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Stratified diffractive optic approach for creating high efficiency gratings

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1. Introduction

Gratings with high efficiency in a single diffracted order can be realized with both volume holographic and diffractive optical elements. However, each method has limitations that restrict the applications in which they can be used. For example, high efficiency volume holographic gratings require an appropriate combination of thickness and permittivity modulation throughout the bulk of the material. Possible combinations of those two characteristics are limited by properties of currently available materials, thus restricting the range of applications for volume holographic gratings. Efficiency of a diffractive optic grating is dependent on its approximation of an ideal analog profile using discrete features. The size of constituent features and, consequently, the number that can be used within a required grating period restricts the applications in which diffractive optic gratings can be used. These limitations imply that there are applications which cannot be addressed by either technology. In this paper we propose to address a number of applications in this category with a new method of creating high efficiency gratings which we call stratified diffractive optic gratings. In this approach diffractive optic techniques are used to create an optical structure that emulates volume grating behavior.

To illustrate the stratified diffractive optic grating concept we consider a specific application, a scanner for a space-based coherent wind lidar, with requirements that would be difficult to meet by either volume holographic or diffractive optic methods. The lidar instrument design specifies a transmissive scanner element with the input beam *normally* incident and the exiting beam deflected at a fixed angle from the optical axis. The element will be rotated about the optical axis to produce a conical scan pattern. The wavelength of the incident beam is 2.06 μm and the required deflection angle is 30 degrees, implying a grating period of ~4μm. Creating a high efficiency volume grating with these parameters would require a grating thickness that cannot be attained with current photosensitive materials. For a diffractive optic grating, the number of binary steps necessary to produce high efficiency combined with the grating period requires feature sizes and alignment tolerances that are also unattainable with current techniques. Rotation of the grating and integration into a space-based lidar system impose the additional requirements that it be insensitive to polarization orientation, that its mass be minimized and that it be able to withstand launch and space environments.

2. Stratified diffractive optic grating as an alternative

We propose an alternative approach that is inspired in part by previous work on stratified volume holographic optical elements (SVHOE's).[1,2] In that work, diffraction efficiencies comparable to those of a volume grating were achieved by interleaving thin holographic grating layers with homogeneous layers whose thickness was appropriate to ensure phase matching between the zero and first orders. This led to consideration of a similar structure for diffractive optic gratings, *i.e.* stratified diffractive optic gratings.

2.1 Stratified diffractive optic grating structure

In a stratified diffractive optic grating the thin holographic grating layers of SVHOE's are replaced by binary grating layers which are interleaved with homogeneous layers as illustrated in Figure 1. The ridges of the grating layers form surfaces of constant permittivity similar to the
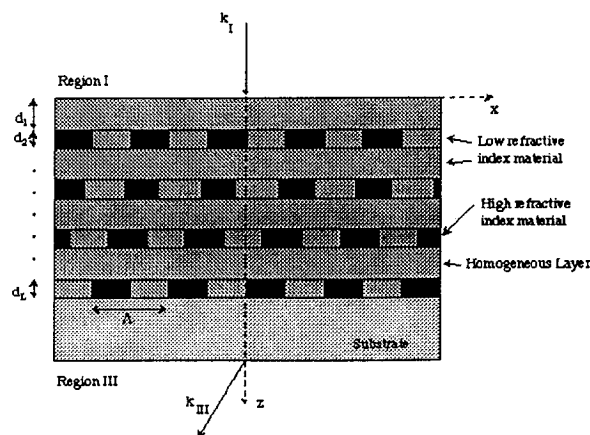

Figure 1: Example stratified diffractive optic grating

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fringes in a volume grating. Laterally shifting the binary grating layers creates a stratified diffractive optic structure corresponding to a volume grating with slanted fringes. Refractive index of both the ridges and the grooves of the binary gratings and of the homogeneous layers may be varied as well as layer thickness to enforce phase matching through the structure. The number of layers may also be varied in order to optimize the efficiency of the element.

2.2 Modeling

The grating structure discussed above has an index modulation that is large compared to that of photosensitive materials and, for the example considered here, a small period to wavelength ratio (*e.g.* < 10). Accurate prediction of diffraction efficiency under these conditions requires a rigorous electromagnetic diffraction theory. Rigorous coupled-wave analysis (RCWA) as formulated by Moharam, *et al*[3,4] was chosen as the algorithm to model the behavior of these stratified structures. The implementation encompasses planar diffraction for both TE and TM polarization orientations and conical diffraction. Recent modifications which improve convergence of RCWA for TM polarization and conical diffraction have also been incorporated.[5]

Extension of the published RCWA algorithm to accommodate the unique structure of stratified diffractive optic gratings was necessary. In our version of the algorithm, any number of uniform and grating layers can be sequenced in any order. Binary grating layers can be shifted independently of one another. Refractive index and dispersion can be specified for each uniform layer as well as for both ridges and grooves in each grating layer. These modifications permit examination of general stratified elements.

3. Example design and performance

An initial design process for the lidar scanner element considered stratified diffractive optic grating structures consisting of 2,3,4 and 5 binary grating layers interleaved with homogeneous layers. All homogeneous layers were assumed identical as were all grating layers, with the exception of lateral position. Since the lidar system required normal incidence, the position of the grating layers was shifted such that the fringes they represented were slanted at the Bragg angle. The refractive index of grating ridges was chosen to be 2.0 while the refractive index of grating grooves and uniform layers were both set to 1.5. Iteration of the thickness of grating and homogeneous layers and the associated grating shifts revealed an optimum cumulative grating thickness of 3 μm. Peak diffraction efficiency for the case of two binary grating layers was approximately 70% while the case of three layers increased to 88.5%. Five grating layers yielded a peak efficiency of 90%.

The design with three layers was chosen for further study since it predicted high diffraction efficiency in a relatively simple structure. Figure 2 shows the efficiency of this structure as a function of angle of incidence of the input beam. Note that it maintains greater than 85% efficiency in a region of +/- 1 degree about normal incidence. Figure 3 illustrates that the diffraction efficiency is relatively insensitive to polarization. Figure 4 shows a plot of the electric field as it traverses the stratified binary grating structure. As the wavefronts pass through the first grating layer they are slightly disrupted while passing through the second grating layer causes them to become completely fractured. The third grating layer connects a lagging wavefront with a leading wavefront to effect the redirection of the beam to the desired deflection angle.
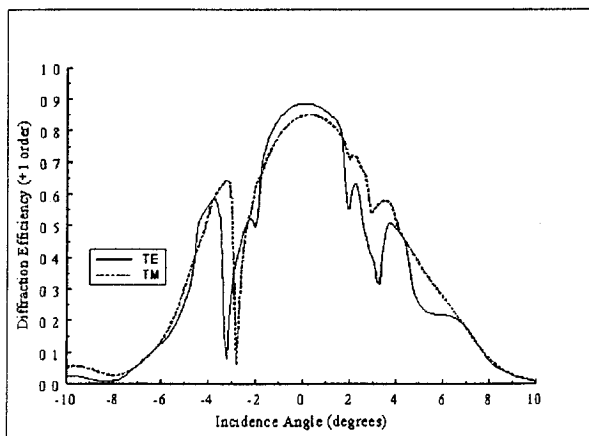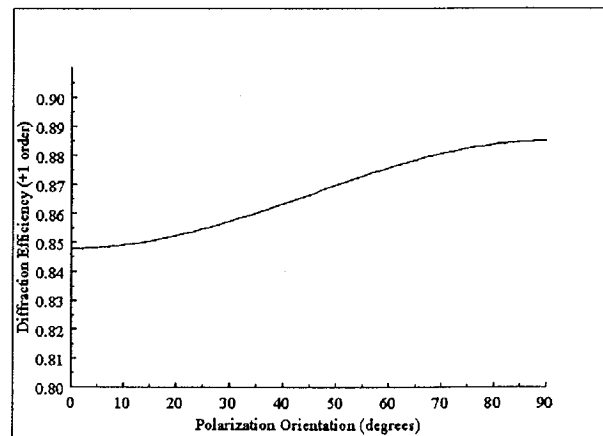

Figure 2: Efficiency vs. Incidence Angle

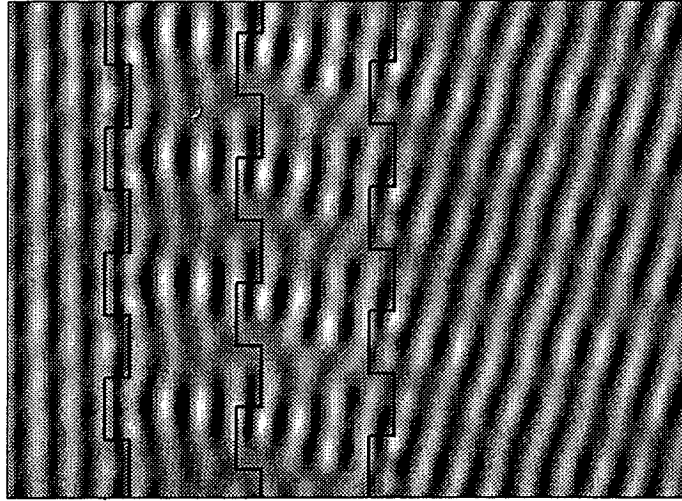Figure 3: Efficiency vs. Polarization Orientation

Figure 4: Electric field through stratified diffractive optic grating structure

4. Summary

Stratified diffractive optic gratings have been proposed as a means of producing gratings for applications where the requirements are not suited to traditional volume holographic and diffractive optics techniques. An example application has been studied to illustrate a set of operational and performance requirements that are best met by an approach of using diffractive optic fabrication techniques to emulate volume grating behavior. A modeling algorithm based on RCWA has been described and an example stratified diffractive optic grating structure for the coherent wind lidar application has been discussed. This design yielded a diffraction efficiency of 88.5%.

References

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