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Modulated gratings and grating-modulated holograms: their spectral and polarization properties and protection possibilities

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Gratings produced by using electron beams (e-beam gratings) and simple rainbow holograms modulated by sinusoidal holographic gratings of relatively high spatial frequency (2500–4100 lines/mm) are the subject of this paper. Their spectral properties and abilities to polarize the light are qualified as a significant feature for the comparison of an original grating/holographic structure with its copies. The results obtained allow us to suppose that holograms modulated by gratings of various relief profiles can be very difficult to counterfeit, especially to remake.

1. Introduction

Among the most interesting properties of diffraction gratings [1] are the grating response to wavelength and polarization state of the incident light. Although diffraction gratings are widely used in modern optical security technology [2]–[8], their properties just mentioned were up to now beyond the scope of investigations dealing with distinguishing between original optical security marks and their illegal copies.

Most of modern security labels based on imaging diffraction structures are designed mainly for visual observation [2]–[15]. Consequently, the most important property of optical signs is the image and especially its geometry and brightness. Manufacturers of security holograms often try to complicate scenes seen in the hologram plane by creating additionally more or less chaotic microreliefs. Up to now, however, polarizing and spectral properties of such microreliefs were considered a less significant feature or a problem difficult to evaluate quantitatively or even qualitatively. We try to abandon such an approach to this problem.

In general, copying and counterfeiting diffraction security signs are not easy objects for evaluation. Methods used by counterfeiters are shortly commented on in [16]. Electrolytic duplication of an uncovered relief is probably always possible. Every opinion on the effectiveness of other copying methods is subjective to a certain extent and depends on producer's experience. In our opinion, there are at least two cases that must be taken into consideration. One of them was precisely analysed in [16], where many examples of commercially produced fake holograms were described. Those examples clearly confirm that typical illegal labels are amateurish fakes of very bad quality and can be easily recognized while comparing them with the original. The second case where copies are produced by specialists in a laboratory is qualified as a possible security problem [16], [17]. Contact and holographic copies can give good images, but opticists familiar with holography will probably be able to distinguish them from the original, because they can observe such details of the hologram surface which cannot be seen or taken into account by other individuals who are not familiar with light diffraction. Repeating of an original technological process on the basis of the knowledge of scattered light distribution and of the shape of observed image is qualified as a more advanced technique. If it is correctly performed and, additionally, a proper technological method is chosen, not only the image produced by illegal copies but also their reliefs can be very similar to those of the original. Therefore, two main classes of diffraction features are used for protecting security holograms against copying. The first class is constituted by hidden structures [5], [11], the second one contains visible reliefs, which are very hard to copy or remake due to their technological complexity [2], [3], [8]–[10].

In this paper, a new (to our knowledge) diffraction structure is proposed. It consists of two parts: a set of e-beam gratings, and modulated rainbow hologram. The gratings can be included in the second class mentioned above and they are useful for machine reading. On the other hand, modulated hologram can be regarded as a kind of hidden structure.

2. Gratings of various profile shapes

The simplest diffraction microstructures are linear gratings. Commonly, such gratings, formed with the use of classical methods, have typical relief shapes (for example, rectangular for e-beam gratings, quasi-sinusoidal for holographic rasters, u- or v-shaped relief for chemically etched gratings on crystal surface [18], and other shapes) and can be relatively easy to repeat in similar technological processes. Such gratings, however, can be additionally modulated (reprofiled), for example, by using the same or similar classical method as a next litographic processing, mechanically (*e.g.*, by a very smooth polishing), thermally, chemically by very slow etching *etc*. As a result of these operations one can create modulated linear structures of somewhat irregular profiles. Producing a second identical copy can be hard if the way of the modulation process is not exactly known to individuals who want to make the copy.

We used a series of holographic gratings recorded in photoresist whose grating profiles were modulated by using the above mentioned mechanical and physicochemical processes. This experiment was undertaken to produce some variations in grating relief shapes and determine their influence on diffraction efficiency and resulting changes in image contrasts between gratings over the visible spectrum.

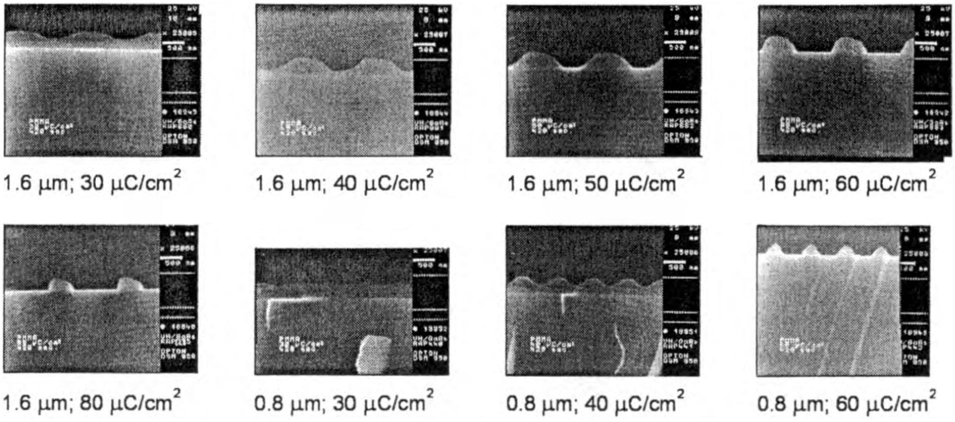

Fig. 1. Classes of profile shapes obtained simply by changing the electron dose absorbed by resist (photographs from electron scanning microscope OPTON DSM 850). Captions underneath the photos decribe the grating period and electron dose, respectively.

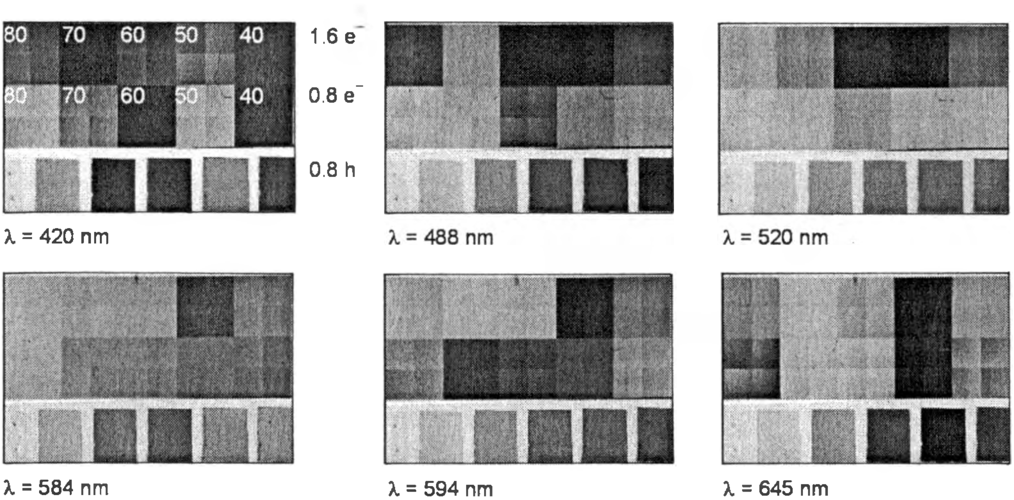

Fig. 2. Examples of corresponding spectral dependence of contrasts between fields covered with respective e-beam gratings (polarization P, angle of incidence 21°, zero diffraction order). In the last bottom row a series of holographic gratings are added for comparison. 1.6 e^- – electron grating of 1.6 μm pitch, 0.8 h – holographic grating of 0.8 μm pitch, and so on. White numbers denote electron dose.

Firstly, various e-beam gratings were produced and tested. Figure 1 shows photographs of surface cross-sections of these e-beam gratings. Examples of corresponding contrasts between areas covered by these gratings are also displayed in light of various wavelengths (Fig. 2, two top rows). One row of holographic gratings is added at the bottom. The periods of these gratings are 0.8 μm and 1.6 μm. From comparison, it follows that diffraction efficiency (*i.e.*, contrast) changes more rapidly for e-beam gratings.

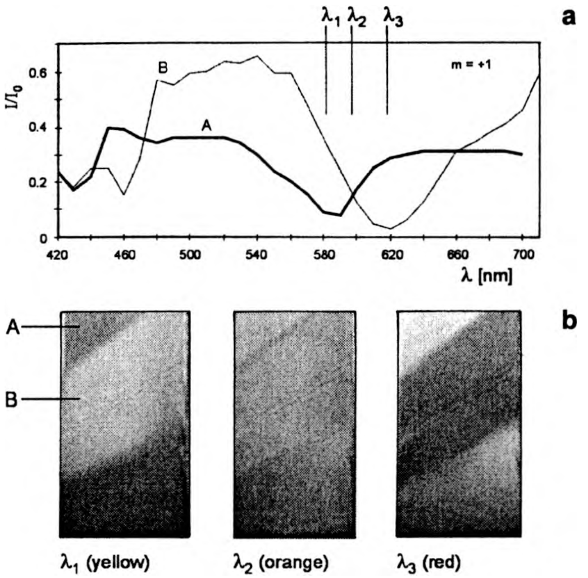

Fig. 3. Change of diffraction efficiency curve after modifying the relief of a holographic sinusoidal grating (**a**). The photographs of the grating at three wavelengths. A – area of the grating with its original relief, B – with modulated relief (**b**).

Another example is a two-part (A and B) modulated structure (Fig. 3). Its surface observed in light of various wavelengths is shown in Fig. 3**b**. The structure was originally a uniform "pure holographic" line grating. Its relief in the central oblique area B was slightly modified. In Figure 3**a** the diffraction efficiency of the +1 order versus wavelength is drawn for both areas A and B. It can be seen from Figs. 3**a** and **b** that contrast between A and B changes with light wavelength (colour). Such a spectral situation as produced by λ_2 (contrast between A and B approximately equal to zero) can be especially useful as the reference image for the examination of copies. The change of any relief on a copy causes a change of the brightness of respective area and, in consequence, contrast appears between areas (in this case, A and B) or becomes greater or smaller than on the original.

3. Grating-modulated rainbow holograms

Grating structures as described previously can be useful for machine inspection but are not attractive from the visual point of view. They do not provide 3-D images and can be observed with both eyes by using only diffused light source of wide angular dimensions. In contrast, easily perceptible 3-D image is the advantage of rainbow holograms, but they are less sensitive to the polarization state of the light. Their polarizing properties, however, can be amplified by a respective modulation of their microrelief. To this end, two examples of qualitatively various methods were described in [2] and [3]. We propose a somewhat different method for producing a strongly polarizing grating structure. The idea is quite similar to that described in the previous section, but in this case a matrix of variously shaped grating structure of relatively high spatial frequency should modulate the rainbow hologram. We carried out preliminary experiments with a very simple superposition of two holographic elementary microstructures to confirm that the resulting diffraction element can constitute a potential security mark.

In the first experiment, the non-coherent superposition of a rainbow hologram of a 2-D diffuse object and a holographic grating was registered on the same photoresist layer. Directions of fringes of both interference patterns were approximately parallel. The period of hologram fringes was $d_2 = 0.77$ μm and that of the grating was $d_1 = 0.26$ μm. The non-coherent superposition of linear-like structures can be regarded in terms of the theory of combined gratings based on Fresnel–Kirchhoff's approximation [19]. It can be characterized by an effective period d_{ij}:

$$\frac{1}{d_{ij}} = \frac{m_i}{d_1} + \frac{m_j}{d_2}, \qquad \sin\alpha + \sin\beta = \frac{\lambda}{d_{ij}} \tag{1}$$

where d_1 and d_2 are the periods of each elementary structure, m_i, m_j denote the order numbers, α is the angle of incidence, and β is the angle of diffraction. Parameters d_{ij} should be understood as periods of hypothetical elementary components of the structure producing a constructive interference for wavelength λ at the angle of diffraction β. The first few possible effective periods for $\lambda = 436$ nm (for example) are as follows:

$(m_1, m_2) =$	(0, 0)	(1,0)	(0, 1)	(0, 2)	(1, −1)	(1, −2)
d_{ij} [μm] =	reflection	0.26	0.764	0.382	0.394	0.814.

These mixed diffraction orders can propagate and carry the image information when a grating is illuminated with visible light. The visibility and other properties of images depend on contributions of each complementary structure to the resulting relief. This phenomenon can be considered as a consequence of nonlinearity of holographic recording [19], [20]. For a more precise analysis taking into account polarization state of illuminating light a theory like grating theories is needed, especially in the case where the hologram is modulated by a grating of high spatial frequency.

The hologram was placed in the light outgoing from a monochromator slit and the angle between directions to the slit and camera was equal to 26°. The change of the light wavelength from the monochromator was compensated for by a respective rotation of the hologram, and thus the angular position of the observed image remained unchanged. In Figure 4, the ordinary first order (0, 1) image is shown in the polarized light the wavelength λ of which was changed from 510 to 630 nm. Its part left to the line separating the scene with dark strip is modulated by the linear grating and the right part is a pure rainbow hologram. At some wavelengths the influence of polarization on brightness is observed, but within the whole spectrum this dependence is rather slight. When the hologram is rotated under a typical desk lamp, both its parts differ somewhat but no evident differences between them are observed.

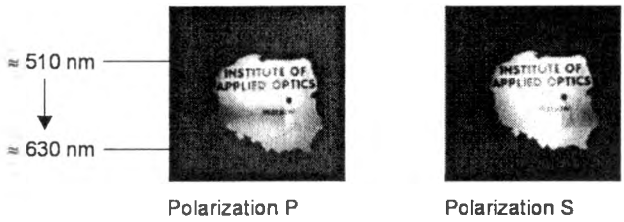

Fig. 4. Polychromatic first order image from the whole surface of the hologram. The range of reemitted spectrum wavelengths was approximately 510 nm to 630 nm.

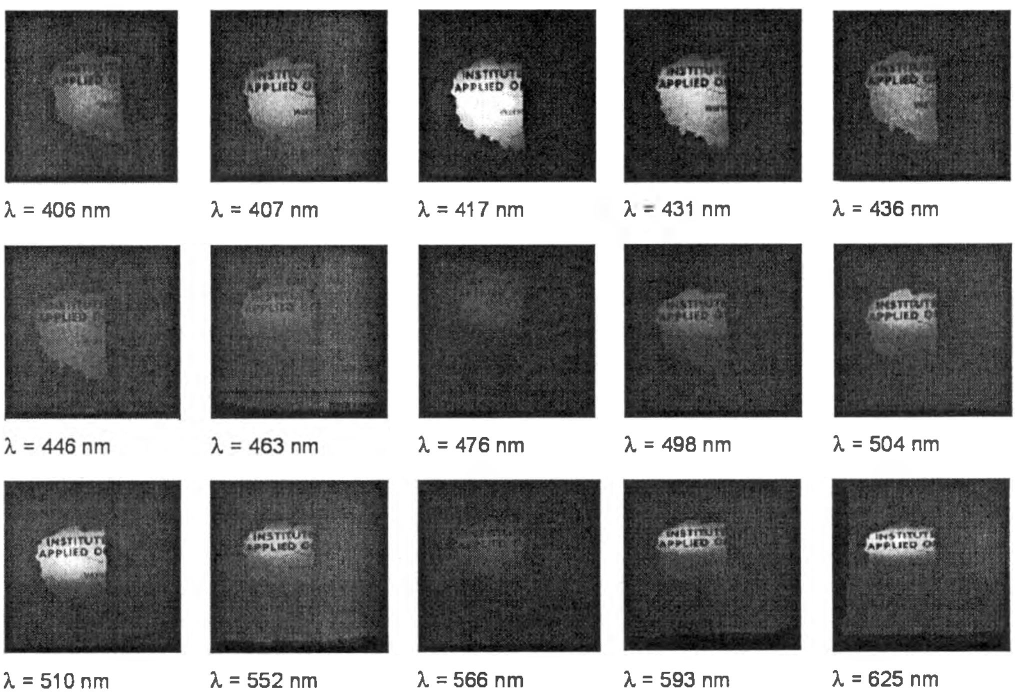

Fig. 5. Second order images from the modulated rainbow hologram in unpolarized monochromatic light (from monochromator mentioned earlier).

The situation changes completely when the second-order images are observed. A sequence of these images is presented in Fig. 5 for non-polarized monochromatic illumination. An image from the ordinary (not modulated) hologram practically does not exist. Only the left part produces the image. Its intensity, however, has relatively sharp minima and maxima over the wavelength spectrum. They are a consequence of the amplified sensitivity of modulated structure to the polarization state of light. Contributions from both polarizations, S and P, to the total intensity are not similar. For the sake of brevity, the respective photos are not shown, but a qualitative impression, during changing both the wavelength and polarization, is illustrated in

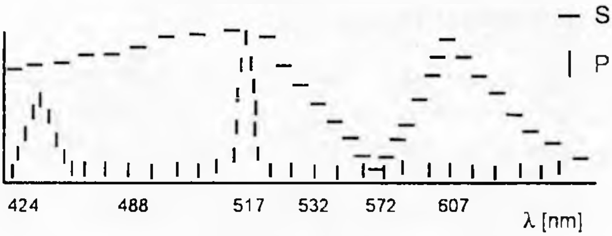

Fig. 6. Qualitative evaluation of the modulated image brightness of various colours for both polarizations.

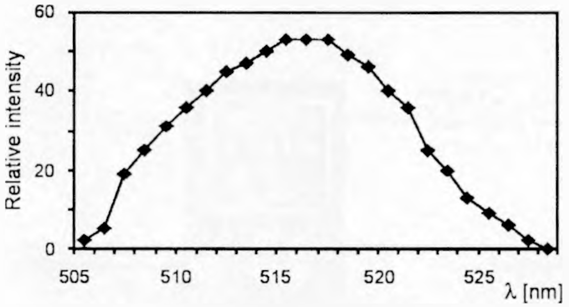

Fig. 7. Local spectral distribution of light intensity from the modulated hologram *vs.* the wavelength (0-noise level, relative units).

Fig. 6. For a better illustration of spectral selectivity of the modulated hologram the most interesting peak of intensity at P polarization was precisely measured. The result is shown in Fig. 7. As it follows from the values d_{ij} given above, the propagation directions of orders (0, 2) and (1, −1) are very close to each other (0.382 μm and 0.384 μm) and both monochromatic waves almost overlap. From spectral and polarizing properties of the image examined it can be deduced that we observe (1,−1)-order image.

Energy distribution among diffraction orders is rather complicated. Depending on the wavelength and polarization, the energy can be transferred mainly into the zero, first or second orders of the hologram and eventually into the first order of the modulation grating (for wavelengths $\lambda < 2 \times d_1 = 0.52$ μm). In other situations, the energy is approximately equally distributed into two various orders. For example, deep minimum near to 572 nm is caused by a strong reemittance into the zero-order and simultaneously into the bright first-order image.

It is worth noting that all the above effects concerning the modulated images can be easily observed qualitatively with the use of a polarizer and a desk lamp.

By means of ray tracing analysis, based on the algorithm taken from [21] with necessary modifications [22], it can be shown that spectral and geometrical properties of both second-order images are different. This is a natural consequence of Eq. (1). Such analysis was performed and the results will be reported in a separate paper.

4. Modulated hologram and its contact copies

For the purpose of testing, a combined three-component structure was developed (Fig. 8**a**). It is composed of 6 e-beam gratings similar to those described in Section 2, 2-D rainbow hologram and modified hologram similar to that described in Section 3. The gratings and holograms were made by using an e-beam sensitive resist and photoresist, respectively. All components were made on the same surface and can be processed together, for example for obtaining a nickel shim. A copy from the original is shown in Fig. 8**b**.

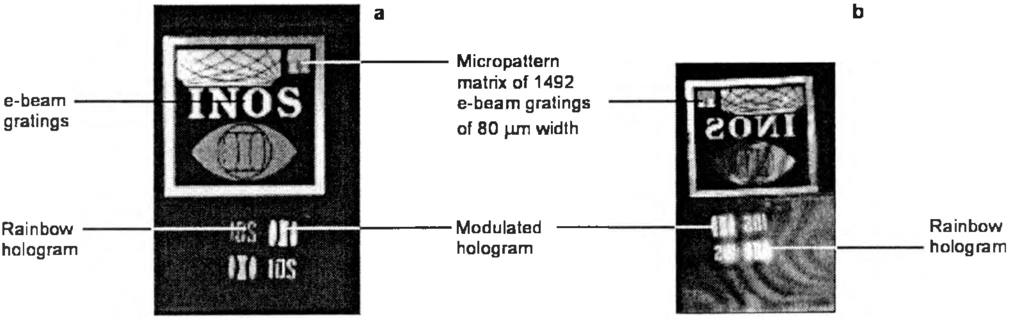

Fig. 8. Original combination (**a**) and one of its contact copies (**b**).

The copy was recorded on a typical plane-parallel plate 1.5 mm thick covered by photoresist AZ 1350. A high pressure mercury lamp (HBO 200) with separated 40 nm visible spectral band near to $\lambda = 400$ nm was used as a light source. In some experiments, glycerin was used as an immersion liquid between the photoresist and copied surface for decreasing the intensity of light reflected from the photoresist. Non -polarized light illuminated the sample at an angle 0°. The distance between the original and the copy was relatively long and slightly variable across the copied structure. Therefore we could not obtain copies free of disturbing Newton fringes. The area equal to 3.1×3.1 mm and covered by the matrix of microgratings, seen in the right corner of the original, lies on a single wide Newton fringe and can be compared with the original image. The result of comparison is shown in (Fig. 9). Both samples (the original and its copies) were compared at wavelengths to which a characteristic image from the original corresponds (for example, the contrast between one of two rooks and its background vanishes). The relation between brightness of the copy and original generally differs from that shown in Fig. 9. This, however, is not important because only corresponding contrasts are the feature under examination. We can easily see that contrast changes in higher diffraction orders are almost equally fast. For example, the right rook is practically black in the first-order image and becomes white in the second order.

In Figure 10, the photographs of holographic part of the test scene are compared for the original and the same copy as previously. On the copy the images in the second

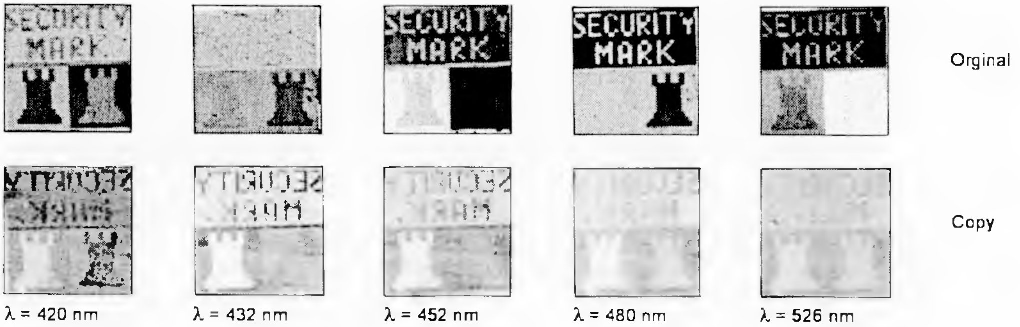

Fig. 9. Comparison of contrast changes in the micropattern areas of the original and its copy. Monochromatic light, zero-order, P polarization, angle of incidence 17°.

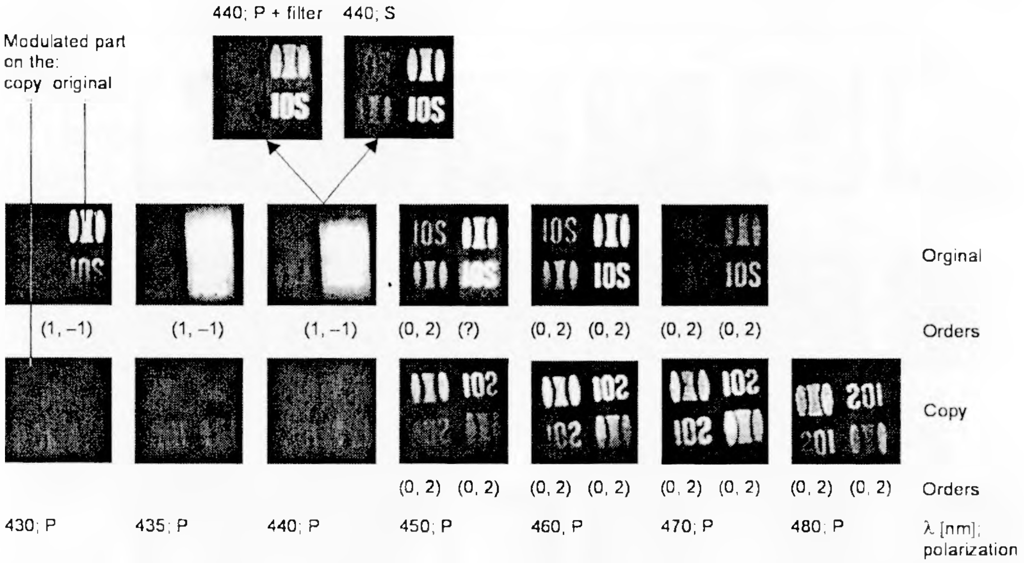

Fig. 10. Comparison of the original hologram and a copy with transferred holographic structure but without modulation grating. Polarization P.

order of hologram are seen on both holographic structures (modulated by grating and original) but the spectrum of the modulating linear structure does not exist, which can be easily proved in the laser light. During the comparison, the hologram was immovable and only the wavelength was changed. The measured effective periods d_{02} and $d_{1,-1}$ appear to be shifted by about 0.017 μm what corresponds to about 20 nm shift in wavelength domain when the images are observed at the same angular position defined by the direction to the camera. When the observation starts at $\lambda = 430$ nm and the wavelength λ increases, the sequence of observed images is different for the original (the 2nd and top rows in Fig. 10) and for the copy (bottom row). For the original, a very bright $(1, -1)$ image is registered at $\lambda = 435$–440 nm and then it becomes darker and simultaneously the image (0, 2) appears near to $\lambda = 450$ nm. Two top photos pointed by arrows show sensitivity of the (1, −1) image to polarization. Its intensity at S polarization is comparable with that at P polarization suppressed additionally by a filter of 16% transmission. As can be seen in the bottom row, the structure of the copy does not give the (1, −1) image at all, and its appearance is a feature identifying the grating component on the copy.

The next series of photographs show also a number of images from the original and another copy placed on a specially prepared 1.5 cm thick prism with an antireflection coating and recorded without immersion liquid. In this case, the copy includes a modulating grating component. A grating spectrum was visible not only in the laser light but also under a desk lamp. We can see that the image (1, −1) exists on the copy and we can compare its properties on the original and the copy. In Figure 11 only the (1, −1) image is shown. Wavelength was changed as in the previous case, but for each moment of observation the hologram was rotated to achieve maximum

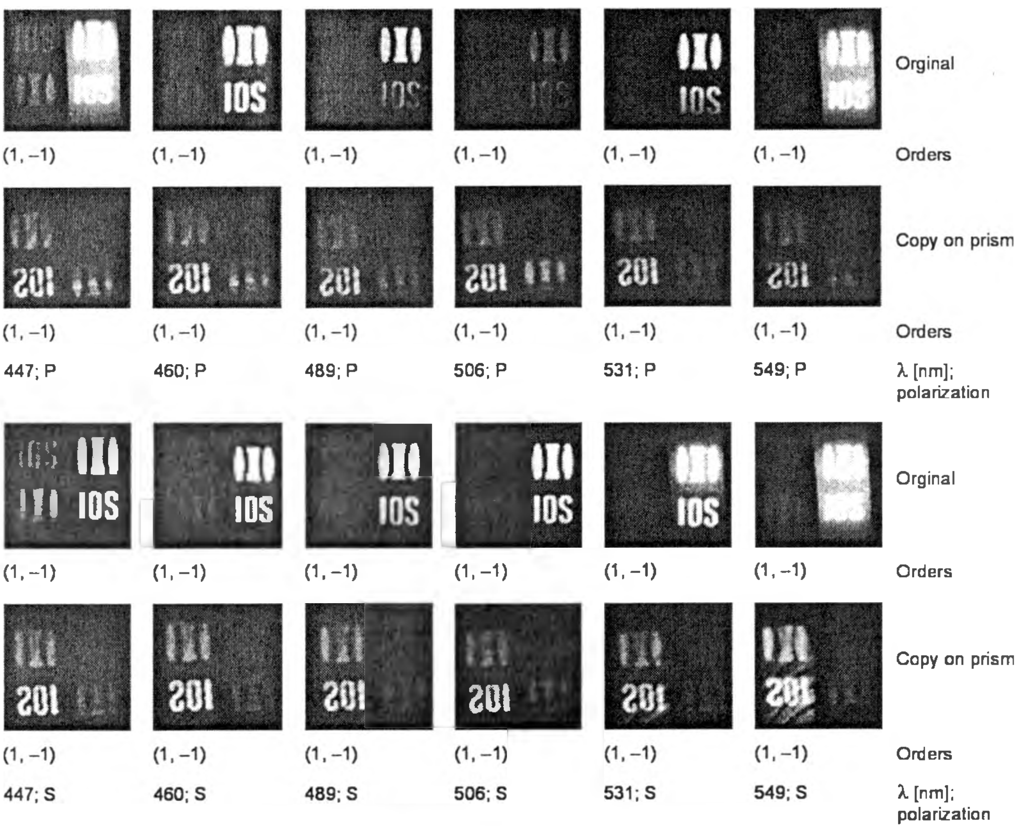

Fig. 11. Comparison of the original hologram and a copy with modulated holographic structure and modulation grating.

intensity in the $(1, -1)$ order. Even if we take into account a great difference between the brightnesses of both structures (original and modulated copy) and the presence of disturbing fringes, we can formulate some conclusions. At S polarization the image shows similar character for both the original and the copy and one can only claim that the copy is darker, but there is no significant qualitative difference between the spectral behaviour of images. This feature is not the case for P polarization; the intensity shows a maximum at $\lambda = 447$ nm, minimum at $\lambda = 506$ nm and, the second maximum at $\lambda = 549$ nm, and can be a proof that the $(1, -1)$ wave was emitted by a fake hologram.

5. Conclusions

We have presented simple linear gratings and superpositions of gratings with rainbow holograms, and examined their spectral and polarization properties from the point of view of their application to protection of documents. The advantages of our structures are as follows:

1. A single modulated rainbow hologram can simultaneously provide a 3-D image and strongly polarized light.

2. Images of the zero, first, and at least second orders of a hologram and grating can be analyzed to distinguish between their legal and illegal copies. The effects in higher mixed orders can be present even if the main holographic image of respective order is suppressed. It is enough only to examine the respective holographic image to check whether the modulating grating is copied or not and whether its relief is original.

3. Spatial frequencies of gratings can potentially amount to over 5000 lines/mm. Such a grating does not give diffraction orders in the visible light and can be hard to perceive on the holographic background, but modifies visible images. A matrix of simple gratings of frequencies over 5000 lines/mm is a security mark for analysis in UV and the inspection method (based on comparison of contrasts) can be directly transferred into UV region.

4. Local spectral sensitivity of the grating-modulated hologram can be compared with that of volume holograms

5. Gratings can be formed as typical structures (sinusoidal holographic, rectangular e-beam, u-,v-shaped in etched crystal) or as modifications of these typical structures by means of the same or other technology. If relief shapes are "exotic" enough, remaking of each one can be practically impossible for each single profile and the problem grows for the whole matrix. A counterfeiter cannot use effectively measured distribution of scattered light, because it does not allow precise determination of the shape of the surface (not from a physical point of view, but as a consequence of the lack of appropriate theory of inverse diffraction).

6. Even if each structure is unique and the manufacturer can neither prescribe nor duplicate it with demanded precision, it is still possible to measure its contrasts or other

needed parameters after forming the relief and use this set of values as a reference one when comparing the original and the copy.

7. Gratings formed by means of various technologies can be placed on the same substrate.

8. Some tests, not presented here, confirm the possibility of modifying of optical holograms by e-beam gratings. These experiments will be continued.

We hope that such a simple security label, as presented herein, is not less protected against copying (not only optical) than conventional commercial holograms. It is certainly not so attractive for visual observation but better for machine inspection.

All investigations were performed in laboratory conditions. This means that gratings were formed in ideally flat layers of photo- and e-beam sensitive materials put on hard glass blanks. Implementation of the proposed method in practice is connected with further investigations of the properties of gratings formed in various hard and soft materials by means of duplicating process (above all embossing). The method is very sensitive and the problem is to answer the question of how great can be maximal technological relief deformations and their statistical distribution at which all legal copies would be recognized as originals. Probably statistical examinations will be needed for each case of application on new materials. Other interesting issues include designing and manufacturing more exotic imaging and simultaneously polarizing diffraction elements.

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