Optical testing of fine grating structures

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ABSTRACT

The ability to measure the relief parameters and the absolute position accuracy of micrometer-sized structures is of obvious importance, not only to determine if the desired structure has been realized, but also to optimize the fabrication process. In this paper a simple characterization method is presented allowing fast and non-destructive testing of phase and amplitude gratings over large areas. Local line width and position errors can be detected. The theoretical modeling is based on rigorous diffraction theory.

Keywords: Optical testing, grating structures, rigorous diffraction theory.

1. INTRODUCTION

Advancement in the areas of phase shift optical lithography, e-beam lithography, and x-ray lithography have enabled the realization of very fine relief structures in the nanometer-micrometer range. The characterization of such structures is of obvious importance. The wish list for metrology includes non-destructive testing, testing of large areas, and testing of large aspect ratio structures having sub-μm lateral dimensions. Current techniques for measurement are optical microscopy,[1] scanning electron microscopy[2] (SEM), and scanning force microscopy.[3] None of these techniques, however, is capable of providing rapid accurate sub-μm measurements over larger areas. Recently, optical testing methods have been applied to address these requirements. The relevant parameters of a lithographic process, i. e. the depth and width of a grating like test structure, can be determined by scattering an incident laser beam at the structures and measuring the far-field intensity distribution.[4] The main drawback is that these techniques only determine the average parameters, and are unable to determine local errors such as single line defects.

Therefore, we investigated the scanning spot metrology (SSM) which provides accurate information about surface-relief grating structures.[5] The method involves illuminating the structure with a small spot size focused laser beam and evaluating the diffraction pattern as the structure is scanned. The method has been applied to amplitude gratings, realized typically by opaque and transparent line structures on chrome masks. The total transmitted power gives information about the edge locations of the lines.[5] In this paper, we apply the SSM to the analysis of binary phase gratings. In additions, we have applied rigorous diffraction theory to describe exactly the interaction of light with these structures.

In the following, we introduce the basic principle of the scanning spot metrology (section 2.). In section 3. we explain the rigorous diffraction model used to simulate the diffraction pattern and its application for measuring fine phase grating structures. Finally in section 4., we apply the rigorous analysis to amplitude gratings and compare the results to those presented in a previous paper.[5]

2. SCANNING SPOT METROLOGY: BASIC PRINCIPLE

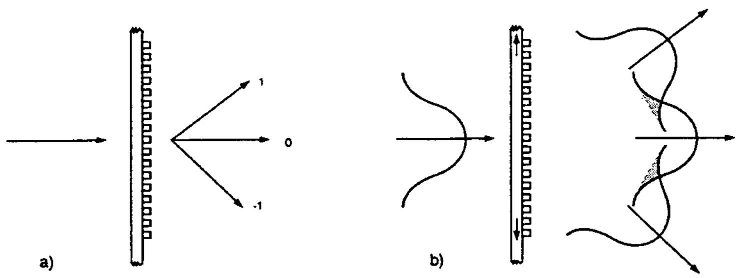

Figure 1: a) Fine grating structures show only few diffraction orders. b) Scanning spot principle: A binary test grating is illuminated by a focused beam. Scanning the mask introduces a phase shift of the higher diffraction orders. The resulting interference pattern between the diffraction orders may be measured and used for finding the edges location of the binary grating structure.

Fine grating structures illuminated with an infinite plane wave have only few propagating diffraction orders [Fig. 1 a)]. Measuring the diffraction efficiency and the phase of each diffraction order doesn't allow to reconstruct the original relief. Furthermore, it is not possible to extract local information. On the other hand, if the grating is illuminated with a focused laser beam each diffraction order generates a diffraction pattern. If the beam size is small, i.e. has a large angular spectrum, the diffraction pattern of the diffracted orders overlap and interfere.

Scanning the mask introduces a (linear) phase change of the higher diffraction orders. The resulting modulation depends on the ratio between the grating period and the focus spot size. This modulation may be used to extract the edge locations. If the period is small compared to the beam size, the orders are not overlaying anymore and the interference vanishes. Therefore, this method is limited (as all far-field method) to characterize gratings which have a period larger than half of the illumination wavelength. Finer gratings generate only the zero diffraction order.

The next section presents the interaction between light and fine grating structures. The principle discussed above justifies the rigorous diffraction computations.

3. RIGOROUS APPROACH

Formally, the diffraction problem of grating structures may be expressed as following: given a specific periodic permittivity distribution $\epsilon(x) = \epsilon(x - \Lambda)$ (see Fig. 2), the electric field in the input and the output regions may be written in terms of plane waves

$$E_1(\vec{x}) = u_0 e^{-i\vec{k}_1\vec{x}} + \sum_m r_m e^{-i\vec{k}_{1m}\vec{x}} \quad , \tag{1}$$

$$E_3(\vec{x}) = \sum_m t_m e^{-i\vec{k}_{3m}\vec{x}} \quad , \tag{2}$$

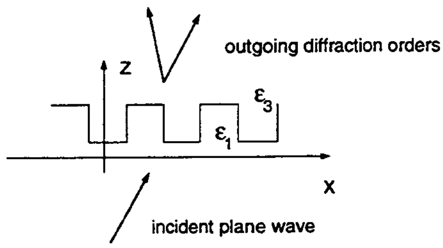

Figure 2: Periodic surface relief grating.

where u_0 is the amplitude of the incident plane wave propagating in the direction of k_1. The directions of the plane waves $\vec{k}_{1m}$ and $\vec{k}_{3m}$ are given by the Floquet condition. The unknown quantities of Eqs. (1) and (2) are the amplitudes r_m and t_m of the plane waves . The permittivity $\epsilon(x)$ is real and positive for dielectrics, and complex for metallic structures. Since the size of the structures is in the order of the illumination wavelength, the light interaction has to be modeled rigorously. Different rigorous diffraction theories for gratings are reported in literature.[6–10] One of the most popular is the rigorous coupled wave approach (RCWA) by Moharam and Gaylord.[9,10] In this approach the field inside the modulated region is expanded in terms of space harmonics. The amplitude of the transmitted and reflected waves (r_m and t_m) are found by matching the electromagnetic boundary conditions at the interfaces. In the classical RCWA the infinite grating structure is illuminated with an (infinite) plane wave ($u_0 e^{-i\vec{k}_1\vec{x}}$). For finite illumination, as used in the scanning spot metroloy, the incident field E_0 has to be decomposited in his plane wave spectra:

$$E_0(\vec{x}) = \int_{-\infty}^{\infty} u(k_{0x}) \exp[-i(k_{0x}x + k_{0z}z)] \quad dk_{0x} \qquad , \tag{3}$$

For numerical computation the integral is replaced by a sum

$$E_0 = \sum_l E_{0l}(\vec{x}) = \sum_l u_{0l} e^{-i\vec{k}_{0x}\vec{x}} \qquad \text{with} \qquad u_{0l} = \int_{-\infty}^{\infty} u(k_{0x})\delta(k_{0x} - lK_{0x}) \quad dk_{0x} \qquad . \tag{4}$$

For each plane wave E_{0l} of the incident beam the coupled wave equations are solved.

Scanning the structure while illuminating it with a finite beam may also be expressed as moving the illumination beam on a fixed structure. A shift of x_0 of the incident field adds a linear phase in the spectrum of the field

$$E_{0l}(\vec{x} - \hat{x}x_0) = E_{0l}(\vec{x}) \exp[-ilK_{0x}x_0] \qquad , \tag{5}$$

where $\hat{x}$ is a unit vector in x-direction. Thus, the scanning effect can be introduced after solving the coupled wave equation while superposing the individual plane waves. Figure 3 shows the diffraction pattern generated by a focused Gaussian beam (TE-polarization) with beam waist $2w = \lambda/1.5$ on a dielectric (phase-) grating structure with grating period $\Lambda = \lambda$ and a grating depth $d = \lambda$. The permittivity of the modulation is $\epsilon_3 = 2.25$, resp. $\epsilon_1 = 1$. The diffraction pattern shown in Fig. 3 c) is generated if the incident beam position coincides with the middle of a groove as shown in 3 a), pattern 3 d) if the beam is shifted by $0.1 * \Lambda$ as shown in Fig. 3 b).

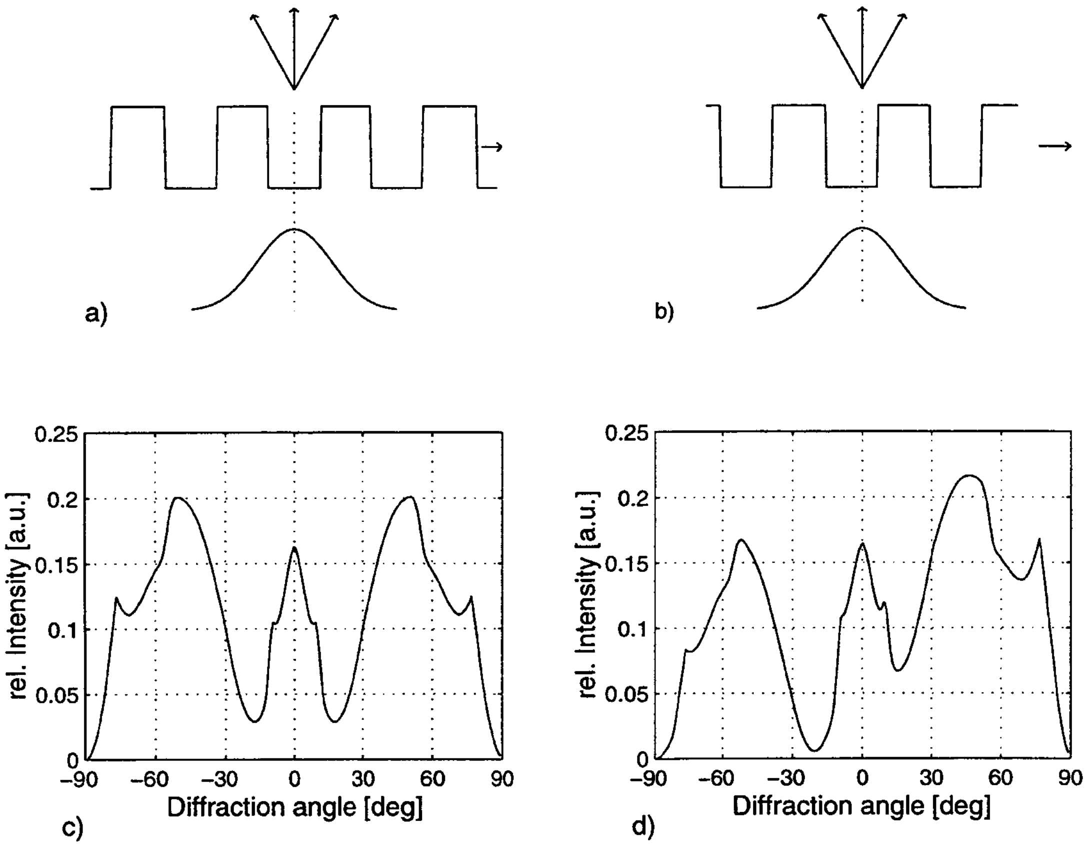

Figure 3: Diffraction pattern generated by a grating illuminated with a focused beam. The pattern c) and d) correspond to the situation a) and b), respectively. The grating period is $\Lambda = \lambda$, the structure height is $d = \lambda$, the permittivities are $\epsilon_1 = 1$ and $\epsilon_3 = 2.25$.

Note that the diffraction pattern mainly changes in an angular range between 10 and 70 degrees. This is due to the phase changes in the higher diffraction orders introduced by scanning the structure, whereas the amplitude and phase of the zero diffraction order doesn't change. The decomposition of the diffraction patterns into the individual contributions of each diffraction order, shown in Fig. 4, illustrates well this behavior: the phases of the 1 and -1 order in Fig. 4 d) are shifted compared to the case shown in Fig. 4 c).

The grating parameters could now be extracted by numerical analysis of the diffraction pattern. The experimental set-up would include a scanning device for the image detection system. Another possibility is to locate a detector at a diffraction angle showing high modulation (28^o in the example shown in Fig. 3. In order to keep the scanning spot method simple, we propose here a third method : the diffraction pattern is integrated between -90 and 0 degrees with the help of an integrating sphere.

Figure 5 shows the resulting modulation of the integrated power as the structure is moved. The modulation depth is given by the ratio $r = 2w/\Lambda$ between the grating period Λ and the beam waist w. The contrast modulation versus r is presented in Fig. 6 . The edge locations may be obtained similar to the algorithm presented in Ref. 5. It has been shown that it is possible to determine the edge positions based on the modulation function with an accuracy of 10-30 nm typically. The contrast function indicates well the application range of the scanning spot metrology. If the grating period is much smaller than the illumination beam diameter, the structure may not be resolved. Note that the contrast function may be calculated in advanced in order to reduce the computational

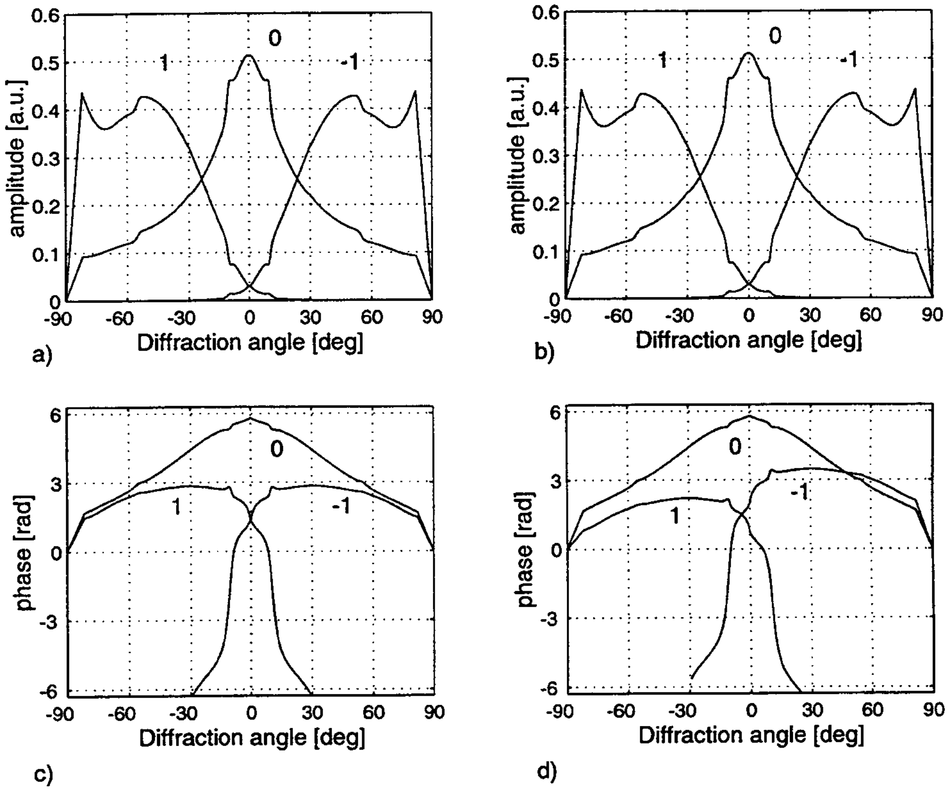

Figure 4: Amplitude and phase of the $1, 0, -1$ diffraction order generated by a grating illuminated with a focused beam. The amplitude a) and phase c) correspond to the situation illustrated in Fig. 3 a), Figure b) and d) to the situation shown in Fig. 3 b). Note that a shift of the mask changes the phase of the 1 and -1 diffraction order.

effort of real time signal processing.

4. AMPLITUDE GRATINGS

In section 3., we discussed a grating characterization method based on rigorous diffraction theory for general dielectric and metallic structures. We consider now the case of amplitude gratings realized typically by opaque and transparent line structures on chrome masks. The modulation function of an amplitude grating doesn't depend on the structure depth. Indeed, if the total transmitted power is measured the diffraction pattern is given as in the case of the knife edge methods in terms of an integrated Gaussian intensity. Figure 7 shows the contrast function obtained by rigorous diffraction theory applied to an amplitude grating structure compared with the contrast function obtain by the inverse knife edge method presented in paper 5. The grating was realized by a 200nm thick chrome mask having opaque and transparent lines. The good agreement of the approximative theory in respect to the rigorous method justifies the simplified model developed.

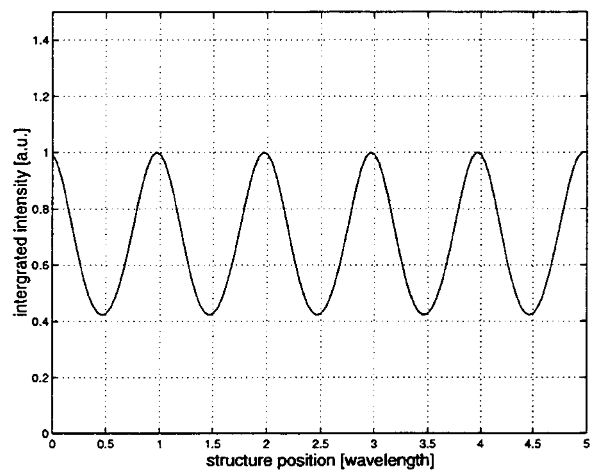

Figure 5: Transmitted power obtained by scanning a phase grating structure using a focused beam. The intensity is integrated between -90 and 0 degree.

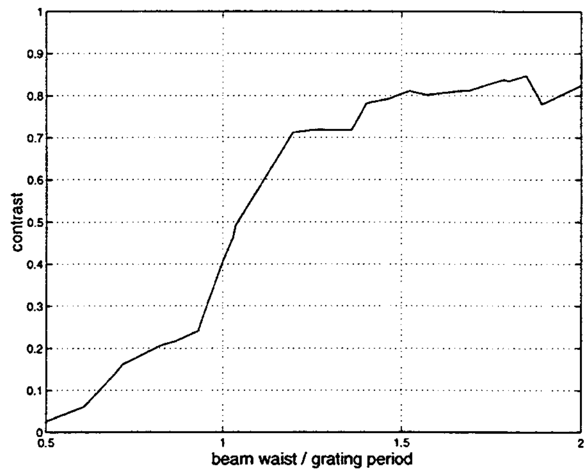

Figure 6: Contrast of the modulation of the transmitted power for a phase grating structure scanned with a focused Gaussian beam

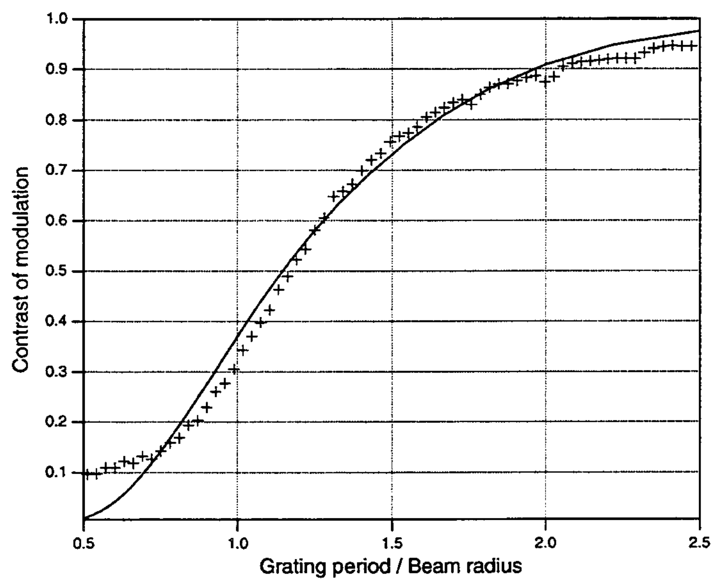

Figure 7: Contrast of the modulation of the transmitted power for a amplitude grating structure scanned with a focused gaussien beam. The cross markers correspond to the rigorous approach while the line is obtain by the gaussien beam integration.

5. CONCLUSION

We have developed a simple method allowing the characterization of amplitude and phase gratings. The method involves scanning a grating element through a focused laser beam and analyzing the resulting diffraction pattern. In the case of amplitude gratings the analysis can be done by simply integrating the total transmitted power. This approach leads to the method presented in Ref. 5 which is based on the knife edge metrology. For phase gratings we use the effect that the diffraction pattern changes asymmetrically. Integrating the transmitted power between 0 and 90^o results in a modulated signal which can be used to extract the edge locations . The theoretical considerations in this paper are based on rigorous diffraction theory.

6. REFERENCES

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