and y-meridian planes and two holographic lenses on a monolithic BK7 glass substrate with thickness of 20 mm and refractive index of 1.517 are fabricated. This element is performed with the setup shown in Fig. 3, in which a piece of ground glass is used for the imaging plane and a CCD camera is focused on this plane. For testing its performances, the ground glass is located at P_1, P_2, and P_3 to take the beam shapes and their results are shown in Figs. 4(a), 4(b), and 4(c), respectively. Figure 4(a) represents the beam shape of the incident light at H_1. And Figs. 4(b) and 4(c) represent the beam shapes of the output light at 100 and 500 mm after the element, respectively. From these figures, it is obvious that this element has good performance on collimating and beam shaping for the laser diode we use. Although there is a lateral shift between the incident light and the emergent light as this element is used, their optical axes are parallel and perpendicular to the element, and it is very easy to introduce this device into an optical system. And the collimating and beam shaping elements for other laser diodes with different wavelengths can be fabricated similarly.

A new type of substrate-mode holographic collimating and beam shaping element for laser diodes is presented. The feasibility of this element is demonstrated, it can be made with easy fabrication, low cost, normal input/output coupling, compact monolithic structure, and it is very easy to introduce this element into an optical system. With the potentials of the laser diode, it may be very useful in imaging systems and optical interconnections.

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