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SYNTHESIZED DIFFRACTION ELEMENTS FOR DATA READING FROM OPTICAL DISKS

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Abstract—Design of the structure of diffraction elements with reference to the focusing of semiconductor laser radiation is discussed. For optimal choice of parameters of the synthesized structure, a single diffraction lens is shown to be usable as a high-aperture objective, focusing the radiation of a single- or multiple-mode semiconductor laser into a diffractionally limited spot whose size allows reliable readout from optical disks.

The basic optical elements for reading data from optical disks are a radiation source, normally a semiconducting laser (SL), and an objective which focuses the radiation into micron sized spots. The focusing can be accomplished by a high-aperture objective well-corrected for spherical aberration and possessing a low level of chromatic aberration.

The necessity for correcting the chromatism of the objective is due to a series of factors: firstly, sample-to-sample variation of the radiation wavelength from the same type of laser; secondly, the variation of laser radiation wavelength resulting from temperature fluctuations; and thirdly, the fact that in a multimode SL the spectral width of the radiation to be focused is quite large. The reading devices are equipped with autofocus, so that the first two factors are responsible for requiring spherochromatism for the focusing objective, and the third, for positional chromatism.

When designing focusing objectives from uniform lenses with spherical refracting surfaces, the main problem is the elimination of spherical aberrations, and its solution usually requires at least four lenses. If, instead, a single diffracting lens (DL) is used as a focusing objective, spherical aberration is automatically eliminated by appropriately choosing the sequence of rings in the lens microstructure.

Spherochromatic aberration, arising from SL wavelength variation from sample to sample, may be practically eliminated at the sub-assembly stage involving the SL and DL. Indeed, it is easy to show that the third-order spherochromatic coefficient of the DL vanishes if the distance s from the constriction of the laser to the plane of the lens satisfies

$$s = -f'_0 \Bigg/ \left(\frac{\mu}{2} \pm \sqrt{\frac{1 + \beta_0 + \beta_0^2}{3(1 - \beta_0)^2} - \frac{\mu^2}{12}} \right), \tag{1}$$

where f'_0 is the focusing distance of the DL at the reference wavelength λ_0, $\mu = \lambda/\lambda_0$, λ is the wavelength of the SL radiation, and β_0 determines the ratio of the entrance to exit aperture at the reference wavelength λ_0, and is numerically equal to the transverse magnification of the DL at λ_0.

Spherical aberration, which is due to thermal wavelength drift, is uniquely determined by the focusing distance of the DL for a given value of β_0. Given the operating temperature interval of the SL, and knowing the gradient of the thermal drift for the radiation wavelength, one can find the largest possible focusing distance of the DL by using the Strehl criterion, according to which the focused spot is practically indistinguishable from the diffraction limited size as long as the normalized intensity at the diffraction focus is at least 0.8 [1]. As a result, we obtain

$$f'_0 \leqslant \frac{24\lambda_0^2}{\pi(2 + \beta_0)(1 - \beta_0)^3 \operatorname{tg}^4 u'} \frac{1}{|\Delta\lambda_T|}, \tag{2}$$

where $|\Delta\lambda_T|$ is the maximum value of the thermal wavelength drift in the SL, and $\sin u'$ is the exit pupil of the DL.

When regarded as an inequality (1) sets an upper limit on the admissible value of the focusing distance of the DL for monochromatic radiation (i.e. single-mode laser radiation).

If a multimode SL is used the condition imposed on the DL focusing distance is relaxed. This is because the broadening of the focused spot, induced by the polychromatic radiation and the positional chromatism, and proportional to the focusing distance of the DL, will not be compensated automatically. In this case the limiting possible value of the DL focusing distance will be determined by the spectral characteristics of the multimode SL. Indeed, since the diffraction limit of resolution is practically identical for all radiation modes, the relative fraction of energy concentrated in a spot whose radius is the Airy disk is given by

$$E_\Sigma(\delta) = \frac{\sum_n I(\lambda_n) E_{\lambda_n}(\delta)}{\sum_n I(\lambda_n)}, \tag{3}$$

where $I(\lambda_n)$ is the relative intensity of the λ_n mode in the SL radiation spectrum, and $E_{\lambda_n}(\delta)$ is the relative fraction of radiant energy entering this mode concentrated in a spot whose radius is the Airy disk, while a summation is performed over the whole set of SL modes.

The focused spot is practically indistinguishable from the diffraction limited size as long as $E_\Sigma(\delta) \geqslant 0.73$ [2]. Noting that $E_{\lambda_n}(\delta)$ depends on the DL focusing distance, Eq. (3) can be used to determine the limiting admissible focusing distance for a known radiation spectrum. In particular, an estimate of the minimum focusing distance has been made for a DL destined to focus radiation of a multimode SL whose parameters were close to those of the ML-4102A and ML-4402A type lasers [3]. The calculation showed that the focusing distance at which the laser radiation is focused into a spot is practically indistinguishable from the diffraction limited value, and this in a working temperature range of ± 15°C is completely acceptable from a design, technological and other points of view.

The material medium for the DL structure is an optically transparent plane-parallel backing, with the structure itself being either recorded on a photosensitive film deposited on the backing, or formed as a relief directly in the backing [4, 5]. In addition to this unit, the optical circuit of the data reading device may include optical components realized in the form of plane-parallel slabs, or elements which are effectively equivalent to these. The design parameters of these backings and elements, namely, the reference wavelength, the entrance and exit pupils and the focusing distance of the DL will determine their structure uniquely. The correct sequence of rings in the diffracting structure may be found from the condition that at the reference wavelength of the DL the optical element must be free from spherical aberration. To do this one produces rays from the conjugate points of the optical component with diffraction cosines m_y and m'_y such that the rays intersect in the plane of the synthesized DL structure. The distance between the point of intersection and the optical axis is related to the direction cosines by the following relations:

$$\begin{aligned} y &= m_y\left[-\frac{1}{\sqrt{1-m_y^2}}\left(z+\sum_{k=1}^{K} d_k\right)+\sum_{k=1}^{K}\frac{d_k}{\sqrt{n_k^2-m_y^2}}\right]; \\ y &= m'_y\left[\frac{1}{\sqrt{1-m_y'^2}}\left(z'-\sum_{l=1}^{L} d'_1\right)+\sum_{l=1}^{L}\frac{d'_l}{\sqrt{n'_l-m_y'^2}}\right]. \end{aligned} \tag{4}$$

Here d_k and n_k are the thickness and the refractive index of the kth plane-parallel slab, situated in the object space of the DL, $(k = 1, 2, \ldots, K)$ d'_1 and n'_1 are the thickness and refractive index of the first slab, situated in the image space of the DL $(l = 1, 2, \ldots, L)$, and z, z' are the distances from the plane of the DL structure to the conjugate points:

$$\left.\begin{aligned} -z &= -\frac{1-\beta_0}{\beta_0} f'_0 + \sum_{k=1}^{K} \frac{(n_k-1)}{n_k} d_k \\ z' &= (1-\beta_0) f'_0 + \sum_{l=1}^{L} \frac{(n'_l-1)}{n'_l} d'_l \end{aligned}\right\}. \tag{5}$$

The spatial frequency of the DL structure is related to the direction cosines by

$$\nu = \frac{m'_y - m_y}{\lambda_0}. \tag{6}$$

The spatial frequency can be expressed as a function of y. To do this one expands (4) in a power series

$$\left.\begin{aligned} y &= \sum_{p=0}^{\infty} a_p m_y^{2p+1} \\ y &= \sum_{p=0}^{\infty} b_p m_y'^{2p+1} \end{aligned}\right\}. \tag{7}$$

Inverting (7) and using (6), we obtain the spatial frequency behaviour in the DL plane in the form

$$v = \sum_{p=0}^{\infty} v_p y^{2p+1}. \tag{8}$$

The number of terms to be retained in this series depends on the desired accuracy. Practical calculations have shown that, for a DL with apertures of the order 0.4–0.6, four or five terms will suffice. If one knows the coefficients v_p $(p = 0, 1, \ldots, P)$, the radius Γ_m delimiting the $(m-1)$ and mth zone of the diffracting structure will be determined by the equation:

$$(m - \tfrac{1}{2}) = \sum_{p=0}^{P} \frac{1}{p+1} v_p r_m^{2(p+1)}. \tag{9}$$

Solving this equation for $m = 1, 2, \ldots$ gives the required sequence of rings of the DL structure.

To sum up, we have shown here that a single diffracting lens may be used successfully to focus the radiation of a semiconducting laser used in reading data from optical disks, and have provided an algorithm for calculating the structure of the lens.

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