Off-plane grazing-incidence fan-groove blazed grating to serve as a high-efficiency spectral purity filter for EUV lithography

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ABSTRACT

Reflecting large-blaze-angle diffraction gratings operating in the off-plane grazing configuration can be used to advantage as high-efficiency tools permitting separation and focusing of a 2%-wavelength about 13.5-nm. A cooled multiple grating with fan-groove geometry is used as a model to select the desired spectral range and obtain a record-high efficiency and stigmatic image focusing for a high dispersion in adjacent orders. A maximal relative efficiency of 0.96–0.99 and reflectances of 0.71–0.96 can be readily obtained with an off-plane fine-pitch grating intercepting at incidence angles of 70–85° a converging unpolarized light beam from an EUV collector, a figure higher than that of a grating in an in-plane mount. An absolute efficiency of ~0.72, calculated with a PCGrate®-SX™ code using the AFM-measured groove profile, is reached in the -1st order of a Mo-coated 200-nm-pitch Si test grating in unpolarized light.

Keywords: EUV lithography, spectral purity filter, fan-groove blazed grating, off-plane grazing configuration, diffraction efficiency, PCGrate modeling

1. INTRODUCTION

Proper separation of the broadband emission spectrum produced by laser and plasma discharge sources of extreme ultraviolet (EUV) and soft x-ray radiation [1] calls for use of special filters. Spectral instruments and multilayer imaging optics operating in the soft-x-ray–EUV ranges employ thin-film absorption filters of various designs (both free-standing and grid mounted) and film materials (Zr, Zr/Si, Zr/B_4C, Mo/Si etc.) [2, 3]. The films should sustain long-term thermal loads and pressure drops when illuminated at high time-averaged power levels (~W/cm^2). The transmittance of such filters at the wavelength λ=13.5 nm may be as high as 0.8 or even higher, but their application potential is limited by the requirement of a high enough radiation and mechanical strength. The spectral purity of the radiation delivered by the lighting and projection optics of EUV lithographic equipment may also be improved by using an optimized Mo/Si multilayer coating which permits considerable attenuation of unwanted radiation in the soft x-ray and EUV regions for an acceptable decrease of reflectance in the vicinity of the operating wavelength [4, 5]. This approach offers only a complementary way to solving the complex metrological problem of filtration of high-power radiation over a broad range extending from soft x-ray to infrared wavelengths.

Projection EUV lithography provides a possibility of designing a spectral purity filter which is essentially a multiple blazed diffraction grating operating in reflection in the in-plane (“classical”) grazing-incidence mounting [6]. Such a variable-pitch grating patterned on a high thermal-conductivity substrate can efficiently disperse and focus into the -1st diffraction order the intense converging broadband radiation produced by an EUV collector. While the relative efficiency of a blazed grazing-incidence grating may be as high as 0.8 at λ=13.5 in the dispersion plane, in practice the absolute efficiency does not reach 0.6 at the maximum. This should be assigned to the real groove profile of a low-frequency grating and the small blaze-angle employed in the in-plane diffraction mounting. Application of a high-frequency reflecting diffraction grating with a comparatively large blaze angle operating in the off-plane (“conical”) grazing-incidence configuration is a more efficient and comparatively simple approach permitting one to isolate a 2% wavelength band about 13.5 nm.

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2. DESIGN AND TECHNOLOGY OF FABRICATION OF OFF-PLANE GRATINGS

To isolate the desired spectral range and reach a record-high efficiency and stigmatic image focusing at a high dispersion of adjacent orders we chose the model of a plane high-frequency grating with fan-groove geometry. The selection of the conical as opposed to classical configuration is governed to a considerable extent by the ease of design and available techniques of fabrication and replication of optimized gratings with high diffraction efficiency. Besides having other assets, the proposed solution is ready for implementation based on the latest progress in shaping, patterning, and replication of sawtooth-groove gratings (Fig. 1), which were developed for the Reflection Grating Spectrometer (RGS) of the Constellation-X mission [7]. These techniques include anisotropic etching of graze-cut Si wafers to produce close-to-ideally smooth groove facets (rms microroughness ≤0.2 nm), scanning-beam interference lithography to fabricate large (≤300 mm in diameter) fine-pitch (≥100 nm) gratings, and nanoimprint lithography for grating replication with a high reproducibility at a low cost. Rather than claiming this to be the only technology appropriate for the goal, the author believes it to be preferable for fabrication of such gratings. The Si grating intended for removal of the heat generated by high-intensity radiation can be actively cooled either by water or cryogenically with liquid nitrogen [8].

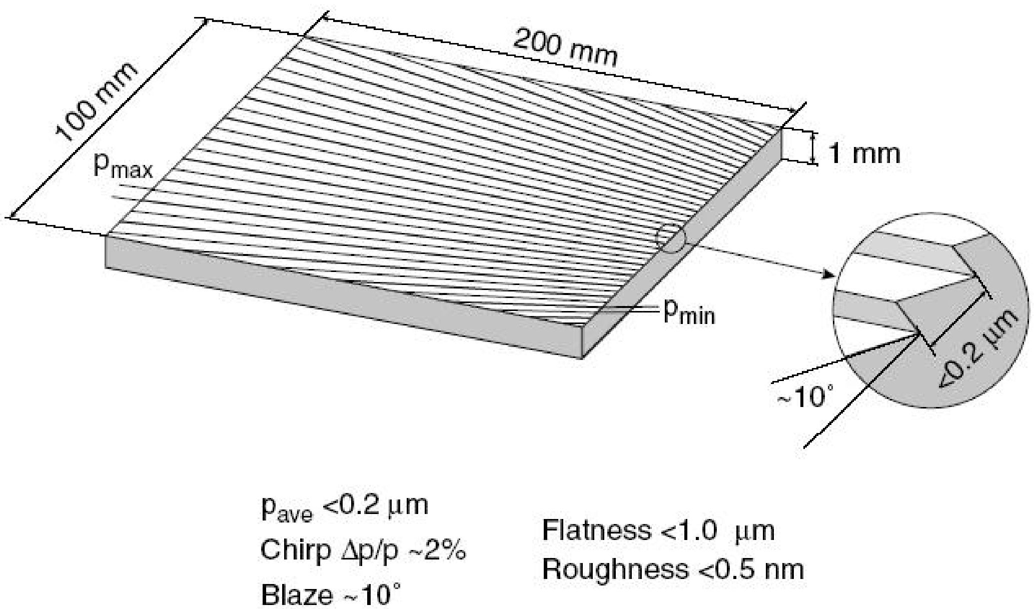

Fig.1. Grating groove geometry for off-plane reflection and focusing of grazing-incidence soft-x-ray–EUV radiation.

The plane grating under consideration is intended for operation in the broad converging EUV collector beam, which gives rise to a large difference between the grazing incidence angles at its opposite sides. In a grating with straight grooves, this gives rise to diffraction-order aberrations, which can be readily compensated by properly varying the grating pitch as a function of distance along the optical axis [9]. In an off-plane mount, this variation in pitch calls for fabrication of grooves featuring a fan geometry with a variable pitch p along distance r from the point of ray incidence on a grating to the projection of zero-order focus onto the grating plane, thus canceling first-order aberrations

$$p(r, 0) = rw_0, \tag{1}$$

where w_0 is the groove fanning angle.

Aberrations of the second and higher orders can be practically canceled for the given correction wavelength by fabrication of a fan-shaped grating with variable groove angular separation [10]

$$p(r, w) = p(r, 0)(1 + 0.5w^2), \tag{2}$$

where w is the angle in the grating plane.

Novel technologies of diffraction grating fabrication, including the one discussed above, provide for fabrication of variable-pitch, radial-groove gratings.

The integral absolute efficiency of a blazed grating operating in a broad converging beam is substantially lower than the maximum value, but this can be compensated for by employing several gratings arranged in fan geometry relative to the incoming converging beam [10]. To simplify the design and reduce light losses, the number of such grating segments should be chosen as small as possible. The segmented geometry should be such as (1) to ensure the required focusing from all gratings while (2) not changing the total collector optical path length [6]. Minimization of the aberrations of a segmented grating operating in the desired EUV collector configuration, just as obtaining a focal spot of required geometry, call for a comprehensive ray tracing modeling [11].

3. EFFICIENCY OF AN OFF-PLANE GRATING WITH IDEAL GROOVE PROFILE

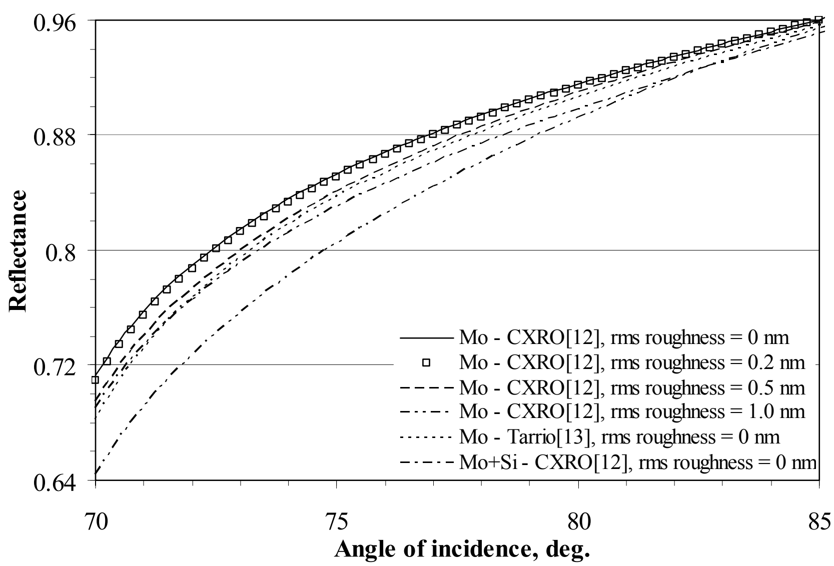

Fig. 2. Reflectance of Mo and Mo + Si (2 nm) mirrors for different rms boundary microroughnesses and Mo refractive index values calculated vs angle of incidence of unpolarized light with a wavelength of 13.5 nm.

Calculations based on available refractive index data [12, 13] suggest Mo as the best candidate for coating the grating under study operating at λ=13.5 nm within an incidence angle interval from 70 to 85^{o}. Molybdenum coatings being prone to oxidation, they should be protected, for instance, by deposition of a thin Si film [14]. Figure 2 plots reflectance curves vs the angle of incidence of unpolarized radiation for a variety of mirror materials, refractive indices, and rms microroughness of the interfaces. Examination of the curves reveals that the reflectance of molybdenum coatings with perfect boundaries and a refractive index taken from [12] can reach as high as 0.71–0.96 within the chosen range of the angles of incidence. Boundary rms microroughness of 0.2 nm practically does not affect reflectance within the angle of incidence range covered. An rms microroughness of 0.5 nm or the use of Mo refractive index from [13] in calculations brings about a decrease of reflectance at moderate angles of incidence by a few percent, the same figure being obtained for the case of a 2-nm-thick protective Si layer. For a 1-nm rms microroughness, this difference is larger by a few times. The Debye-Waller factor was used to account for the boundary microroughness.

The PCGrate®-SX™ program developed by Goray *et al.* [15] and based on the rigorous modified boundary integral method (MIM) was used to model gratings with grooves of different shapes intended to operate under grazing-incidence and conical diffraction conditions in the soft x-ray range in the RGS [16]. The results of the investigation [16] demonstrated a high accuracy and speed of the program used in the modeling, as well as a strong dependence of efficiency on the groove profile shape and working grating mounting. Other publications dealing with the design and investigation of the off-plane RGS gratings reported on efficiency measurements performed in both laboratory conditions [7, 17, 18] and on synchrotron sources of polarized soft x-ray radiation [11], and validated the need of employing exact numerical methods for the efficiency optimization.

The present communication presents optimization calculations performed with the PCGrate-SX code and aimed at reaching the maximal relative and absolute efficiencies of off-plane blazed gratings operating at grazing-incidence angles at λ=13.5 nm. The blaze condition for an off-plane grazing-incidence grating can be written as [19]

$$\lambda = 2p \sin\theta \cos\varphi, \tag{3}$$

where θ is the angle of incidence in the dispersion plane reckoned from the normal to the grating plane, which is equal to the blaze angle of the working facet, and φ is the off-plane angle of incidence along the grooves measured relative to the dispersion plane (Fig. 3). Equation (3) defines the relation coupling the line space of a grating with its blaze angle; we readily see that the smaller the line space, the larger should be the blaze angle for a given incidence angle along the grating grooves.

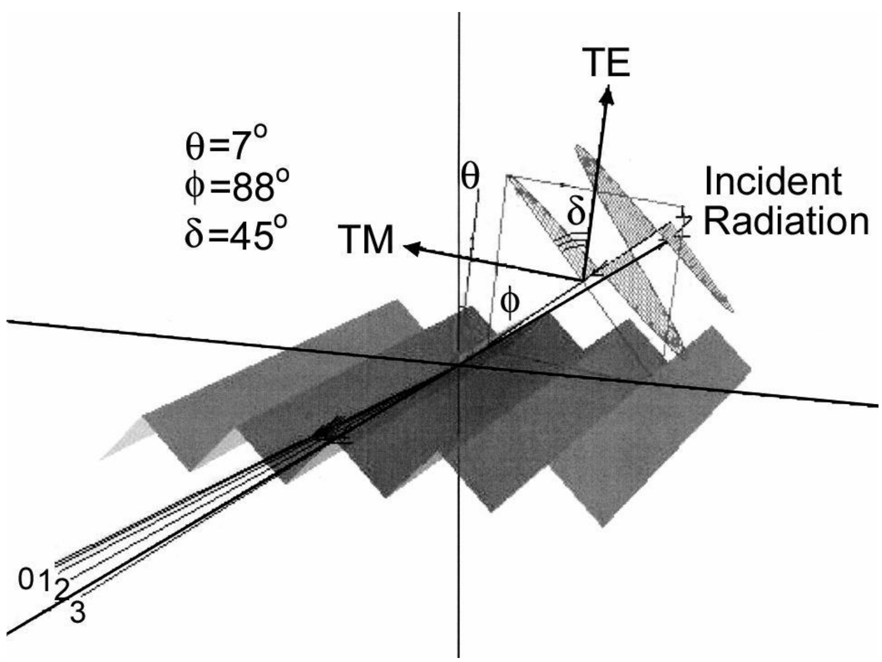

Fig. 3. Schematic of the off-plane grazing-incidence grating and the conical diffraction pattern.

Figure 4 displays curves of the relative (grating) efficiency plotted vs the blaze angle of ideally conducting gratings which were obtained for an off-plane angle φ=75° and three frequencies: 3600, 5000, and 6000 groove/mm (gr/mm). The blaze (in-plane) angle of the 3600-gr/mm grating defined by Eq. (3) is 5.4°, which is exactly the position of the 100%-maximum in efficiency for TM polarized radiation in Fig. 4. An efficiency maximum in excess of 0.96 is reached for unpolarized radiation near the blaze angle of 5.5°. As the grating frequency increases, the blaze angle corresponding to the maximum efficiency for unpolarized radiation deviates ever more from the value predicted by Eq. (3) because of the maximum for TE polarized light shifting toward larger blaze angles. The amplitude of the maximum for unpolarized light decreases slightly with increasing frequency to become ~0.94 for the 6000-gr/mm grating.

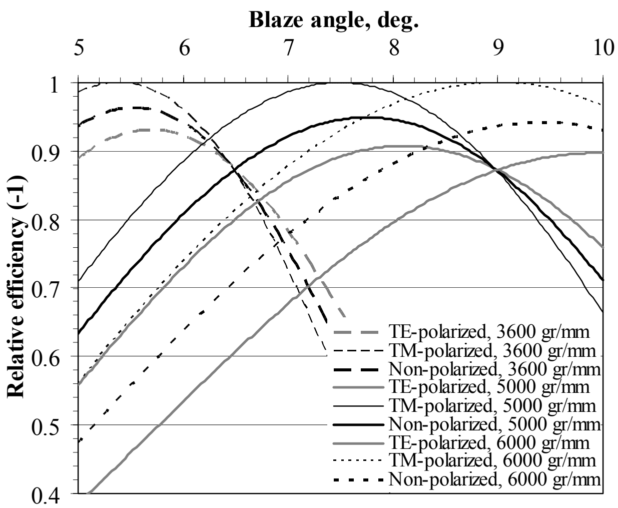

Fig. 4. Relative efficiency in the -1st order of blazed gratings of different frequencies calculated vs blaze (in-plane) angle for polarized 13.5-nm radiation incident at an off-plane angle of 75°.

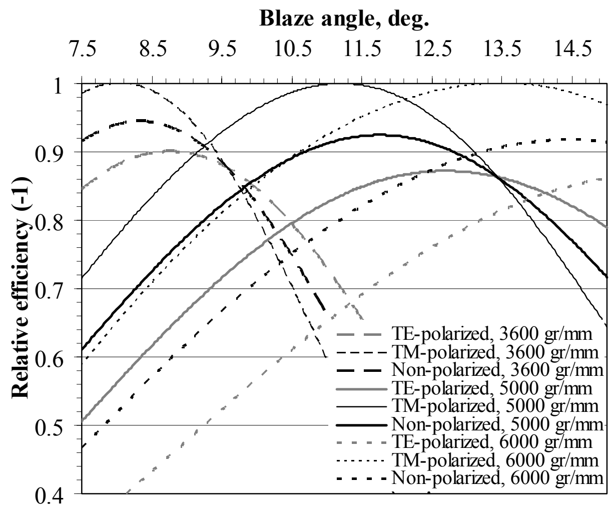

Fig. 5. Relative efficiency in the -1st order of blazed gratings of different frequencies calculated vs blaze (in-plane) angle for polarized 13.5-nm radiation incident at an off-plane angle of 80°.

Figure 5 plots the dependence of relative efficiency on blaze angle for gratings with the same frequencies as in the preceding illustration but for an off-plane angle $\varphi=80^o$. The blaze angle grows with increasing off-plane angle of incidence as predicted by Eq. (3). The efficiency curves calculated for different polarizations behave exactly as they did for $\varphi=75^o$. As the blaze angle grows, the maximum in the efficiency of unpolarized radiation continues to shift in position relative to that for TM polarization toward larger blaze angles, and its amplitude falls off slowly. Significantly, despite the correct prediction by Eq. (3) of the position and amplitude of the maxima in relative efficiency for the TM polarization, exact efficiency calculation of a grazing-incidence grating with blaze angle >5° should be based on rigorous vector theories such as the MIM [16].

Figure 6 presents relative and absolute efficiencies of an off-plane, Mo-coated 5000-gr/mm grating with a blaze angle of 7.5° illuminated by 13.5-nm polarized light in the azimuthal angle interval from 70 to 79°. We readily see that the maximum in relative efficiency of >0.95 for unpolarized light corresponds approximately to an azimuthal angle of 74.3°, and that in absolute efficiency of ~0.81, to an angle of 75.1°. The relative efficiency curve for unpolarized light does not fall below 0.8 within an azimuthal angle interval of ±3° from the position of its maximum. A similar cutoff for the absolute efficiency is 0.7. Beyond this angular interval of ±3°, the efficiency curves exhibit a significant decrease. Thus, within the azimuthal angle-of-incidence interval of ~6° the efficiency may be considered not to fall noticeably from the maximum achievable level.

The effect caused by variation of the angle of incidence along the grating grooves can be quantified by calculating the integral efficiency of one grating operating in a converging beam. For an angular collector beam width of 6°, the integral relative and absolute efficiencies are less than the efficiency at maximum by only ~4%. For a beam width of 12°, the integral relative efficiency is less than the amplitude value by 15%, and the absolute efficiency, by 16%, an appreciable figure for a spectral purity filter. Therefore, for a beam 12° wide one should use two grating segments, and for a 18° width, two or three of them.

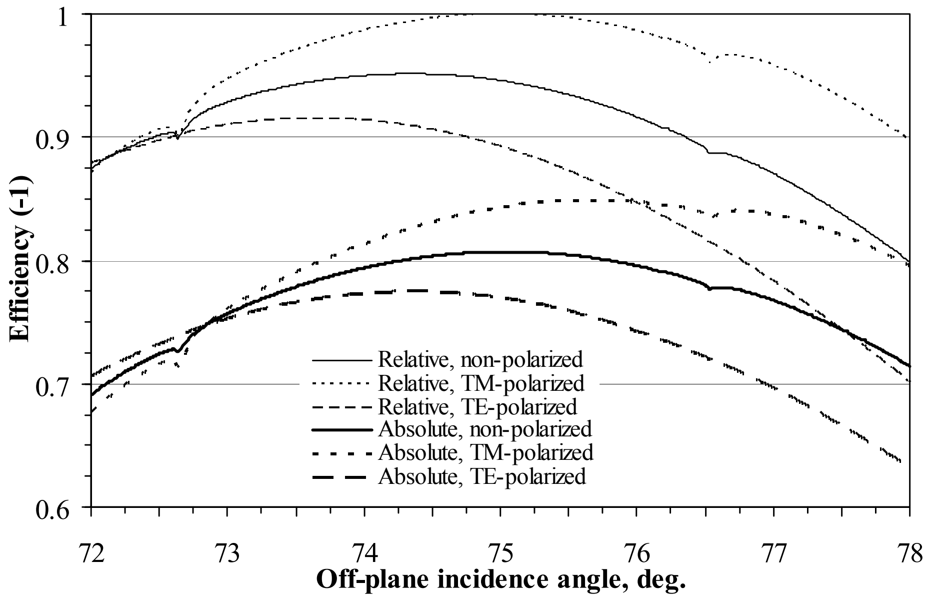

Fig. 6. Relative and absolute efficiencies in the -1st order of a 5000 gr/mm Mo grating with a blaze angle of 7.5^{o} calculated vs off-plane angle for polarized 13.5-nm radiation incident at an in-plane angle of 7.5^{o}.

4. EFFICIENCY OF AN OFF-PLANE GRATING WITH REAL GROOVE PROFILE

The efficiency of a grazing-incidence grating fabricated by the above technique for the RGS on the Constellation-X mission has been recently tested experimentally [20]. The off-plane TE and TM efficiency components for a test grating with 200-nm line space and a nominal blaze angle of 7.5^{o} fabricated on a dia. 200-mm Si wafer were measured with polarized synchrotron radiation and compared with calculations made by the PCGrate-SX program. The record-high absolute efficiency of ~0.45 in the -1st order was observed at the wavelength of ~2.5 nm of TE polarized radiation striking the Au-imprinted grating.

The calculated and measured efficiencies are in quantitative accord when one uses an averaged groove profile derived from AFM measurements. Figure 7(a) plots AFM scans made across the grooves, with each scan offset vertically for the sake of conveniency by 1 nm. The rms deviation of experimental points from the averaged scan curve is 0.89 nm, which is a measure of roughness. Figure 7(b) shows a histogram of angles between each pair of points in a scan fitted by a Gaussian curve. The top corners of the groove profiles are rounded, which gives rise to a fairly broad distribution of the angles with a centroid at 13^{o}. The average blaze angle measured at seven points distributed over the patterned area varies from 8.9 to 15^{o}, and the rms microroughness, from 0.66 to 0.92 nm. Thus, groove profiles measured over the 5-cm patterned area exhibit a substantial variation. AFM measurements performed before deposition of the Ti/Au protective coating on the imprinted grating yielded a microroughness of ~0.2 nm for a blaze angle of ~8^{o} [21], which suggests a noticeable change in groove profile induced by deposition of metal films on the polymer-based imprint resist.

The present modeling of the relative and absolute efficiencies was performed with a similar real (i.e., AFM-measured) groove profile. The relative (>0.77) and absolute (~0.72) efficiencies are reached in the -1st order of a Mo-coated grating with AFM-measured profile and with due account of the 0.5-nm rms microroughness at the 13.5-nm wavelength of unpolarized light within the preset angle-of-incidence range (Fig. 8). Note that the AFM groove profile used in the efficiency calculations illustrated in Fig. 8 is not optimal to reach maximum efficiency in a broad converging beam at 13.5 nm and at not too grazing angles of incidence. This particular case is, however, a revealing demonstration of the possibilities inherent in this technology of fabrication of large high-efficiency Si-based gratings, which calls for the need of further studies aimed at optimization of their parameters.

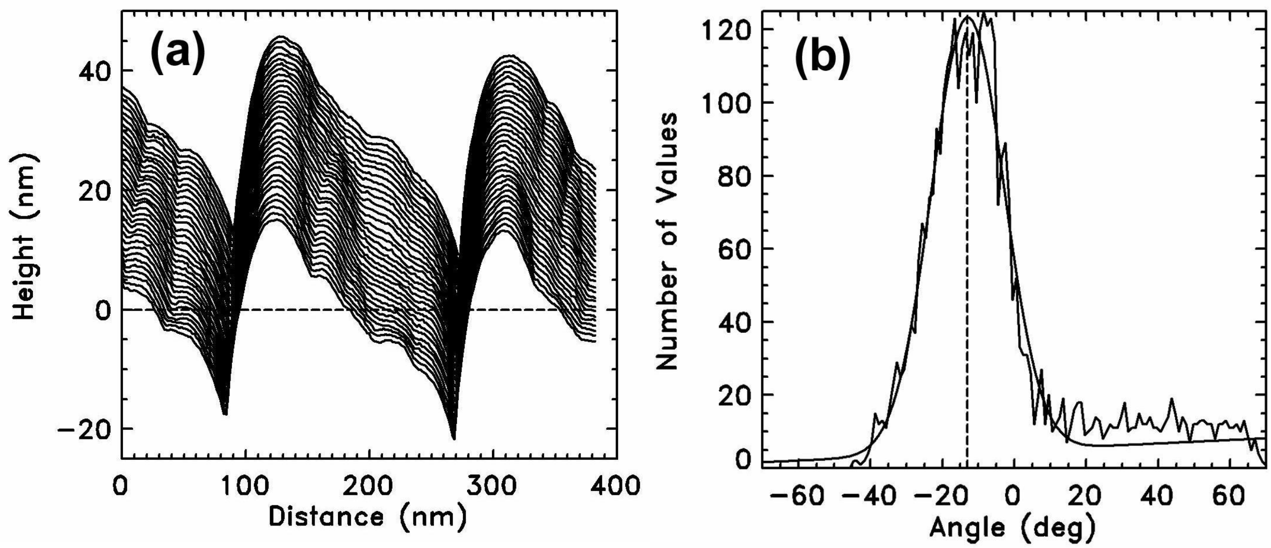

Fig. 7. (a) AFM scans made across the grooves of a 5000 gr/mm Au-imprinted grating near its center; (b) Histogram of the angles of pairs of points in AFM scans yielding the average blaze angle.

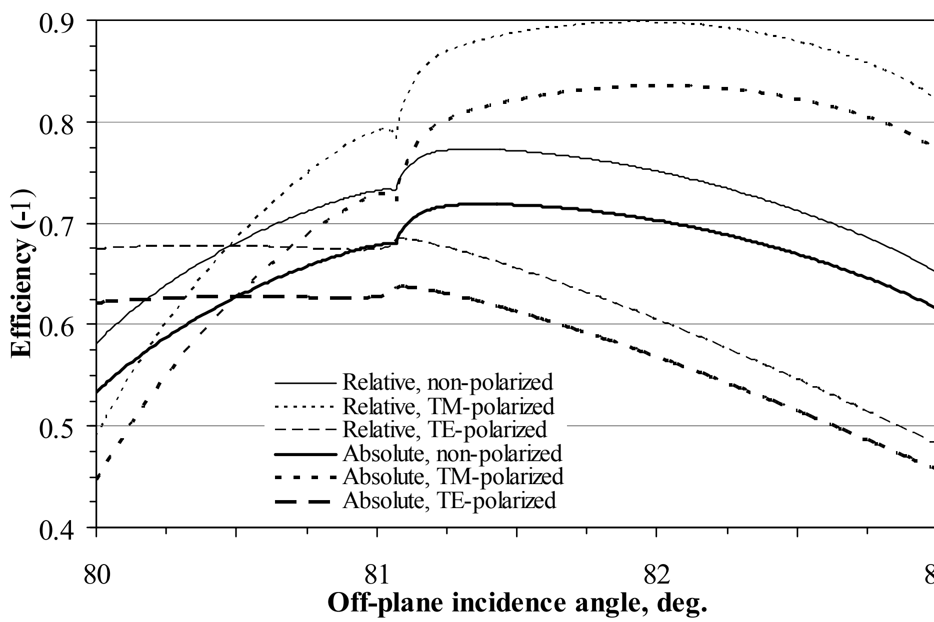

Fig. 8. Relative and absolute efficiencies in the -1st order of a 5000 gr/mm Mo grating with AFM measured groove profile and 0.5-nm rms microroughness calculated vs off-plane angle for 13.5-nm light incident at an in-plane angle of 7.5^{o}.

5. CONCLUSIONS

To sum up, we are formulating now the most essential conclusions of the present study and suggest possible related directions to be pursued.

High-frequency, fan-groove reflecting diffraction gratings with a relatively large blaze angle operating in a conical mount at large off-plane angles of incidence provide a most efficient way to isolate and focus a 2% wavelength band in the vicinity of 13.5 nm.

The novel technologies of shaping, patterning, and replicating sawtooth-shaped gratings involving anisotropic etching of graze-cut Si wafers, scanning-beam interference and nanoimprint lithography offer a possibility of fabrication of desired high-quality gratings at a low cost.

The main aberrations of an off-plane grating for a given wavelength can be readily compensated by arranging grooves in a fan-shaped geometry. Residual aberrations of a multiple grating and focal spot shape can be studied by analyzing ray tracing in the actual geometry of the EUV collector.

The maximum theoretical absolute efficiency of the grating under study operating in unpolarized light is in excess of 0.8, and its integral efficiency for an angular beam width of 6^o is only a few percent below the maximum value. Application of a multiple grating with two–three segments should permit one to intercept a broad incident beam 12–18^o in angular width.

The MIM-based calculated absolute efficiency of the test grating with the AFM measured groove profile differs from that of a similar grating with an ideal profile by ~11%, and this figure can be further improved by fabricating operating gratings with parameters optimized for the given configuration.

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