Broadband Efficiency Improvements in Infrared Diffractive Optics

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Abstract

Diamond-turned diffractive structures, widely used to simplify infrared lens systems, suffer from limited broadband diffraction efficiency. Blazed-binary diffractive components composed of sub-wavelength structures to improve efficiency have been investigated. Modeling these structures for applications in the scalar domain, such as chromatic aberration correction, is very important. A model has been developed and used to design a blazed-binary lens etched into a gallium arsenide substrate for broadband operation in the long-wave infrared.

Keywords: IR Lenses, Diffractive Optics, Blazed Binary Structures

Introduction

Blazed-binary optical elements are diffractive components composed of sub-wavelength (i.e. with typical size smaller than the wavelength) ridges, pillars, holes or other simple geometries etched into a dielectric material. They mimic standard échelette-type diffractive optical elements (DOEs), achieving a blaze effect in a specified order by synthesizing artificial materials with binary structures compatible with one masking level. Their operation exploits effective-medium theory which relates the effective index of an artificial material to the local fraction of etched material. By spatially varying this fraction, any refractive index distribution or phase distribution can be synthesized [1,2]. Experimental results have shown interesting properties of this family of DOEs [3,4]. In particular, due to their dispersion property, which is intrinsic to the artificial material, they can provide high efficiency over a broad spectral range [5, 6]. Hence they are of prime interest for broadband applications, particularly for chromatic aberration correction, in the 8-12 μm spectral band where the sub-wavelength features size is compatible with low cost manufacturing such as photolithography and Inductively Coupled Plasma (ICP) etching.

However, for chromatic aberration correction, the DOEs operate in the scalar domain. They are characterized by large Fresnel zones and a phase function which is slowly varying when compared to the wavelength. In terms of modeling, standard échelette-type diffractive components can be analyzed using the well-known scalar theory. In contrast, whereas blazed-binary structures are analyzed with electromagnetic theory in the resonance domain (small Fresnel zones), it is more complex in the scalar domain: both large Fresnel zones and the local sub-wavelength structure need to be considered. So for studying such blazed-binary components, it is important to develop a model which overcomes the difficulties to provide accurate numerical results with the rigorous electromagnetic theory. The new model that we will present is even more general and is able to address any kind of diffractive structure, provided that their phase function is slowly varying at the scale of the wavelength.

Model formulation

Because of the slowly varying assumption, we first define a complex-amplitude transmittance for the blazed-binary diffractive element. This transmittance is defined as the ratio between the transmitted U_t and the incident U_i complex scalar wave-functions, which is the usual approach for calculating propagation in Fourier optics. These two functions are such that the square of their modulus represents intensity.

For the design of any diffractive element, we consider an unwrapped phase function, $\varphi(x)$, which is specified at a given (design) wavelength λ_0, and at a given angle of incidence (in general normal incidence); see Figure 1(a). From the specified unwrapped phase function, the corresponding diffractive phase function, $\Psi(x)$, equal to $\varphi(x)$ modulo 2π, is generated; see Figure 1(b). To encode this phase function with blazed-binary elements, we exploit the effective medium theory. Practically speaking, we use a calibration curve which relates the effective index of the artificial material to the local fraction of etched material. So a specific phase shift Ψ_1, in Figure 1(c), is associated with a specific sub-wavelength structure characterized by its geometry and size. As a result, a systematic relationship exists between the designed blazed-binary structure and the unwrapped phase function; the geometry of the designed blazed-binary component is a 2π-periodic function of the unwrapped phase $\varphi(x)$.

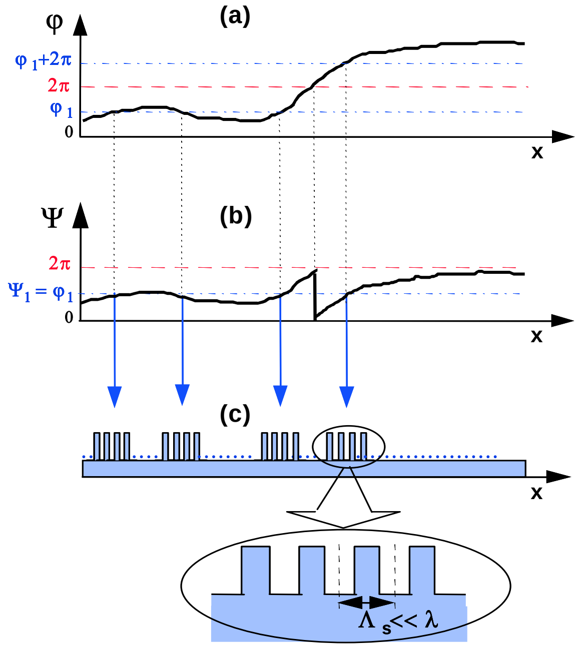

Figure 1 : Encoding a phase transfer function with blazed-binary structures. (a) Unwrapped phase transfer function φ. (b) Phase function of the corresponding diffractive optical element Ψ. (c) The corresponding blazed-binary structure.

Because of the identified relationship, the transmittance, $t(\varphi)$, of the blazed-binary diffractive element is also a 2π-periodic function of the unwrapped phase, φ. So, it can be expanded in the following Fourier series:

$$t(\varphi) = \sum_{-\infty}^{+\infty} c_m exp(jm\varphi), \quad (1)$$

where the c_m coefficients are given by,

$$c_m = \frac{1}{2\pi}\int_0^{2\pi} t(\varphi)\exp(-jm\varphi)d\varphi. \quad (2)$$

The m^{th}-transmitted-order diffraction efficiency η_m is given by,

$$\eta_m = |c_m|^2. \quad (3)$$

The expansion in Eq. (1) describes the transmittance of the blazed-binary structures as a coherent superposition of scalar wave-functions with a weighted intensity distribution given by the η_m's. The diffraction efficiencies, η_m, are computed through the numerical integration of the right-hand-side of Eq. (2). This integration requires a knowledge of the complex-amplitude transmittance, $t(\varphi)$.

In order to calculate the amplitude transmittance, $t(\varphi)$, we make use again of the slowly varying phase. As a result, an incident plane wave A_i ,illuminating the structure, sees a 0^{th}-order grating at the scale of several wavelengths. By 0^{th}-order grating, we mean a grating in which all orders are evanescent except the 0^{th} reflected and transmitted ones. The response of this 0^{th}-order grating is easily computed with electromagnetic grating theory. Although we have restricted the analysis to the transmitted far field, the reflected field is straightforwardly obtained through the computation of the normalized amplitudes of the 0^{th}-reflected diffraction order. More details about the model can be found in Ref. [7].

Validation of the model

In order to validate the model, we consider a very simple case; an échelette-type diffractive lens. In fact, the scalar theory [8] provides the m^{th} transmitted order diffraction efficiency expression, assuming no spectral dispersion of the material, as follows:

$$\eta_m = T \sin c^2\left(\pi\left(p\frac{\lambda_0}{\lambda} - m\right)\right), \quad (4)$$

where λ_0 is the design wavelength of the diffractive structure, p the blaze order, m the diffraction order and T the transmission intensity coefficient at the interface (air/substrate). Hence, by studying an échelette-type diffractive lens it is possible to check the results of the model against a rigorous theoretical expression.

The geometry used in the model is a thin layer of variable thickness. The maximum thickness is achieved to optimise the 1^{st} transmitted order diffraction efficiency, which is given by $h_0 = \lambda_0/(n-1)$.

Both methods, the scalar theory and the model, are applied to the particular test case shown in Figure 2. It consists of a lens etched into a gallium arsenide substrate designed at λ_0 and at normal incidence.

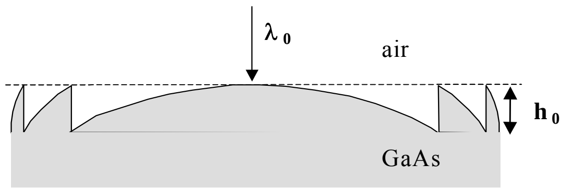

Figure 2: Sketch of the échelette-type diffractive lens used for testing the model.

Figure 3 illustrates the 1^{st} transmitted order diffraction efficiency as a function of the normalized wavelength (illumination wavelength normalized to the design wavelength), assuming incidence from the air side. The results are obtained with both methods: the model and the analytical expression.

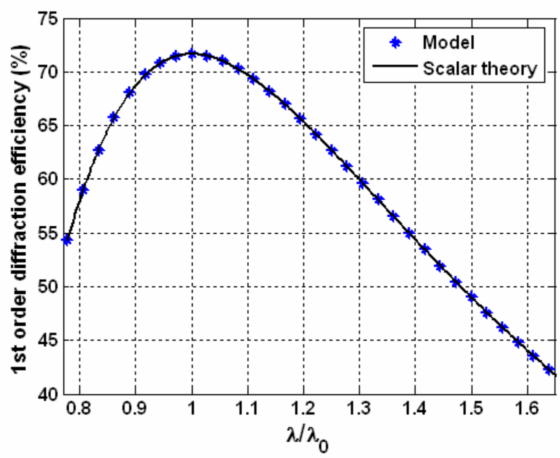

Figure 3: Validation of the model on an échelette-type diffractive lens. First-order diffraction efficiency as a

function of the wavelength. (Diamonds: model results. Solid line: analytic expression of Eq. (4) with p = m = 1).

From Figure 3, a very good agreement is seen between the model results and the calculation using the scalar theory, which validates the model.

Application of the model: design of a blazed-binary lens operating in the scalar domain

The model is now used to design a blazed-binary diffractive lens etched into a gallium arsenide substrate (n=3.28 at λ_0=9 µm) operating in the scalar domain. The component is designed at normal incidence for broadband application in the 8-12 µm spectral range. The sampling period, which is the center-to-center distance between two consecutive microstructures, is 2.8 µm. The design of the component for broadband application is carried out by making use of the artificial material dispersion property. To achieve a first-order blazing at λ_0, a phase variation between 0 and 2π is encoded using a variation in the effective index of between 1.88 and 3.28, and a grating depth of 6.4 µm. In order to decrease the aspect-ratio of the structure, it is composed of both holes and pillars. A simplified sketch of the structure, corresponding to two Fresnel zones, is shown in Figure 4.

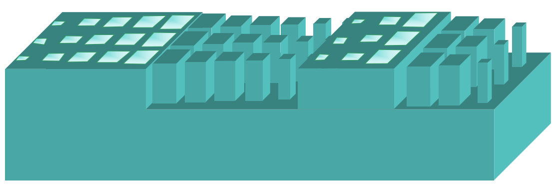

Figure 4: Simplified sketch of part of two Fresnel zones of the blazed-binary structure.

As a matter of comparison, we have designed a blazed-binary grating characterized by the same properties as the blazed-binary lens (same type of local geometries, sampling period, depth, minimum and maximum effective indices). The grating period is 140µm.

Figure 4 shows the 1st transmitted order diffraction efficiency (normalized to the total energy diffracted in all transmitted orders) for both structures; the blazed-binary lens operating in the scalar domain (solid line in Fig. 5) and the 140 µm-period grating (diamonds in Fig. 5). The lens efficiency is computed with the model whereas the grating is computed using rigorous electromagnetic computations using the Fourier Modal Method [9]. Both components are illuminated from the substrate at normal incidence and with non-polarized light.

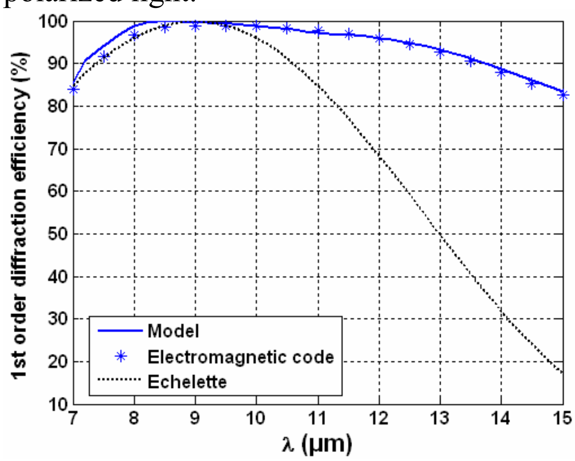

Figure 5: First order diffraction efficiency (normalized to the total energy diffracted in all transmitted orders) of two blazed-binary structures.
(Solid line: model results for a blazed-binary lens operating in the scalar domain. Diamonds : rigorous electromagnetic code for a 140 µm-period blazed-binary grating. Dotted line: analytical expression of an échelette-type diffractive lens efficiency operating in the scalar domain).

Figure 5 shows a good agreement between the lens operating in the scalar domain (Fresnel zones >> $100\lambda_0$) and the grating, which has a period ~15 λ_0. We have demonstrated therefore that the model gives good predictions, even for finite Fresnel zones.

Secondly, for comparison we have evaluated the performance of a standard échelette-type lens operating in the scalar domain (dotted line of Fig. 5). It results that both blazed-binary elements offer a high efficiency, >96% over 8-12 µm and >82% over 7-15 µm, which is not the case for the échelette-type element.

Conclusions

For hybrid optics applications, blazed-binary diffractive elements are characterized by very large Fresnel zones (larger than hundreds of wavelengths) and a slowly varying phase, despite their local sub-wavelength structures. As a result, it is difficult to ensure accurate numerical results with the rigorous electromagnetic theory.

To overcome this difficulty, we have developed a model which can address any type of diffractive element with slowly varying phase, including blazed-binary optics. The model has been verified fully against scalar theory on an échelette-type diffractive lens.

This model has been used to design a blazed-binary lens with a slowly varying phase, composed of sub-wavelength holes and pillars etched into a gallium arsenide substrate, for broadband operation in the 8-12 µm waveband. The component consists of structures of dimensions compatible with low-cost manufacturing processes, such as photo-lithography and reactive ion etching. It has been computed with the model, demonstrating the feasibility of achieving an average efficiency higher than 96% over the 8-12 µm spectral interval.

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