Nonlinear diffractive optical elements

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Abstract: We propose diffractive optical elements with a spatially-varying nonlinear refractive index. Such a component acts as a diffractive optical element whose properties depend on the intensity of the incoming beam. We present a method for designing such elements, and as specific examples we study three types of nonlinear diffractive optical elements: Nonlinear Fresnel Zone Plates, Two-foci Nonlinear Fresnel Zone Plates, and Fresnel Zone Plate to Grating interpolator.

OCIS codes: (050.1970) Diffractive optics; (190.4360) Nonlinear optics, devices; (230.3990) Micro-optical devices

References and links

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1. Introduction

Diffractive optical elements (DOEs) are optical components that rely on diffraction, that is, on the wave nature of light, unlike standard lens and mirrors, which rely on refraction and reflection. This reliance on diffraction can be accomplished by spatially varying the thickness of a plate or the plate’s refractive index, thus changing the optical path length the wavefront experience at each point. In addition, the opacity of the element may also be spatially-varied. The simplest examples of a DOE are gratings and Fresnel Zone Plates (FZP).

Diffractive optical elements play an important role in various applications, such as laser beam shaping (e.g., generation of a flat-top intensity profile from Gaussian beams [1]), intensity-profile sampling, beam splitting, optical photolithography [2], trapping of nano-scale objects (optical tweezers), and manipulation of high-power laser beams (e.g., for materials processing applications). For high-power-laser applications, one of the advantages of DOEs over ordinary lenses is their ability to reduce nonlinear phase-retardation.

In contrast, in this paper we propose to utilize the nonlinear-phase in order to engineer DOEs that change their properties as a function of intensity: Nonlinear Diffractive Optical Elements (NDOE). The basic idea is simple: a NDOE is a diffractive optical element with spatially-varying nonlinear properties. Such an element will act as a DOE whose properties depend on the intensity profile and the power of the incoming beam.

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This idea may be implemented in several ways; possibly, the simplest one, at least in terms of design, is to use a flat plate whose both linear and nonlinear properties change spatially. Here, by "nonlinear properties" we refer to phenomena in which the refractive index changes as a function of the light intensity, such as the optical Kerr effect or saturable nonlinearity [3]. Another approach is to implement the NDOE with two layers: the first deals with the nonlinear properties and the other handles the linear optical path length variations, through modulation of the refractive index or of the surface relief (Fig. 1).

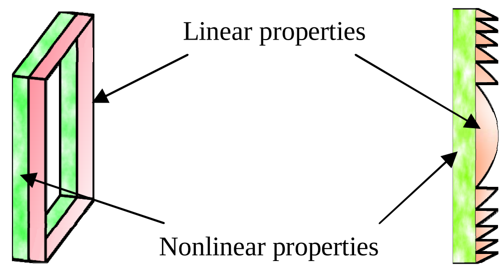

Fig. 1. NDOE implemented with the two-layer approach: One layer deals with the nonlinear properties and the other handles the linear properties, by spatially varying the linear refractive index (left), or the surface relief (right).

2. Design method

We start by presenting a method for the design of a NDOE. The challenge is to design such an element in a way that it will fulfill some prescribed properties. The design of a NDOE starts with defining the requirements from the NDOE. These requirements are defined by prescribing how the NDOE should behave at two different intensity-profiles. That is, one needs to define what the output field should look like for some incoming beam of field $\psi_1(x,y)$ and intensity $I_1(x,y)=|\psi_1|^2$, and how it should look like for some other incoming beam of field $\psi_2(x,y)$ and intensity $I_2(x,y)=|\psi_2|^2$. (Here, x and y are the transverse coordinates, and z is the propagation direction). For example, one may require that a plane wave of some low intensity will experience focusing, while a plane wave of some high intensity will go through the NDOE unaffected. Assuming that the optical element is thin, we may represent its influence on the beam by an amplitude transmission function (TF) [4]: $t(x,y)=\exp(i\phi(x,y))$. Here, we concentrate on phase elements, so the element can also be described by its real phase function $\phi(x,y)$. From the two incoming fields and the two outgoing fields one can calculate two TFs for the element: $t_1(x,y)=\exp(i\phi_1(x,y))$ at the intensity I_1, and $t_2(x,y)=\exp(i\phi_2(x,y))$ at the intensity I_2. This may be done using known DOE-design methods [5]. Alternatively, instead of prescribing the output field one may prescribe directly the two phase functions ϕ_1 and ϕ_2. We emphasize that in contrast to linear-DOEs design, where only the incoming field **profile** is important and not the actual amplitude, here the two particular intensities are important, since the problem is nonlinear.

Now, we need to determine the optical properties of the NDOE that will fulfill our requirements. Consider a plate with spatially-varying linear refractive index $\Delta n_L(x,y)$ and nonlinear refractive index coefficient $n_2(x,y)$. The objective is to find the spatial variations of $\Delta n_L(x,y)$ and $n_2(x,y)$ that generate the required TFs, for a given wavelength λ and a given nonlinearity type: $\Delta n_{NL}=n_2(x,y)g(I(x,y))$. (For simplicity, we ignore here the possibility to spatially vary also the thickness of the plate L). At each point (x,y) the relation between the refractive indices and the phase accumulated by the field can be written as a simple system of two linear equations in two variables - $\Delta n_L(x,y)$ and $n_2(x,y)$:

$$\phi_1(x,y)=Lk\left[\Delta n_L(x,y)+n_2(x,y)g\left(I_1(x,y)\right)\right], \tag{1a}$$

$$\phi_2(x,y)=Lk\left[\Delta n_L(x,y)+n_2(x,y)g\left(I_2(x,y)\right)\right]. \tag{1b}$$

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These systems of equations can be easily solved analytically:

$$n_2(x,y) = \frac{1}{kL}\frac{\Delta\phi}{\Delta g}, \tag{2a}$$

$$\Delta n_L(x,y) = \frac{1}{kL}\frac{\phi_1 g_2 - \phi_2 g_1}{\Delta g}, \tag{2b}$$

where $\Delta\phi=\phi_1(x,y)-\phi_2(x,y)$, $g_1=g(I_1(x,y))$, $g_2=g(I_2(x,y))$, and $\Delta g=g_1-g_2$. The thickness L can be chosen to get a reasonable value for the maximal required $\Delta n_{NL}(x,y)$.

Certainly, the main obstacle for the implementation of these ideas is the ability to create plates with high nonlinear refractive indices that vary appreciably on short length-scales (desirably of several wavelengths). This implies that a possible way to realize NDOEs would be to construct them as a micro-designed composition of two materials, with nearly identical linear refractive indices, but with their nonlinear properties widely differing (say, by an order of magnitude). These requirements are currently possibly with today's technology in organic nonlinear materials, such as polymers [6]. Another approach would be to construct a liquid-crystal (LC) device (e.g., like the type reported in [7]), where a liquid-crystal layer is sandwiched between two transparent cover glasses together with a poly(methyl methacrylate) (PMMA) layer. The surface relief of the PMMA can be shaped using direct electron-beam lithography, or using nano-imprinting [8]. Patterned transparent electrodes may be used to spatially vary the LC properties. Thus, the strength of the nonlinearity may be controlled at each point by two means: the voltage across the LC and the PMMA surface relief (at a point where the PMMA would be made thinner, the LC would be made thicker, so effectively the accumulated nonlinear phase is larger). These two degrees of control enable setting at each point both the effective linear and nonlinear refractive indices experienced by the beam. Moreover, this approach will enable to electrically tune the NDOE properties. For example, at 633-nm wavelength, the refractive index of the LC for extraordinarily-polarized light is n_e~1.7 and for ordinarily-polarized light is n_o~1.5, which is approximately equal to the refractive index of the PMMA. Thus, variations of the effective linear refractive index up to n_e-n_o~0.2 can be achieved. (Using a substrate other than PMMA, with a refractive index smaller than n_o or much larger than n_e, will enable larger variations of the linear refractive index). To estimate the expected thickness, we assume that typically the maximal required phase shift is about π-radians, so assuming $\Delta n_{NL}=5\cdot10^{-3}$ for intensities on the order of 1 to 10 mW/cm^2, a 50-μm ($\approx\lambda/2/\Delta n_{NL}$) thick LC is required. The response time of such a device would be on the scale of milliseconds.

3. Examples of NDOEs

Below we provide several examples of NDOEs. The simplest type of a NDOE is as follows: Given some linear DOE with TF $t(x,y)=\exp(i\phi(x,y))$, make a plate with a constant linear refractive index, and vary the nonlinear refractive index in proportion to the function $\phi(x,y)$. As a result, a low-intensity beam experiences propagation through a simple plate with a uniform refractive index, and thus it is unaffected by the plate, apart from a phase shift. However, when a high-intensity beam goes through the nonlinear medium, it experiences propagation through a DOE. In the same vein, a complementary NDOE would be one in which the linear properties are identical to those of the given linear DOE, and the nonlinear refractive index acts to eliminate the spatial variations of the linear refractive index for sufficiently high intensities. Possible DOEs that can be considered as a basis for designing NDOEs of this type are Fresnel zone plates (FZP), prisms, gratings, arrays of lens, etc.

We simulate the NDOE using two alternative methods: the more accurate one uses a beam propagation method to propagate the beam through the NDOE and then in free space. A second, approximated method, is to multiply the field incident on the NDOE by the NDOE's

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transmission function (thin element approximation), which depends on the intensity of the incoming beam. For circularly symmetric NDOE we calculate the on-axis field using the Rayleigh-Sommerfeld scalar diffraction formula. This integral formula gives the on-axis field from a ring of inner radius r_m and outer radius r_{m+1} to be: $z\cdot[exp(i\rho_m)/\rho_m - exp(i\rho_{m+1})/\rho_{m+1}]$, where z is the distance from the plate to the on-axis point and $\rho_m = \sqrt{r_m^2 + z^2}$. Using this expression for each ring, and taking into account the proper phase for each ring, we get a fast approximation to the on-axis field.

3.1 Nonlinear Fresnel Zone Plate

A specific example of a NDOE of the type described above is the Nonlinear Fresnel Zone Plate. A Nonlinear phase Fresnel Zone Plate is an element designed to interpolate between a simple transparent plate for incoming plane waves of low intensity and a FZP for high intensities. Consider a plate with a constant linear refractive index and a radially-symmetric distribution of the nonlinear refractive index, i.e., the spatial variation of the nonlinear refractive index consists of concentric rings of radii r_m. The nonlinear refractive index is Δn_0 for $r_{2n}<r<r_{2n+1}$ n=0,1,2,3…, and zero everywhere else. The radii r_m are given by $r_m=[m\lambda f+(m\lambda)^2/4]^{1/2}$, where f is the focal length, and m=0,1,2,3,… (See Fig. 2(a) where the black rings represent non-zero nonlinear refractive index). This formula for r_m is exactly the radius formula for a linear FZP. The thickness of the plate is chosen so that the maximal refractive index achievable will give a π phase-shift relative to the phase of a low intensity beam, i.e. $\Delta n_{NL} L\cdot 2\pi/\lambda=\pi$. Now, as it was described above, a low-intensity beam propagating through this element experiences propagation through a simple plate with a uniform refractive index, whereas a high-intensity beam experiences focusing to the focal point at a distance f away from the plate. The location of the focus does not vary with intensity (Fig. 2(b)); however, as the intensity I_0 of the incoming plane wave increases, the NDOE focuses the beam more and more efficiently, and as a result the intensity at the focus increases as a power function of I_0 ($I_0^{2.72}$ for the specific example given in Fig. 2(c)). We emphasize that the intensity in Fig. 2(b) is normalized to the intensity of the incoming beam, hence, had the system been linear, all the graphs would overlap. In the examples presented in Fig. 2, the thickness of the plate is 85μm, the focal length is 3mm, and the NDOE has 80 rings up to a radius of ~350μm, with the smallest feature size ~2.2μm. The maximal index change is 0.003 and λ=0.51μm.

Figure 2(d) shows the peak intensity at the focus for the complementary nonlinear FZP – a NDOE whose linear refractive index is of a linear phase FZP, and its nonlinear response acts to eliminate the linear refractive index variations. As a result, for a large range of incoming intensities (I_0=0.25 - 0.6), the intensity at the focus changes by no more than ±15%.

3.2 Two-foci Nonlinear Fresnel Zone Plate

In the following example, we use the nonlinearity to interpolate between a FZP with a focal length f=3mm for very-low-intensity incoming beams, and a FZP with f=5mm for high intensity (I_0=1) incoming beams. We apply the method described in section 2 above, using the phase functions of a 3mm-FZP and a 5mm-FZP (whose radial cross-sections are plotted in Fig. 3(a,b)) to solve Eqs. (2) for the linear (Fig. 3(c)) and nonlinear (Fig, 3(d)) refractive indices. Here, $\Delta n_L(x,y)$ varies in proportion to the TF of a 3mm FZP, and $n_2(x,y)$ is proportional to the difference between the two TFs (Fig. 3(c,d)). For the above-mentioned focal lengths and for an element of overall radius of ~310μm, 64 rings are required for the 3mm FZP and 38 for the 5mm FPZ, resulting in 102 rings with the smallest feature size ~1μm. As before, the thickness of the plate is 85μm, the maximal index change is 0.003 and λ=0.51μm. This example actually requires feature sizes which are sometimes much smaller than 1μm (Fig. 3(d)); however, we may just ignore these narrow rings without loosing much of the functionality of the NDOE. For low intensities, the Two-foci NFZP focuses the beam to the 1st focus at 3mm (Fig. 3(e), red line). At the prescribed high-intensity (I_0=1) the beam is

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focused to the 5mm-focus, and for moderate intensities the power is divided between the 1st, the 2nd, and an (undesired) focus at 7.58mm. As the incident intensity is increased, the fraction of the intensity going to the 1st focus gradually decreases, and the fraction going to the 2nd focus increases smoothly (Fig. 3(f)).

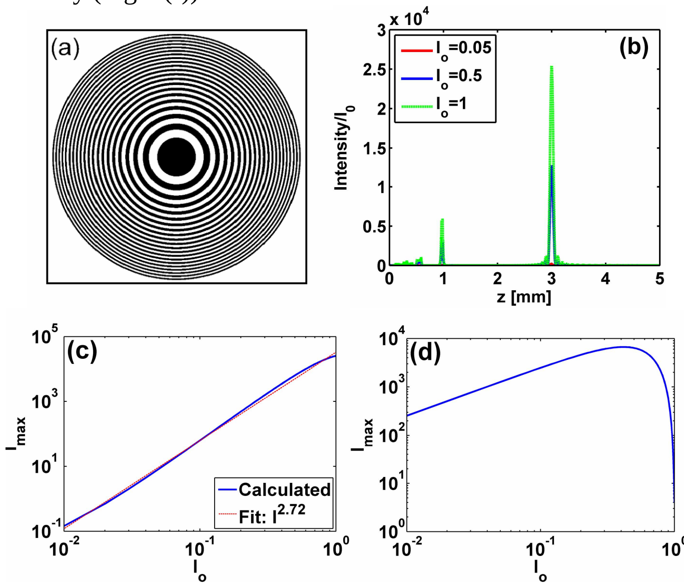

Fig. 2. Nonlinear Fresnel Zone Plate: (a) NFZP pattern: the nonlinear refractive index is different from zero only at the dark rings. (b) The on-axis intensity normalized to the intensity of the incoming plane wave, plotted for low intensity (red line), moderate intensity (blue line), and high intensity (green line). (c) Calculated intensity at the focus as a function of the intensity of the incoming beam (blue line) and power-law fit (red line). (d) Intensity at the focus as a function of the intensity of the incoming beam for a complementary NFZP.

3.3 FZP to Grating Interpolator

The last example is of a plate that interpolates between a FZP for low-intensity beams and a modulated-index grating for high-intensity beams. The purpose of this element is to focus a low-intensity incoming beam to some focal-point, and to deflect a high-intensity beam. In order to design this element we used Eqs. (2), with the phase function of a 3mm-FZP as ϕ_1, and a sinusoidal function for ϕ_2. The resulting linear (Fig. 4(a)) and nonlinear (Fig. 4(b)) refractive indices constitute rather complicated patterns. A low-intensity plane wave incoming at the Bragg angle is focused to the off-axis focal point (Fig. 4(c)), whereas a high-intensity plane wave incoming at the same angle is diffracted to multiple angles. A moderate-intensity plane-wave experience a combination of the two phenomena, as it is both partially focused and diffracted to multiple angles (Fig. 4(d,e)).

4. Summary

In addition to the self-phase-modulation effect, which a strong beam exerts on itself, one may use a strong beam to control a weaker beam through cross-phase-modulation, thus enabling an all-optical-controlled DOE. In a similar vein, one can use a strong beam at one wavelength to control another beam at another wavelength, at which the nonlinearity is weaker (as was done, for example, with soliton-induced waveguiding in photorefractives [9]).

In summary, we have shown that employing thin plates with a spatially-varying nonlinear refractive index, one can create new diffractive optical elements, whose properties vary with the intensity of the optical beam incident upon them. We have presented a method for designing such elements, gave concrete examples, and studied their properties. Such nonlinear diffractive optical elements can be used as optical limiters, all-optical beam steering, control of a weak beam by a stronger beam, etc.

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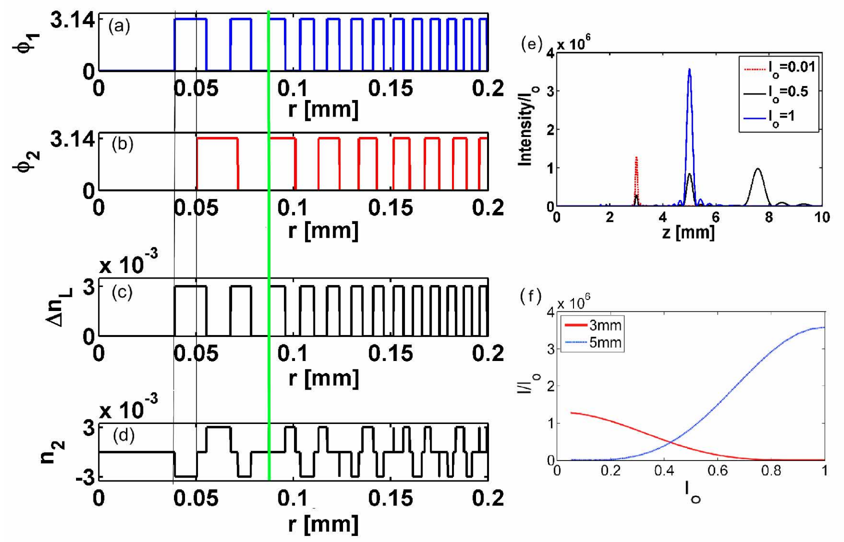

Fig. 3. Two-foci Nonlinear Fresnel Zone Plate: Radial cross-sections of the required phase functions for (a) a 3mm FZP and (b) a 5mm FZP, and the resulting (c) linear and (d) nonlinear refractive indices. (e) Normalized on-axis intensity for low-intensity (red line), moderate-intensity (black line), and high- intensity (blue line) incoming beam. (f) Normalized intensity at the two foci - 3mm (red line) and 5mm (blue line), as a function of the intensity of the incident beam.

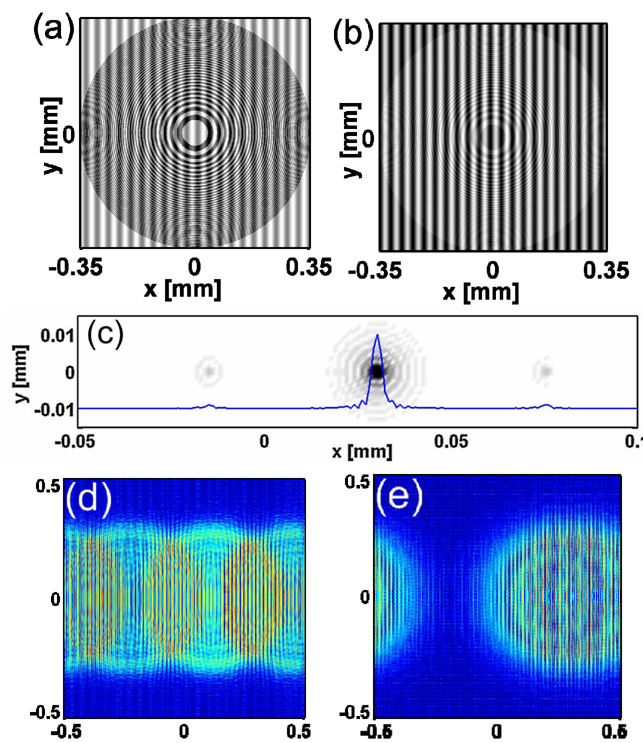

Fig. 4. FZP to Grating Interpolator: Computed linear (a) and nonlinear (b) refractive indices. (c) 2D cross section of the intensity at the focal-plane and 1D cross section of the intensity (blue line) through the focal point. (d) Intensity cross section after short propagation of a moderate-intensity beam, and (e) after longer propagation, showing the combination of diffraction to multiple angles and partial focusing.