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Diffraction element expanding guided beam

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A planar diffraction element which expands a guided beam is described. The element is based on the principle of diffraction on a thick reflection grating the boundary of which is not parallel with the grating lines. An elementary analysis is given. The function of the element was verified experimentally.

1. Introduction

Similarly to 3-D optics, in planar waveguiding optics passive elements for transformation of guided beams are necessary. The main principle, which the elements of classical optics are based on, is the refraction of light. Lenses with spherical boundaries are put together in such a manner that the transformed structure should approach the orginal one. It relates both the formation of an image of an object and the transformation of a light beam. Recently, optical elements based on the diffraction of light started to be used, which is a consequence of the progress in holography.

Similar principles can also be utilized in planar optics. Elements, e.g., lenses, are made so that in a certain suitably formed region the effective index of refraction of a given guided mode has been changed [1], for instance by the change of the waveguide thickness or by deposition of another layer. One of the most suitable elements is the so-called geodesic lens which is characterized by bending of the waveguide layer [2]. Rays propagating through the spherical deppression of the layer are focused behind the element. Two geodesic lenses, one with a small focal length and the other with a small optical power, can serve similarly to 3-D optics as an expander of a guided beam.

Diffraction optical elements are very promising passive optical elements of planar optics, particularly with respect to their compatibility with the planar structure of this branch of optics. A coupling elements [3] which can couple a 3-D beam to a guided beam has been the first application. This element can serve not only as the coupling one, but provided that it has a chirped period and the grating lines have suitable curved form, it can also work as a transforming element [4]. Further types of diffraction elements of holographic origin have been studied from the point of view of their utilization as elements transforming one guided wave into another one [5].

This paper is devoted to a diffraction element which can transform a guided collimated beam to another collimated guided beam of a greater width.

2. Principle of the device

A guided beam can be expanded using two lens-like elements, as mentioned above. Each lens has certain efficiency and the resulting efficiency is the product of both efficiencies, and it must be less than the efficiency of one element. Therefore, it is better to solve the problem of expanding using one element only. Such element based on the light diffraction has been designed, manufactured [6], and used in connection with a simple planar spectrum analyzer [7]. Conditions for manufacturing of the element are discussed in details in [8].

The grating of this element has the form of an extended rectangle, on the narrower side of which the narrow beam impinges. The beam diffracts on the lines of the grating and goes out from the wider side of the grating rectangle. The angle of incidence of rays on the grating lines and the angle of diffraction must obey the Bragg condition of diffraction on a thick grating. A disadvantage of the element of this form is the fact that the last ray must propagate through the whole grating. From this follows that, provided the mudulation is uniform through the whole length of the grating, the outgoing expanded beam has the intensity distribution which drops exponentially from the front to the back edge of the expanded beam. Nonuniform modulation resulting in more uniform intensity distribution in the diffracted beam was extensively investigated [9]. The grating must have relatively small depth of modulation for rays to be able to penetrate deeply enough into the grating.

The disadvantage of this type of expander can be removed by an arranged form of the grating according to Fig. 1. The original grating is cut diagonally and the

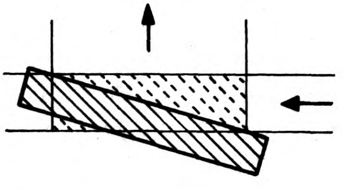

Fig. 1. Principle of the diffraction expander

lower half is removed. Then a triangular form of the grating arises and its hypothenuse is the boundary on which the contact of the impinging beam with the diffracted one is realized. This secures that the rays need not transmit through the whole grating but diffract immediately after entering it. As is obvious, the distribution of intensity in the expanded beam can practically repeat the distribution in the impinging beam. In practice, instead of the wedge form of the grating, the strip form is preferable (Fig. 1).

3. Elementary theoretical analysis of the expander

While the possible similar elemnt in 3-D optics should work on the principle of the thin plane grating, in our case it must be analysed as a thick grating. The direction of its grating lines must obey the Bragg condition for diffraction, and this direction differs from the direction of the working boundary.

Elementary geometric analysis can be performed assuming that the rays do not penetrate very deeply into the grating, this means that the coupling coefficient is relatively high. In this case the intensity distribution in the orginal beam is well reproduced by the intensity distribution of the expanded beam.

On the basis of the geometric relations in Fig. 2, the Bragg condition can be written in the form

$$\frac{\lambda}{n^*} = 2\Lambda\cos\theta \tag{1}$$

where λ is the wavelength of light in a free space, n^* is the effective refractive index of the guided mode, θ is the angle which the impinging beam makes perpendicular to the grating lines, and Λ is the period of the grating.

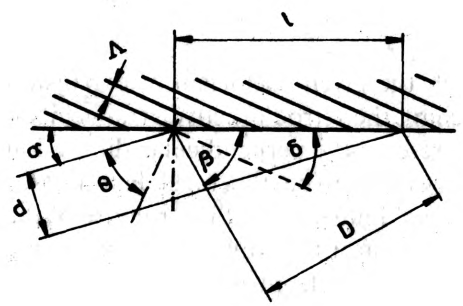

Fig. 2. Geometric relation when the diffraction on the expander takes place

From the geometry, relations between the angle θ, the angle δ (between the direction of the grating lines and the boundary), and angles α, β (under which the beam impinges and diffracts) are $\alpha = 90-(\theta+\delta)$, $\beta = 90-(\theta-\delta)$. As the widths of both the beams are: $d = l\sin\alpha$, $D = l\sin\beta$, where l is the length of the beams spoor on the boundary, it is possible to write for the coefficient of expansion $k = D/d$ the relation

$$k = \frac{\cos(\theta-\delta)}{\cos(\theta+\delta)}. \tag{2}$$

If the Bragg law (1) is substituted into the relation (2), the expression for the expansion coefficient can be written as

$$k = \frac{1+[(2n^*\Lambda/\lambda)^2-1]^{1/2}\tan\delta}{1-[(2n^*\Lambda/\lambda)^2-1]^{1/2}\tan\delta}. \tag{3}$$

A graphical representation of the last relation is depicted in Fig. 3, where the dependence of the coefficient k on the argument $\mu = \lambda/2n^*\Lambda$ is seen.

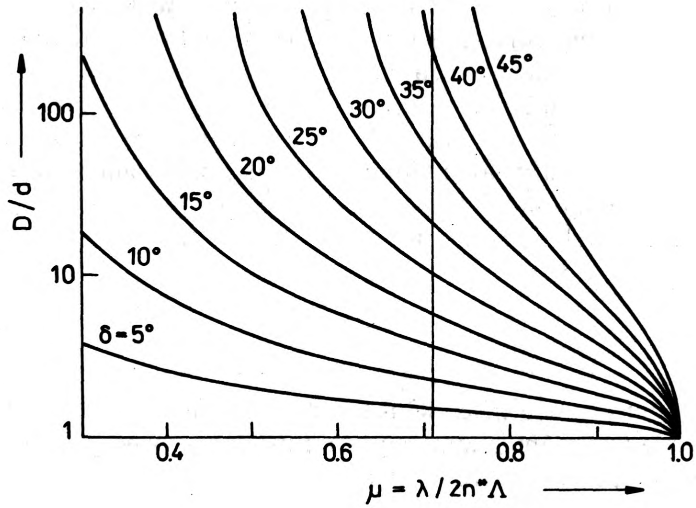

Fig. 3. Graphical plot of the dependence of the coefficient of expansion k on the parameter $\mu = \lambda/(2n^*\Lambda) = \cos\theta$ for various magnitudes of the angle δ between the direction of grating lines and the functional boundary

As it is evident from Figure 3 one can reach the given coefficient of expansion with greater density of the grooves (i.e., approaching the retrodiffractive arrangement) using larger angle δ. The value of $\mu = 0.707$ represents the perpendicular diffraction when the shape characteristics of the whole system an be the most favourable.

With this type of a guided beam expansion some influence on the structure of the expanded beam is connected. When a usual reflection of the waves takes place, the angle between the direction of propagation and the wavefront remains unchanged. When the diffraction takes place, however, the angle changes (Fig. 3). The angle γ between the plane perpendicular to the central ray of the beam and the tangent plane to the wavefront in the point of intersection is given by the simple relation

$$\gamma = \tan^{-1}\left\{\frac{2\tan\delta}{1+(\mu^{-2}-1)^{1/2}\tan\delta}\right\} \tag{4}$$

where the variables δ, μ are chosen as in the relation (3). The direct derivation of the relation (4) from the geometric relations in Fig. 4 is straight forward.

The relation (4) is depicted graphically in Figure 5. It is evident than the angle δ increases with increasing the variable μ and, therefore, with decreasing the angle θ. For the constant μ, the angle γ increases with increasing the angle δ. Should the angle γ be as small as possible, it is convenient to choose the angle δ as small as possible.

The described effect has no special importance for classical optics. However, its importance arises when light pulses have very short duration. These pulses, for instance, start to be wider.

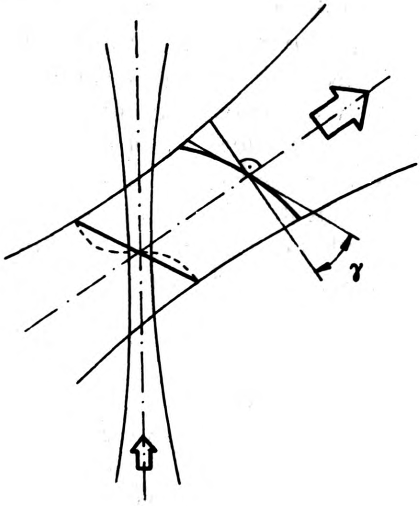

Fig. 4. Angle of inclination γ of the tangent to wavefront in its point of intersection with the central ray against the plane perpendicular to the ray

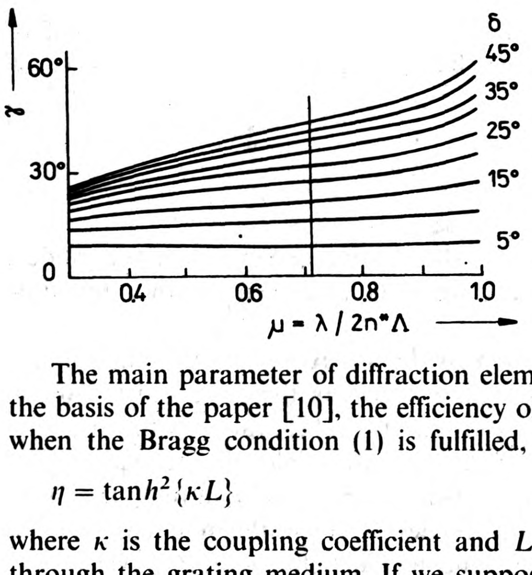

Fig. 5. Graphical plot of dependence of inclination γ on the parameter $\mu = \lambda/(2n^*\Lambda) = \cos\theta$ for various magnitudes of the angle δ

The main parameter of diffraction elements is their effectivity of diffraction. On the basis of the paper [10], the efficiency of the reflection grating of the phase type, when the Bragg condition (1) is fulfilled, is given by the relation

$$\eta = \tanh^2\{\kappa L\} \tag{5}$$

where κ is the coupling coefficient and L is the length of the passage of the ray through the grating medium. If we suppose that the coupling coefficient is rather small and the depth of penetration into the grating is greater than the grating thickness, then the path L is given by the geometric average of the paths from the transmission point on the front boundary to the reflection from the rear boundary, and from this reflection to the back transmission point on the front boundary [11], and therefore

$$L = \left[\frac{d}{\cos\{\theta+\delta\}}\right]^{1/2}\left[\frac{d}{\cos\{\theta-\delta\}}\right]^{1/2} \tag{6}$$

where d is the grating depth (width).

The coupling coefficient κ depends first of all on the depth of modulation of the grating n_1 which is present in the relation $n = n_0 + n_1 \cos Kx$, but also on the polarization of the incident guides beam [12], [13] ($K = 2\pi/\Lambda$). For TM-polarization, when the electric vector vibrates perpendicularly to the plane of diffraction, the coupling coefficient is directly $\kappa_{TM} = (\pi/\lambda)n_1$, while for TE-polarization $\kappa_{TE} = (\pi/\lambda) \times (n_1 \cos\{2\Theta\})$, beacuse behaviour analogous to the Brewster law in 3-D optics appears. From this point of view, it is evident that it is disadvantageous to work with the perpendicular diffraction, particularly with TE-polarized beam. Note that for the Bragg grating the so-called Klein's inequality must hold

$$2\pi\lambda L/n_0\Lambda^2 \geqslant 10. \tag{7}$$

Only in this case a high diffraction efficiency can be reached.

Otherwise, it is evident from the relation (5) that the theoretical efficiency approaches one with argument L increasing asymptotically.

As during the whole path of penetration of the ray into the grating medium, the energy is diffracted, and the geometries of penetration and diffraction are nonsymmetric, secondary effects of interference can arise, and the intensity of the diffracted beam can be spatially modulated. But this modulation can not have too great depth. Strong coupling given by a higher magnitude of the coefficient κ leads to depth of penetration smaller than the thickness of the grating, and thus the effects of modulation are smaller, too.

4. Experimental verification

The diffraction elements of planar optics for the passive expansion of the guided beam, which were described in preceding text, were manufactured and their function verified.

The graded index layer on the glass plate made by ion exchange served as the planar waveguide. The grating medium was manufactured on the photoresist film deposited on the waveguide. On the surface of this film the relief grating with necessary period was made by interference field of the Ar-laser light of the wavelength $\lambda = 457.9$ nm. The positive photoresist AZ 1350 was used and the development was performed with the developer AZ 303. Before development the boundary of the element was masked by illumination with noncoherent light of short wavelengths.

To find out the basic properties of the waveguide layer, first of all the numbers of waveguide modes and their effective indices of refraction, the photoresist relief coupling grating on the guiding layer was fabricated. The angle between interfering beams was not precisely adjusted, expected period was approximately 0.5 μm. The period was exactly measured by means of a goniometer by reading the angles for back diffraction and reflection, and was determined to be $\Lambda = 0.53033$ μm, i.e., the density of grooves was $N = 1885.6$ mm^{-1}. For that grating the coupling angles were measured too, and from them the effective indices of refraction for HeNe-laser light $\lambda = 632.8$ nm were determined for both the main polarizations. These indices were

$n^*_{TE} = 1.5466$, $n^*_{TM} = 1.5453$. The waveguides were found to be single-mode which could be expected from their characteristics.

Gratings for expanding or narrowing the guided beams were manufactured so that their period should be about 0.3 μm. The exact measurement with the goniometer showed the period to be $\Lambda = 0.31327$ μm which gives the density of grooves $N = 3192.1$ mm^{-1}. Functional boundary was masked to make an angle approximately $\delta \approx 30°$. The light was coupled into the waveguide with a prism coupler on one end of the rectangular plate of the waveguide. The expanded or narrowed beam leaved the plate from its edge.

In Figure 6 the function of the diffraction waveguide expander is demonstrated. The plate is put in a frame with the coupling prism. The frame is fixed on the

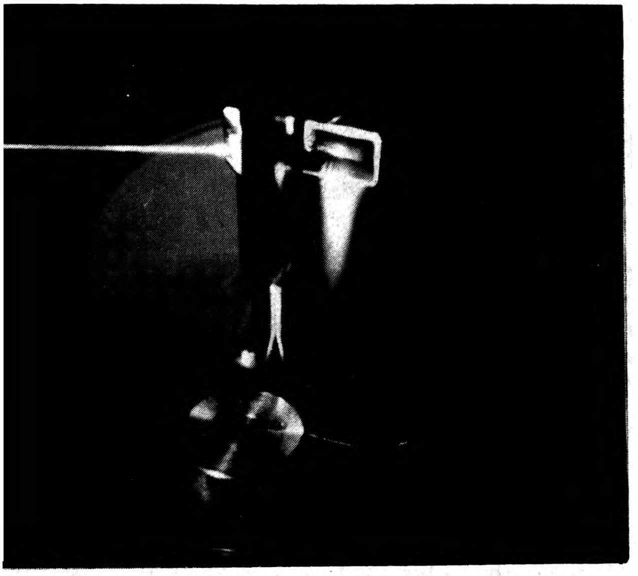

Fig. 6. Demonstration of the function of the guided beam expander

goniometer, and so the coupling from the prism into the waveguide can be adjusted with a sufficient accuracy. The entranced laser beam is visualized, and in the photograph it goes from left to the central part of the picture, where it submerges into the coupling prism. The light propagating inside the waveguide is not visible, but the functional boundary of the grating radiates the scattered light. After deviation of the beam by nearly 100° the expanded beam propagates downwards and on the edge of the plate the visible trace arises. For better demonstration, the beam leaving the plate is also visualized in air and has the form of a clear tongue directed downwards. The shape of the tongue indicates the distribution of the light intensity inside the beam. The picture shows TM-mode of which the angle of incidence is $\theta_{TM} = 49.19°$, while the angle of incidence of the other polarization was a little greater $\theta_{TE} = 49.23°$.

The incident beam had the width $d = 0.75$ mm and the expanded one $D \approx 4.75$ mm, i.e., the coefficient of expansion was $k \approx 6.33$ in tis case. The edge of the sample, shining by the scattered light, was imaged by a photographic lens on CCD-array of detectors composed of 256 elements. The distribution of the light intensity of the expanded beam on the array is shown in the photograph recorded from the oscilloscope screen (Fig.7), where one division is a little less then 1 mm. The same

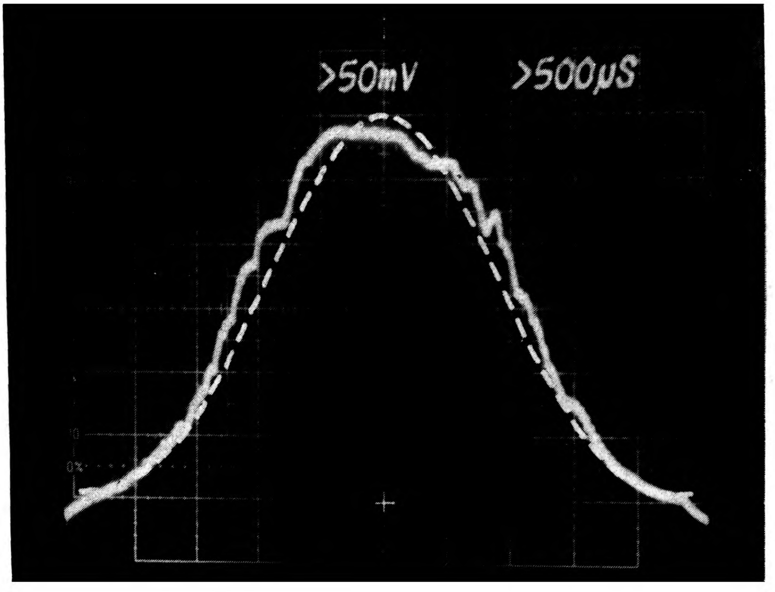

Fig. 7. Distribution of the light intensity in the expanding beam and the fitted curves of the Gaussian distribution

figure presents the Gaussian curve fitted to the oscilloscope one. The measured curve is nearly the peak a little wider then the theoretical which is apparently caused by a nonconstant coupling coefficient through the area of the coupling prism.

5. Conclusion

Expanding or narrowing of the guided optical beam is a fundamental operation of the passive transformation of the beam. In the paper the simple element based on the diffraction of light was described. Its function was verified with the photoresist grating formed on the surface of the guiding layer, but for a utilization in practice the relief corrugation is necessary to manufacture directly on the surface of the waveguide, e.g., by ion etching through a photoresist grating mask. In such a manner it is possible to reach a sufficient diffraction efficiency of the element. In spite of the advantage of simple principle and construction, the element has also some shortages particularly concerning the dependence of its efficiency on the polarization of light and the transformation of the direction of wavefront with regard to the direction of propagation.

A fabrication of elements of this kind is relatively simple and in the case of a possibility of making gratings by a mechanical copying also suitable for mass production of devices of consumer character.

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Дифракционный элемент, расширяющий веденный пучок

Описан плоский дифракционный элемент, расширяющий веденный пучок. Элемент действует, используя принцип дифракции на толстой отражательной решетке, которой край не параллелен к линии решетки. Дан элементарный анализ действия. Функционирование элемента проверено экспериментально.

Перевел Станислав Ганцаж