

Broadband efficiency improvements in infrared diffractive optics

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Abstract

Diamond-turned diffractive structures, used widely to simplify infrared lens systems, suffer from limited broadband diffraction efficiency. Two forms of modified diffractive structure to improve efficiency are being investigated. One modification introduces additional material layers and the other makes use of blazed binary sub-wavelength structures. Design principles are discussed and some interesting design examples are presented.

Keywords: IR Lenses, Diffractive Optics, Blazed Binary Structures

Introduction

res diamond-turned directly onto the surface of conventional refractive lens elements are widely used in infrared optics^(1,2). The diffractive surface in these so-called hybrid refractive-diffractive elements is principally used for the correction of chromatic aberration. Hybrid optics enable a reduction in the number of lens elements and material types required in an optical system, resulting in reduced mass, cost and complexity.

However, these diffractive structures have the disadvantage that a proportion of the incident light is diffracted into spurious diffraction orders, resulting in a degradation of image quality. The most significant effect is a reduction in diffraction efficiency over the operating waveband⁽³⁾. This loss in efficiency, which is fundamental to the conventional diamond-turned blaze structure, currently prevents the full potential benefits of hybrid optics from being realised.

The aim of this project is to develop diffractive structures which provide improved broadband diffraction efficiency for infrared hybrid lens systems.

Diffractive optics in the form of surface-relief 'blaze' structure The investigations are divided into two main areas. Improvements to conventional diamond-turned blaze type structures, by the introduction of additional layers of different materials, is being investigated by Thales Optics Ltd., UK. Thales Research and Technology, France, are investigating the potential of a fundamentally different form of diffractive surface; so-called blazed-binary structures. These structures are characterised by sub-wavelength feature sizes and are manufactured using lithographic techniques.

This paper describes the results of a theoretical study to determine the potential improvements in broadband efficiency from these two approaches, and to develop some design examples. Samples for validation of the theoretical predictions will be manufactured during the next phase of the study.

Multi-Layer Blaze Structures

For the purposes of ray tracing and aberration correction during the optical design process, the diffractive properties of a hybrid refractive-diffractive surface are

completely defined by a design wavelength, λ_0 , design diffraction order, m_0 , and the optical path length (OPL) function, $\varphi_0(\rho)^{(2)}$. Typically, the OPL function is of the following form,

$$\varphi_0(\rho) = D_2\rho^2 + D_4\rho^4 + D_6\rho^6 + \dots \quad (1)$$

where D_2 determines the first-order properties of the diffractive surface.

It is assumed that the diffractive surface imparts an OPL transformation at the design wavelength given by $\varphi(\rho, \lambda_0)$, which is found by calculating $\varphi_0(\rho)$ modulo $m_0\lambda_0$. In a conventional hybrid surface, shown in figure 1(a), we realise this transformation with a surface-relief structure derived using the simple thin phase plate approximation; $\varphi(\rho, \lambda_0) = \{n(\lambda_0)-1\}.z(\rho)$, where n is the refractive index.

In general, the OPL transformation generated by a surface-relief blaze structure at some wavelength, λ , will be given by,

$$\varphi_b(\rho, \lambda) = \beta(\lambda).\varphi(\rho, \lambda_0) \quad (2)$$

where $\beta(\lambda)$ depends on the particular form of the blaze. It can then be shown that the diffraction efficiency at some diffraction order, m , resulting from the transformation $\varphi_b(\rho, \lambda)$ is given by,

$$\eta(\lambda, m) = \text{sinc}^2\{m_0(\lambda_0/\lambda)\beta(\lambda) - m\} \quad (3)$$

Eqn. (3) shows us that 100% diffraction efficiency can be achieved at order m , for any wavelength, if we can satisfy the condition,

$$\beta(\lambda) = m\lambda/m_0\lambda_0 \quad (4)$$

For the conventional type surface shown in figure 1(a), we find that, $\beta(\lambda) = \{n(\lambda)-1\}/\{n(\lambda_0)-1\}$. Whilst eqn. (4) can be satisfied in principle for this geometry, it requires a material with high anomalous

dispersion (e.g. V-values of -2.5 and -2 for the $8-12 \mu\text{m}$ and $3-5 \mu\text{m}$ wavebands respectively!). In practice, for a diffractive structure diamond-turned directly into a typical infrared lens element, the broadband efficiency is largely independent of the material choice. Typical broadband efficiencies, given by finding the integral of eqn.(3) over the operating waveband, are 95% and 93% for the LWIR (long wave infrared) and MWIR (mid-wave infrared) respectively.

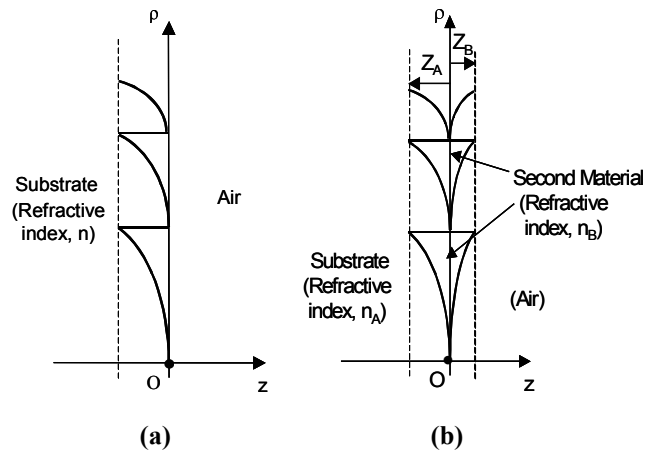


Figure 1 : Hybrid surface geometry
(a) Conventional, (b) Dual-layer

Broadband diffraction efficiency can be improved using a dual-layer structure of the type shown in figure 1(b). The OPL transformation generated by this structure is,

$$\varphi_b(\rho, \lambda) = \{n_A(\lambda)-n_B(\lambda)\}z_A(\rho) + \{n_B(\lambda)-1\}z_B(\rho) \quad (5)$$

Eqns. (2), (4) and (5) provide the necessary condition to satisfy for a diffraction efficiency which is independent of wavelength. Whilst it is not possible in general to choose materials which fully satisfy this condition, there are sufficient degrees of freedom to allow the wavelength variation to be minimised. This is directly analogous to the correction of chromatic aberration in an achromatic doublet lens, where a residual 'secondary spectrum' remains.

Dual-layer design examples have been calculated using the common infrared lens materials. In the LWIR, all the combinations give theoretical average broadband efficiencies of 99.9%. Efficiency in the MWIR is more dependant on the material choice, but several combinations generate better than 99% efficiency. Figure 2 shows a plot of diffraction efficiency over the 3-5 μm waveband for a conventional blaze structure compared with a Silicon/Germanium dual-layer design.

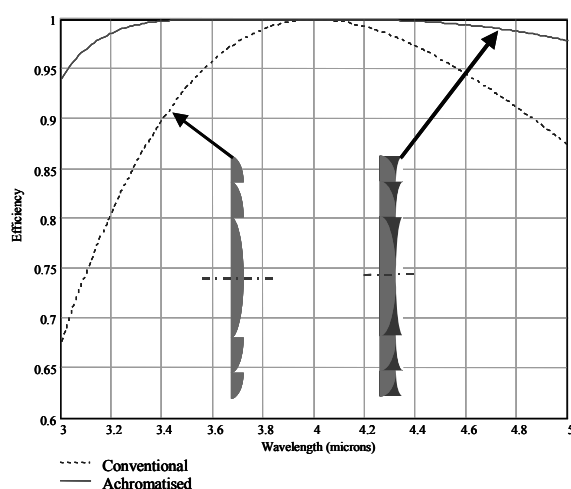


Figure 2 : First-order diffraction efficiency of conventional versus dual-layer (Si/Ge) blaze designs for MWIR ($\lambda_0=4 \mu\text{m}$, $m_0=1$)

A special case of the geometry shown in figure 1(b) exists when the solution satisfies the condition, $z_B(\rho)=0$. In this case, the structure is equivalent to a conventional blaze ‘filled’ with another material, so that the outer surface becomes continuous. Whilst there *may* be advantages in this type of structure in terms of manufacture, the solution requires a fill material of extremely high dispersion in the infrared. There are no solutions of this type using the common infrared lens materials.

Dual-layer designs using combinations of many of the common infrared materials offer the potential for high broadband efficiency. However, there are additional

factors which influence the selection of the optimum materials. Dual-layer structures are significantly deeper than the equivalent conventional designs, typically by one or two orders of magnitude. Large differences in refractive index generally result in shallower structures, but Fresnel reflection losses at the interface between the two layers is increased. Material choice obviously also strongly depends on potential manufacturing processes; this aspect will be examined in detail during the next phase of the study.

Blazed Binary Structures

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 carefully etched into a dielectric material. They mimic standard blazed *échelette*-type diffractive optical elements (DOEs), achieving a blaze effect in a specified order by synthesizing artificial materials with only sub-wavelength binary structures. 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^(4,5). This concept was demonstrated experimentally and, not only have blazing effects been observed for both polarizations, but efficiencies superior to those of equivalent *échelette*-type DOEs have been obtained for small-period gratings⁽⁶⁾ and for diffractive lenses with high numerical aperture⁽⁷⁾. Here, we exploit the highly dispersive properties of artificial dielectrics, composed of binary sub-wavelength structures, to achieve blazed-binary gratings with high efficiency for operation over a broad spectral range.

Let us consider an artificial material composed of a square lattice of square air

holes of width d , perforated in a non-dispersive dielectric material with a refractive index, $n=3.28$. Provided that the periodicity constant Λ_s is small enough compared to the wavelength of light, the sub-wavelength structures are not “resolved” by the light and the heterogeneous structure behaves as a homogeneous material with an “effective refractive index”. The solid curve in figure 3 shows the effective index associated with the fundamental Bloch mode propagating along the surface normal for $\Lambda_s=\lambda_0/n$ as a function of the ratio d/Λ_s . From this curve, a range of effective indices can be derived to achieve the desired phase function at λ_0 . Illuminated at another wavelength λ , the artificial material disperses and a new range of effective indices are generated, as shown by the dashed curve of figure 3. Thus, due to their artificial material properties, these blazed-binary structures offer a new possibility to compensate for the wavelength dispersion of the phase.

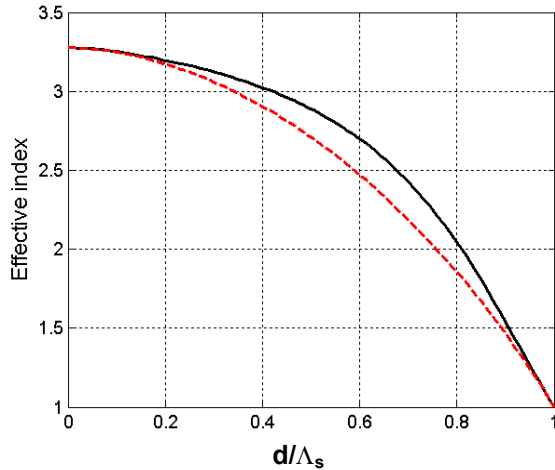


Figure 3 : Effective index of a square lattice of square air holes (width d) etched in a material with a refractive index $n=3.28$.

Solid curve: $\lambda=\lambda_0$; dashed curve: $\lambda=2\lambda_0$.

In order to demonstrate the advantage of this new property, we have studied the following blazed-binary grating. It is composed of 50 square air holes etched into a gallium arsenide substrate ($n=3.28$ at $\lambda=10 \mu\text{m}$). The center-to-center distance

between two holes is $\Lambda_s= 3.05 \mu\text{m}$. Thus the period of the grating is $152.58 \mu\text{m}$ (or $\approx 15.3\lambda_0$, with $\lambda_0=10 \mu\text{m}$). Along the grating period, the size of each hole is determined through the calibration curve of figure 3, so as to generate a gradual effective index variation and thus a gradual phase variation. As a result, the largest ridge size is $1.85 \mu\text{m}$ and the smallest ridge size is set to $0.12 \mu\text{m}$, which leads to a variation of the effective index between 2.68 and 3.28. The grating depth is $16.7 \mu\text{m}$, to guarantee a first-order blazing at $\lambda=\lambda_0$. More details concerning the design procedure can be found at reference (8).

Once the grating has been designed, the diffraction efficiencies in all transmitted orders are calculated by rigorous electromagnetic computations with the Fourier Modal Method⁽⁹⁾. The grating is assumed to be illuminated at normal incidence from the substrate ($n=3.28$) under TE polarisation. The first-order efficiency, normalized to the total energy diffracted in all transmitted orders, is plotted in figure 4 (see the solid curve). For comparison, the efficiency of a blazed-échelette grating operating in the scalar domain is represented by the dashed curve.

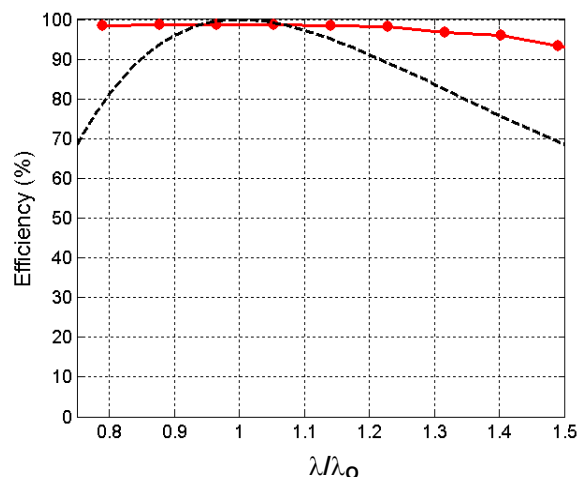


Figure 4 : Computation of the first order efficiency of a blazed binary grating composed of 50 square air holes etched into a GaAs substrate ($n=3.28$). The sampling period is $\Lambda_s=3.05\mu\text{m}$. The grating is illuminated from the substrate at normal incidence under TE polarization.

The dashed curve corresponds to the efficiency of the standard échelette-type blazed grating operating in the scalar domain.

This graph shows unique spectral properties, which significantly differ from those of conventional échelette-type DOEs : the blazed-binary grating offers a high efficiency (>99%) over a spectral interval of $[0.8\lambda_0-1.2\lambda_0]$, which corresponds to an 8-12 μm spectral band. Note that the efficiency is not equal to 100% at the nominal wavelength. The small deviation results from a slight shadowing effect due to the finite grating period. This effect is expected to vanish for larger periods.

Although the present grating design doesn't take into account manufacturing constraints, we believe from this preliminary work that a further design with a lower aspect ratio can be considered. Such a design would be compatible with low-cost manufacture technologies, such as photolithography and reactive ion etching.

The result obtained for blazed-binary gratings can be generalized to blazed-binary optics, which opens interesting properties for applications such as diffractive optical systems designed to operate in finite spectral bands, especially in the LWIR and MWIR bands, where standard fabrication processes allow the manufacture of deep etches in semiconductors with high refractive indices (i.e. artificial dielectrics with high dispersion).

Conclusions and Future Work

We have showed theoretically that both dual-layer and blazed-binary structures offer the possibility of improved broadband efficiency in hybrid lens systems designed for the LWIR and MWIR spectral bands.

The next phase of the work will concentrate on the manufacture of samples for the verification of our design predictions.

Acknowledgment : The authors would like to thank Philippe Lalanne from the Laboratoire Charles Fabry de l'Institut d'Optique for fruitful discussions.

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