Diffractive gratings with a varying period's shape

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Abstract—The aim of this short review is to recall various designs of diffraction gratings when the condition of the period's identity is relaxed and to mention some of this resulting applications. Among others, the apodization function can be implemented as a variable diffraction efficiency due to a gradual change of the period's shape. Another possible application is passive achromatization of diffraction efficiency of blazed gratings by randomizing their blaze angle.

By definition, a diffractive grating is understood as a set of equidistant identical periods. Thereby the transmittance of a diffraction grating can be expressed as:

$$t(x) = \frac{1}{d} t_P(x) \otimes comb\ (x/d)\, rect\ (x/D), \text{ where}$$
$$comb\ (x/d) = d \sum_{m=-\infty}^{\infty} \delta(x - md),\ rect\ (x) = \begin{cases} 1 & \text{for } |x| \le 1/2 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

D is the aperture of the grating, d means its period, and $t_P(x)$ stands for the transmittance of a single period.

The intensity distribution in the far field diffraction zone of the grating will be proportional to the squared Fourier transform of the above expression and can be thus customarily written as a product of two factors. One of them, termed as the grating factor is the squared convolution of the *comb* function with the Fourier transform of the entire grating's aperture given by *rect*(*x/D*) and divides the illuminating beam into diffraction orders. In turn, the second expression, termed as the period factor and appearing due to the Fourier transform of the single period's transmittance, governs the distribution of energy between different diffraction orders, i.e., their diffraction efficiencies. The period's identity condition means that $t_P(x)$ does not change along the period's length but maintains its shape for all periods.

However, there exist situations when departing from this condition may bring benefits. One of them is a possibility of implementing an amplitude function by making the diffraction efficiency spatially variable, e.g., for the purposes of apodization or beam shaping. Usually such manipulation requires an additional element with continuously varying amplitude transmittance and its fabrication is quite troublesome from a practical point of view [1]. This difficulty can be avoided by applying an additional phase element which is diffracting light onto the principal one and creating on its plane the desired amplitude distribution [2–3].

A single diffractive element can be used instead of two, if its diffraction efficiency would be able to imitate the apodization function. Such attempts were realized, first in the case of binary gratings. In the case of amplitude binary gratings it can be achieved by changing correspondingly its opening ratio only [4–6]. In the case of a binary phase grating it can be made also by splitting the phase step [7] or by changing locally the phase step height [8–9].

A further step (and greater efficiency) would be to change the shape of the period of multistep diffraction gratings which are obtained with multi-mask lithographic methods as an approximation of the blazed profile. There exist many ways of transforming gradually the grating into its conjugate counterpart and sending, by degrees, light from a given diffraction order into its conjugated counterpart, avoiding additionally the appearance of light in the neighbouring orders. Two of possible period's shape transformations are shown in Fig. 1 after Refs. [10] and [11].

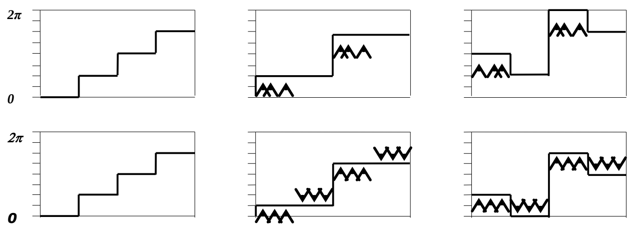

Fig. 1. Conversion of a quaternary grating into its conjugate through an intermediate stage of binary phase grating by a) gradually increasing phase heights of the odd steps by π rad; b) gradually decreasing phase heights of the even steps and increasing the odd steps by π/2 rad.

The stepwise change of the diffraction efficiency allows to combine in one diffractive element both the distribution of amplitude and the phase of the diffracted wave and thus enabling numerous applications. Among

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them one should mention the application of apodized phase masks for the exposure of the fiber Bragg gratings [12–13]. This particular approach allows to decrease cross talks in the neighbouring channels thanks to decreasing sidelobes in their spectra due to the use of apodized fiber Bragg gratings. Additionally, a constant effective refractive index along the whole Bragg grating is ensured, which allows to avoid undesirable short-wavelength side broadening of its spectral characteristic [14]. Such phase masks with a varying height of phase step along their lengths can be manufactured with the help of High Energy Beam Sensitive (HEBS) glasses, which after e-beam exposure are used as amplitude masks for the exposure of a final phase mask. This mask will have a varying phase step height if the photoresist layer with an approximately linear sensitivity curve will be applied [15]. Since the exposure of the Bragg fiber grating should take place at a proper distance from the phase mask in one of its Fresnel images plane, the influence of possible wrong placement of the fiber should be taken into account [16]. Another important issue is the appearance of higher harmonics and its effect on the performance of the grating [17–18].

The same principle of a local change in diffraction efficiency can be applied in the case of other diffractive optical elements with a known phase function. As an example, there can serve solutions for creating the Bessel beams, which can be considered as a special case of beam shaping. Since the Bessel beams have the transmittance of a mixed, amplitude-phase character, it is necessary to resort to application of a two-element setup, analogous to the case of beam shaping or apodization function implementation mentioned previously [19–20]. Similarly, a single element containing the phase function of a linear axicon and with an additionally included amplitude function proportional to $r^{-1/2}$ will be an asymptotic expression for the Bessel function, which holds for large arguments [21–23]:

$$J_0(r) \approx \sqrt{2/\pi r}\, cos\,(r - \pi/4). \tag{2}$$

Diffractive optical elements with spatially variable diffraction efficiency probably have found the most widespread applications in the case of diffractive multifocal intraocular lenses (MIOL). In contrary to refractive IOLs, where a given part of the lens is related to a given value of optical power, the diffractive MIOLs have different foci associated with different diffractive orders and the whole surface of the element takes part in their creation [24–26]. The spatially variable diffraction efficiency allows for an additional degree of freedom, namely, to introduce intentional gradual distribution of energy in particular foci as a function of aperture diameter, an important issue from a practical point of view (and lifestyle of the patient [27–28]).

Another example of application of binary phase gratings with a varying phase step can be found in calibrating of Spatial Light Modulators (SLMs) based on evaluation of Fresnel images. As it is well known, Fresnel images generated by a binary phase diffraction grating - in our case displayed on SLM - appear as binary irradiance distributions whose visibility depends on phase modulation [29–32]. The introduction of a linearly increasing phase step height along its length, where the transmittance of a single period is given by:

$$t_P(x,y) = rect\left[\frac{(x - d/4)}{d/2}\right] + rect\left[\frac{(x - 3d/4)}{d/2}\right] exp\left(i\varphi_{max}\; y / D_y\right), \tag{3}$$

φ_{max} is the maximum phase change obtainable with the SLM device and D_y is the periods length, makes it possible to observe the resulting distribution of the visibility function in the corresponding Fresnel image in a manner similar to the interference fringe pattern with a carrier frequency, and not in a uniform field, as was the case in some of the previous approaches [33]. The visibility function of the Fresnel images in the case of perfect SLM takes then the following form of equidistant fringes:

$$V = \frac{I_2 - I_1}{I_2 + I_1} = sin\left(\varphi_{max}\; y / D_y\right). \tag{4}$$

and any improper value of phase is manifested as a deviation of fringes from the straight line.

The identity condition of the grating's period may also be affected by changing the profile of the period from one to another. In the case of binary phase gratings such analysis was performed in the case of a random change in the phase step height [34]. One of possible applications of such manipulation in the case of the blazed grating could be a trial of diffraction efficiency achromatization. As it is commonly known, the diffraction efficiency of the blazed diffraction grating achieves 100% efficiency only for a single, blazed wavelength λ_B and. in general. is described as follows [35]:

$$\eta = sin\; c\left(1 - \lambda_B/\lambda\right) \tag{5}$$

One of possible proposed solutions are two aligned sandwich diffraction gratings made of materials with properly matched refractive indexes [36-39] or space-variant manipulation of the state of polarization by applying birefringent binary diffractive structures [40], [41]. Another possibility would be to optimize the heights and widths of phase steps composing the period of the quaternary grating [42] or to modify its pitch width [43].

All these solutions retain the condition of period's identity. Another approach is possible when the blaze angles of gratings' periods are distributed randomly around a certain mean value [44]. Similar or even better results are obtained when there are only two different blaze angles distributed randomly among different periods across the grating's aperture [45]. Basing on such arrangements, spectrometers with a flattened spectral response are possible to design [46].

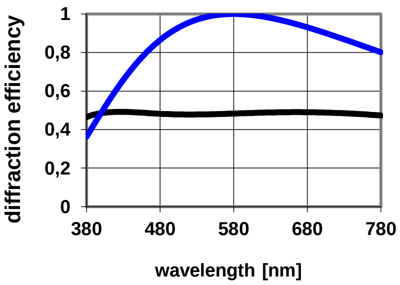

Fig. 2. Diffraction efficiency vs wavelength. Blue line - the blazed grating with blaze wavelength $\lambda_0 = 580$ nm according to Eq. (5). Black line – the grating optimized in the spectral range 380–780 nm and with two values of the blaze angle only (λ_1 = 485 nm, 74.3% of all facets, $\lambda_2 = 815$ nm, 25.7% of all facets).

A review of different advantages was made by leaving out the identity condition of all periods of diffractive optical elements. For the lack of space, this review is far from being complete, nevertheless some important practical applications were outlined. One of them results from the introduction of variable diffraction efficiency making possible the exposure of apodized fiber Bragg gratings or design of diffractive multifocal intraocular lenses. Another one indicates the possibility of obtaining diffractive gratings with a flattened spectral response.

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