OPTIMIZATION OF WIREGRID POLARIZERS FOR CO_2 LASER

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Abstract–*Metallic gratings (wiregrids) can function as efficient polarizers with high extinction ratio. The polarizing effect is due to the fact that these gratings act as a metal for the polarization parallel to the lines, reflecting most of it and absorbing the rest, and as a dielectric for the polarization perpendicular to the lines, transmitting profusely. A short semi-intuitive explanation of this behavior is given. A wiregrid polarizer for the* CO_2 *lasers is designed and then the parameters of the grating that can be varied - according to the specifics of the available lithographic procedure - are optimized. The sets of optimum polarizer parameters together with the corresponding performances are listed and discussed from a practical point of view.*

Keywords: *polarizer,* CO_2 *laser, Effective Medium Theory, optimization, anisotropy.*

1. INTRODUCTION

One of the most basic applications of lithography is the creation of gratings. There are many types of lithographic procedures among which optical interferometric lithography distinguishes itself by its low cost and experimental simplicity. In the following considerations we kept in mind at all times the experimental limitations of lithography, i.e. the range of values the grating parameters can take. The study of the quality of the grating polarizers is also a study of the capabilities of the lithographic device we have at our disposal.

Metallic diffraction gratings or wiregrids have the interesting and useful property of behaving very differently according to the polarization of the incident light. If the polarization is parallel to the grating lines, the grating behaves as a metal with a refractive index having the value of the average between the refractive indices of the lines (metal wires) and the spaces (dielectric, usually air). If, on the other hand, the polarization is perpendicular to the wires then the grating behaves as a dielectric. The polarization-selective behavior is more discernible as the refractive index of the metal used for making the grating is more "metallic", i.e. has a very large absolute value. This property is useful because based on it one can design and manufacture polarizers.

In Fig. 1 the parameters of a grating are illustrated: the width of the lines w, the height of the grating h, the pitch Λ, and the grating vector **K** of scalar value $2\pi/\Lambda$. The correspondence of the coordinate axes to the refractive indices of a uniaxial crystal is also shown.

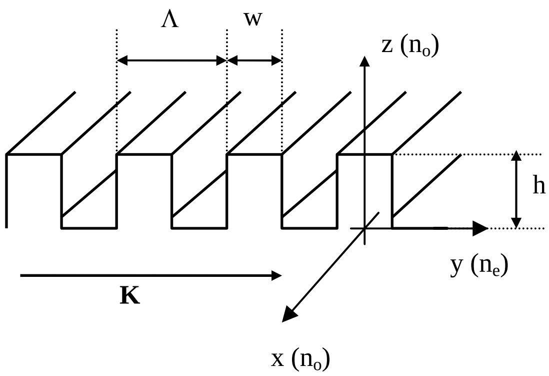

Fig. 1. An example of grating sample. The diffraction grating may be considered a slab of anisotropic uniaxial crystal with the optic axis parallel to the grating vector **K**. The grating vector corresponds to the extraordinary and the two other perpendicular directions to the ordinary refractive indices respectively.

2. THE EFFECTIVE MEDIUM THEORY (EMT)

The knowledge of the optically anisotropic behavior of the gratings goes back quite some time, being mentioned in the classic optics textbook of Born and Wolf [1]. Actually in reference [1] the optical anisotropy was explained in terms of geometric anisotropy, describing the crystals as stacks of parallel planes, similar to gratings. If the wavelength of the light λ is much larger than the pitch it is shown that the effective refractive indices n_e and n_o take the form

$$n_o^2 = f\, n_l^2 + (1 - f)n_s^2\,, \tag{1.a}$$

$$\frac{1}{n_e^2} = \frac{f}{n_l^2} + \frac{1-f}{n_s^2}\,, \tag{1.b}$$

where f is the fill factor of the grating w/Λ, and n_l and n_s are the refractive indices of the lines and spaces respectively. It is Rytov [2] who took further the analysis of gratings in terms of crystalline anisotropy developing a theory that will come to be known as the Effective Medium Theory (EMT). In Rytov's analysis the condition $\lambda >> \Lambda$ is still required but is less restrictive. He obtained the following relations for the effective refractive indices:

$$\begin{aligned}&\sqrt{n_l^2-n_o^2}\tan\left(\pi f\frac{\Lambda}{\lambda}\sqrt{n_l^2-n_o^2}\right)+\\&+\sqrt{n_s^2-n_o^2}\tan\left(\pi(1-f)\frac{\Lambda}{\lambda}\sqrt{n_s^2-n_o^2}\right)=0\end{aligned}\quad, \quad (2.a)$$

$$\begin{aligned}&\frac{\sqrt{n_l^2-n_e^2}}{n_l^2}\tan\left(\pi f\frac{\Lambda}{\lambda}\sqrt{n_l^2-n_e^2}\right)+\\&+\frac{\sqrt{n_s^2-n_e^2}}{n_s^2}\tan\left(\pi(1-f)\frac{\Lambda}{\lambda}\sqrt{n_s^2-n_e^2}\right)=0\end{aligned}\quad . \quad (2.b)$$

One may notice that when $\Lambda/\lambda \to 0$, Eqs. (2) tend to Eqs. (1), i.e. to their zeroth order approximation. The higher orders of the approximation are powers of Λ/λ.

The researchers continued to improve EMT and to look for alternative approaches [3-5], and some even studied specifically the case of wiregrid polarizers for the infrared [6,7], which is also the goal of this paper. However all the EMT versions remain approximate theories, and their predictions for the reflectance and transmittance of a grating, wiregrid or other type, are not rigorous. They only have the advantage of pointing out the polarization selection property of wiregrids and to bring physical insight into the matter. Exact calculations can be made with a rigorous diffraction theory such as Rigorous Coupled-Wave Analysis (RCWA) [8-10]. It is RCWA that will be used through the rest of this paper for the numerical calculations.

We will use this physical insight brought by EMT to prove in a semi-intuitive manner the polarization property of the wiregrids starting with Eqs. (1). If the fill factor f is about 50%, then one can see that the square of the ordinary refractive index is the average of the squares of the refractive indices of the lines and spaces of the grating respectively. In Eq. (1.a) the refractive index of the metal n_l is then the dominant term. Therefore n_o has a metallic character, which means the wiregrid will strongly reflect the incident light polarized parallel to the lines. On the other hand in Eq. (1.b) for the extraordinary refractive index it is the square of the refractive index of the metal that is negligible because its absolute value is high and in the equation appears as a denominator. The term f/n_l^2 is negligible and this time the term $(1-f)/n_s^2$ has the major contribution to the value of the n_e. Therefore incident light perpendicular to the wires "sees" the wiregrid as a dielectric with a small refractive index and the transmission is high. Therefore generally we have a minimum output for the polarization parallel to the wires and a maximum output for the polarization perpendicular to the wires. If we assume n_s=1 and $|n_l|>>1$, then from Eqs. (1) we obtain

$$n_o \approx n_l / 2^{1/2}\,, \quad (3.a)$$

$$n_e \approx 2^{1/2}\,. \quad (3.a)$$

One may notice that for the grating to polarize the light one does not need lines with a large imaginary part of the refractive index, it is enough if the absolute value of the refractive index as a whole is large. This means that if the lines would be made out of a dielectric with a very high refractive index the grating would still act as a polarizer. But in practice we don't have such materials at our disposal. The only materials with the refractive index large as a whole are the metals, and the refractive index of the metals has a larger imaginary than real part, especially at 10.6 μm wavelength, which is the main emission line of the CO_2 lasers. Also, one should not forget that the analysis above is approximate and only a rigorous theory can establish with certainty whether the large imaginary part is necessary or not for the polarizing effect. Unfortunately the rigorous theories do not provide simple and intuitive, easy to interpret formulae as EMT does. Anyway, among the gratings only the wiregrids were proven experimentally to act as polarizers.

3. OPTIMIZATION OF THE WIREGRID POLARIZERS

In this section we present the results of some simulations of the optical behavior of wiregrids at the CO_2 laser wavelength for a number of metals and for various combinations of the possible values of the geometric parameters of the grating, such as the width of the lines w, the pitch Λ, the grating thickness z_g and the thickness z_1 of the homogeneous, isotropic silicon substrate on which the grating is laid, and values of the experimental configuration parameters such as the azimuth ϕ and the incidence angle θ. The refractive indices of the metals and the silicon substrate used for simulations are shown in Table 1. The values of the geometric parameters are those allowed by the lithographic device we analyze; they vary within the prescribed limits with the prescribed increments shown in Table 2.

The values for chrome and aluminum were interpolated and extrapolated respectively. The absorption coefficient of silicon may seem small, but even 1 mm thickness causes an absorption of 14%, which may not be acceptable from a practical point of view because of the damage the heat may cause to the polarizer.

Table 1. Refractive indices of the materials used in the simulations at the wavelength of the CO_2 laser (10.6 μm). ν and κ are the real and imaginary parts of the refractive index respectively.

Metal	ν	κ	Reference
Cu	15.1	44.7	[11]
Cr	13.8	28.1	[12]
Al	27.6	94.0	[13]
Ag	14.8	56.0	[14]
Si	3.4215	1.27×10^{-4}	[15]

In order to optimize the performance of the polarizers, the reflectances and the transmittances for the polarizers with the parameters from Table 2 were calculated. The value of the pitch was chosen 6 μm because a smaller one could not be made and a larger one can cause problems with the apparition of the non-specular diffraction orders and the fact that the approximation $\Lambda \ll \lambda$ does not hold anymore, and all the considerations that lead us to the conclusion that wiregrids are polarization-selective are not valid anymore. The values of the experimental configurations in which the polarizers are supposed to be used, the azimuth and the incidence angle, were chosen also according to practical reasons, and these values are shown also in Table 2. A configuration with normal incidence is preferable because it minimizes the space occupied by the polarizer, but it is not possible for reflection polarizers. For the latter the best value for θ is 45°, because it creates a symmetric configuration.

Table 2. The range of the wiregrid and experimental configuration parameters respectively used in the simulations.

parameters	w μm	z_g μm	z_l mm	Λ μm	ϕ °	θ °
initial value	3	2	1	6	0	0
increment	–	2	1	–	90	45
final value	3	6	5	6	90	45

The criteria for selecting the optimum polarizer are the following:

- large extinction coefficient (large ratio of the maximum output over the minimum output);
- large maximum output, as close to 1 as possible;
- preferably normal incidence for the transmission polarizers.

The parameters of the optimum polarizers and experimental configuration in which they should be used are listed in Table 3.

Table 3. Optimum polarizer parameters. Because w is 3μm and Λ is 6 μm all the time, these parameters were omitted.

No.	Geometrical parameters		Parameters of the experimental configuration		metal	extinction coefficient	maximum output	
	z_g (μm)	z_l (mm)	ϕ (°)	θ (°)			value	type
1	6	1	0	45	Cr	1.95×10^4	0.521	T_p
2	6	1	0	0	Cr	6.25×10^4	0.345	T_p
3	6	1	0	45	Cr	530	0.943	R_s
4	6	1	0	45	Cr	1.48×10^5	0.489	T_p
5	6	1	0	0	Cr	5.11×10^5	0.332	T_p
6	6	1	0	45	Al	2.24×10^5	0.524	T_p
7	6	1	0	0	Al	7.03×10^4	0.346	T_p
8	6	1	0	45	Ag	1.95×10^5	0.525	T_p
9	6	1	0	0	Ag	6.22×10^4	0.347	T_p

One may notice in Table 3 that only one reflection polarizer was included among the optimum polarizers. Indeed, the extinction coefficient of the reflection polarizers does not surpass 530 for all the studied cases, and this is quite small for a quality polarizer. Hence they are not acceptable even if some have large output, almost 1. As expected the optimum value for the thickness of the wiregrid is the maximum one, because even a metallic film, if it is too thin, may be transparent for the light, and does not absorb or reflects a significant amount; i.e. there is no more polarization effect. Again as expected the optimum thickness for the silicon layer is the minimum one, because the absorption of the silicon decreases the value of the maximum output.

Among the 7 polarizers listed in Table 3, probably the best are those labeled 2, 5 and 7, because they have large extinction coefficients, an acceptable maximum output and they are transmission polarizers for normal incidence. Extending the range of investigation of the optimum parameters may reveal polarizers with even better performances.

4. CONCLUSIONS

The Effective Medium Theory gives physical insight in the optical behavior of wiregrids and predicts they can act as polarizers. Rigorous diffraction calculations prove this to be correct and also can be used to optimize the parameters of the polarizers. The simulations made for parameters achievable by lithographic device at our disposal show that wiregrids can be excellent polarizers for CO_2 lasers.

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