Quantum Electronics **35** (6) 569 – 572 (2005)

PACS numbers: 42.40.Eq; 42.65.Re
DOI: 10.1070/QE2005v035n06ABEH006591

Metallised holographic diffraction gratings with the enhanced radiation resistance for laser pulse compression systems

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Abstract. **The methods for improving the radiation resistance and strength of metallised diffraction gratings for laser pulse compression systems are considered. It is shown that the modification of the method for applying gold on the holographic grating surface provides a substantial increase in the grating damage threshold. It is also shown that the use of additional dielectric coatings allows a further doubling of the damage threshold for nanosecond laser pulses.**

Keywords*: diffraction grating, diffraction efficiency, radiation resistance, optical breakdown.*

1. Introduction

At present metallised diffraction gratings are basic dispersion elements used for compression of high-power chirped laser pulses [1, 2]. However, the radiation resistance of such gratings is an order of magnitude and more lower than that of other elements of laser systems, which requires the employment of compressors with a large light aperture. For example, the transverse size of gratings in petawatt laser systems amounts to 1 m [3]. Even a greater grating size is required to achieve the exawatt (10^{18} W) and zettawatt (10^{21} W) peak power levels. The possibilities of the development of such laser systems are considered, for example, in paper [4]. Such a large size of gratings and optical elements used behind them (elements of the diagnostic and focusing optics) greatly increases their cost and the cost of the laser system as a whole. Therefore, the search for and the development of methods for improving the radiation resistance of diffraction gratings are of current interest. Note that the improvement of the radiation resistance should not be accompanied by the decrease in the diffraction efficiency (DE) of gratings, which now exceeds 90 % [5].

There exist several methods for improving the radiation resistance of gratings [2], including the promising method for producing a special grating profile on a dielectric mirror [6, 7]. However, the possibilities of increasing the radiation resistance of standard metallised gratings, which are manufactured by using the well-developed technological process, are also far from being exhausted. These possibilities include optimisation of the thickness of a metal coating and of the method of its applying and will be considered in this paper. Due to such an optimisation, the radiation resistance was increased by a factor of three. The radiation resistance can be further improved by depositing protecting dielectric layers on metal coatings, which results in the doubling of the damage threshold, preserving the high DE in a certain spectral region.

2. Study of the methods for increasing the damage thresholds of metallised diffraction gratings

Diffraction gratings were fabricated by using the technological process developed in [8] and based on the interference recording of holographic gratings in a photosensitive chalcogenide glass by an argon laser, the etching of the recorded hologram, and the deposition of a metal layer of gratings. Diffraction gratings used for compression of high-power laser pulses are covered by gold, as a rule. This is explained by the fact that gold provides a higher damage threshold than, for example, aluminium and the reflection properties of gold do not almost change in air with time. The thickness of a gold coating deposited, as a rule, by the method of electron-beam evaporation is typically 200 nm, which is comparable with the grating profile depth *h*.

The radiation resistance of metal coatings can be improved by increasing their thickness and density. However, the increase in the coating thickness in the electron-beam deposition method is restricted by the decrease in the groove profile depth and by the distortion of the profile itself, resulting in the DE reduction. This effect is illustrated by the electron-beam photography in Fig. 1, which demonstrates a change in the groove profile. The influence of this change on the grating DE is shown in Fig. 2. One can see that, as the gold film thickness is increased from 200 to 400 nm, the DE noticeably decreases in the short-wavelength part of the spectrum. At the same time, the high DE is preserved in the long-wavelength region. A further increase in the gold film thickness reduces the grating

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Received 16 March 2005
Kvantovaya Elektronika **35** (6) 569 – 572 (2005)
Translated by M.N. Sapozhnikov

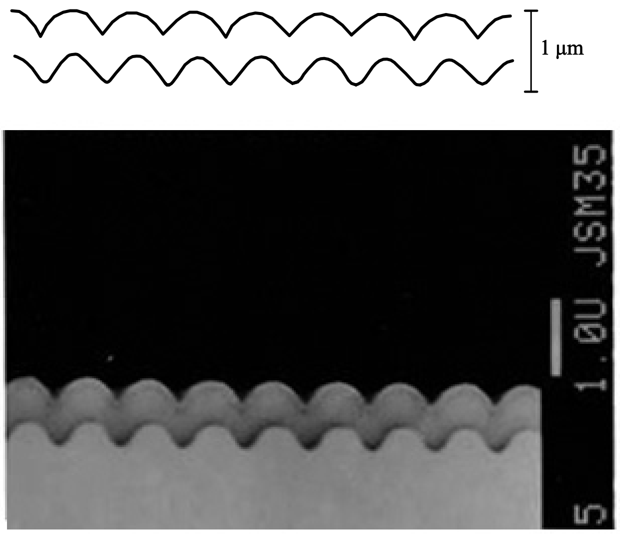

Figure 1. Photograph (bottom) of the relief profile of the 1200-lines mm^{-1} holographic grating coated with a 400-nm thick chromium film deposited by the electron-beam method and the processing of this photograph (top).

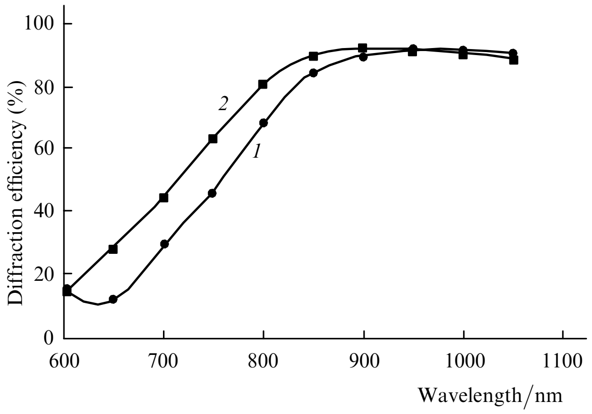

Figure 2. Spectral dependences of the DE of the 1200-lines mm^{-1} grating coated with reflecting gold films of thickness 400 (*1*) and 200 nm (*2*).

DE over the entire spectral range. The damage threshold measured for gratings covered by the gold film of thickness 400 nm was 0.5–0.6 J cm^{-2}, which is nearly twice as large as that for the 200-nm thick gold film. Therefore, the electron-beam technique of gold deposition does not always improve the radiation resistance of gratings by increasing the reflection layer thickness and preserving the high DE.

In this connection we tested another – magnetron method of the gold coating deposition improving the radiation resistance. This method provides a better homogeneity of the metal film deposition and a higher covering density than the electron-beam method.

By comparing the technologies of magnetron sputtering and electron-beam deposition of gold, note that the average energy of particles upon magnetron sputtering is a few tens times higher than that upon electron-beam deposition, resulting in a deeper penetration of particles into a substrate and a denser packing of atoms on the substrate surface. Therefore, a metal film of a better quality is obtained. In addition, electron-beam deposition is usually performed at a higher vacuum and higher temperatures of a metal (equal approximately to the melting temperature). The atoms being evaporated have a longer mean free path and move to a substrate along almost straight trajectories in accordance with the directivity pattern of the evaporated material. For this reason, in the presence of a relief surface on the substrate, the shaded sites appear on it and the deposition inhomogeneity increases, resulting in the profile distortion.

Upon magnetron sputtering of a metal, the mean free path of sputtered particles substantially decreases because sputtering is performed at considerably higher residual gas pressures (5×10^3 mbar). Due to collisions of sputtered particles with gas molecules, the directivity pattern of these particles broadens, thereby reducing the shading effect. These qualitative considerations confirm the electron microscope measurements of the diffraction grating profile (Fig. 3). One can see from Fig. 3 that after deposition of the metal film of thickness 300 nm, the grating relief almost did not change, and such grating can efficiently reflect radiation in the entire operating spectral range. This is confirmed by the spectral dependences of the reflectivity of a 1200-lines mm^{-1} diffraction grating coated with reflecting metal films deposited by different methods (Fig. 4). One can see from Fig. 4 that only magnetron sputtering of gold provides the maximum DE in the entire spectral range.

Measurements of the damage thresholds of holographic diffraction gratings with the magnetron-sputtered gold coating of thickness 400 nm showed that the damage energy

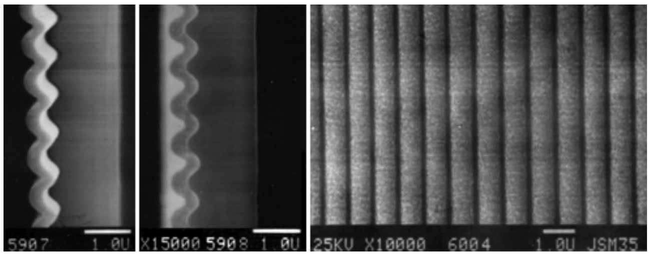

Figure 3. Photographs of the relief profile of the 1200-lines mm^{-1} holographic grating (at the left) and the grating coated with a 300-nm thick magnetron-sputtered aluminium film (in the middle). The top view of the grating is shown at the right.

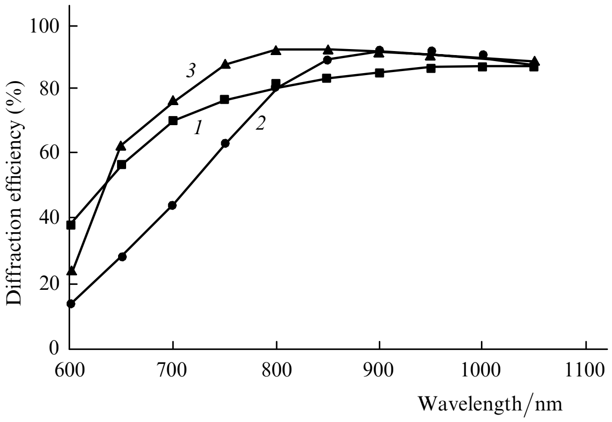

Figure 4. Spectral dependences of the DE of the 1200-lines mm^{-1} gratings coated with reflecting films deposited by different methods: thermal deposition of Al (*1*), deposition of Au by the electron-beam (*2*) and magnetron (*3*) methods.

density for the 1064-nm, 1.5-ns laser pulses achieved 1 J cm^{-2}. This value exceeds more than by a factor of three the damage threshold for gratings coated with 200-nm gold films deposited by the electron-beam method.

The damage threshold of metallised diffraction gratings can be further increased by depositing on a metal several pairs of dielectric layers with high and low refractive indices [9]. The optical thickness of the layers selected by the numerical calculation should be close to $\lambda/4$. Operating as an interference mirror, these layers reduce the laser radiation intensity on the metal. The calculations show [10] that in the ideal case of preserving the grating profile, the radiation intensity on the metal can be decreased by any required number of times by increasing the number of dielectric layers. However, the main problem of this method for increasing the radiation resistance is a change in the grating groove profile caused by the deposition of 'thick' dielectric layers [11]. This effect is illustrated by the electron-beam microscope photograph (Fig. 5). One can see from Fig. 5 that the profile depth decreases approximately by half already after the deposition of two pairs of dielectric layers.

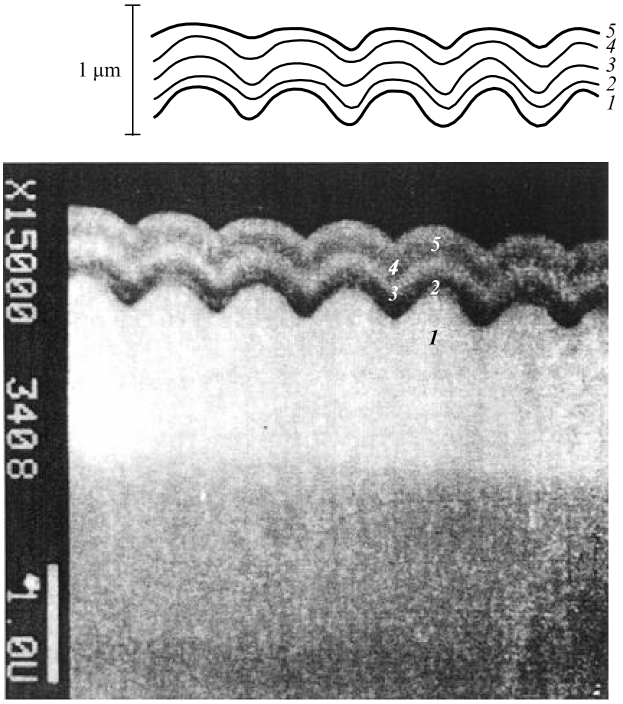

Figure 5. Photograph (bottom) of the relief profile of the 1700-lines mm^{-1} holographic grating coated with gold and two pairs of SiO_2/HfO_2 dielectric layers and the processing of this photograph (top).

The influence of this effect on the grating DE is shown in Fig. 6. The wavelength dependence of the DE is qualitatively the same as that for purely metallised gratings with an increased metal layer: the DE strongly decreases in the short-wavelength part of the spectrum, preserving high values (90 %) in the long-wavelength region, where the ratio of the wavelength of radiation incident on the grating to the grating period is larger than 1.5. The DE decrease in the short-wavelength region in this case substantially exceeds its decrease for metallised gratings, which is explained by the resonance nature of interference. For this reason, to provide the high efficiency of diffraction gratings with dielectric coatings in the near-IR region (700 – 1100 nm), it is necessary to use gratings with the frequency of grooves $N > 1500$ lines mm^{-1}. Our numerous measurements showed that the damage threshold of metallised 1700-lines mm^{-1} diffraction gratings with two additional pairs of SiO_2 and HfO_2 dielectric coatings is doubled on average upon irradiation by nanosecond laser pulses. A further deposition of pairs of dielectric layers in the case of the technologically accessible ratio of the profile depth to the grating period ($h/d < 0.4$) will noticeably reduce the DE for the optimised number of grating grooves.

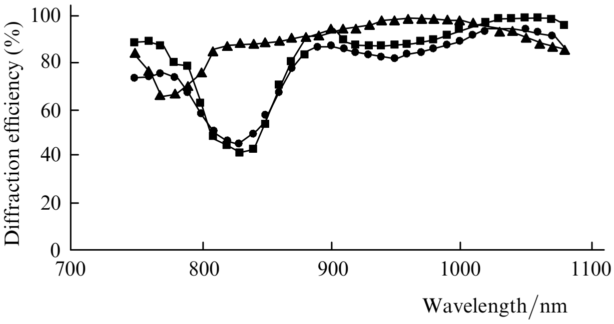

Figure 6. Effect of the change in the groove relief on the DE of a metallised grating coated with two pairs of the SiO_2/HfO_2 dielectric layers: results of measurements (●) and numerical calculations taking into account (■) or neglecting (▲) the groove profile change.

Therefore, purely metallised 1200-lines mm^{-1} gratings with the increased thickness of the magnetron-sputtered gold layer are optimal for using for compression of high-power broadband pulses in systems for parametric amplification of chirped pulses [12]. Such gratings of size 380 × 240 mm were fabricated for applications in parametric systems.

On the other hand, the diffraction gratings with $N = 1500 - 1700$ lines mm^{-1} can be used in high-power subpicosecond laser systems [2–4, 13–15]. Their radiation resistance can be doubled by depositing a few pairs of protective dielectric layers.

3. Conclusions

We have shown that the radiation resistance of conventional metallised diffraction gratings, which are widely used for compression of laser pulses, can be substantially increased.

The increase in the gold coating thickness and optimisation of the deposition method lead to almost threefold increase in the radiation resistance, preserving the high DE over the entire spectral range. The damage threshold can be further increased by depositing two pairs of dielectric layers. However, the high DE is preserved in this case only in the long-wavelength part of the spectrum, which limits the number of grooves by the value $N = 1500$ lines mm^{-1}.

Therefore, the methods for increasing the radiation resistance of metallised diffraction gratings studied in the paper can provide the sixfold increase in the damage threshold for nanosecond laser pulses, by making their resistance nearly the same as that of diffraction gratings fabricated on a dielectric mirror. Such an increase in the radiation resistance makes it possible to reduce considerably the light aperture of compressors in petawatt laser systems being developed at present at different scientific centres worldwide.

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