Optica Applicata, Vol. XXX, No. 2–3, 2000

Computer generated holograms versus synthetic diffraction gratings in optically variable devices

PAWEŁ STĘPIEŃ

Polish Holographic Systems, Co., ul. Kazimierzowska 76/7, 02–518 Warszawa, Poland.

Diffractive optically variable devices (DOVDs) are optical imaging elements such as holograms and diffraction gratings of all types. Visual applications of holograms consist in recording and reconstruction of 3D or 2D objects. Diffraction grating structures are used for visualisation of 2D images with cinematic effects. Computer generated holograms (CGHs) form 3D images of the quality which is hardly acceptable for commercial applications. In this paper, the method of formation of high quality 3D images using multistereograms based on CGHs is presented. CGHs are also used to make Fourier type hidden elements. CGH based hidden elements may be combined with 2D visual features. Grating based DOVDs are used to record bright 2D images with cinematic effects. We show that diffraction gratings recorded using high-resolution equipment can be applied to true colour 3D image recording taking advantage of the stereogram concept. Similarly as in CGHs the recording of simple hidden information is possible in synthetic diffraction gratings.

1. Introduction

Visual applications are currently the most valuable part of holographic industry. Rainbow and volume holograms, diffraction gratings and other types of DOVDs are widely used in security applications [1], for publicity and promotional purposes, packaging and 3D data visualisation. Their main advantage lies in a unique, eye-catching and difficult to copy look of recorded images, both of 3D objects and flat graphics with animation effects.

Visualisation of 3D objects is the most important and definitely the most exciting feature of holography. Since the introduction of the first holograms the quality of 3D images recorded on different types of holograms continuously improves. Classical holographic techniques are briefly described in the next section of this paper. However, limitations of analogue holograms, *i.e.*, necessity of preparing a properly scaled solid model of the 3D object to be recorded, strongly affects their usefulness in general 3D object visualisation. Holographic stereograms are free from this disadvantage, but the way they are recorded limits the resolution of recorded images. Holographic stereograms are presented in Section 3.

After the first works on CGHs and kinoforms [2], [3] were published it was expected that the possibility of almost direct recording of calculated wavefront would soon enable recording of any 3D object. The difficulty with coding complicated, high-resolution wavefronts, however, caused that 3D CGHs of acceptable quality have been realised in Polish Holography laboratory only recently [4]–[7]. Different features of CGHs recorded using technology worked out by the author and their use for volume objects recording [7] are decsribed in Section 4.

Diffraction gratings have been known for centuries for their ability to diffract light and to decompose white light into a rainbow band. The "optically variable" behaviour attracted attention of people looking for highly visible, eye-catching and difficult to copy features for various applications [8]–[11]. However, simplicity of diffraction gratings prevented scientists from using them for 3D-object visualisation until versatile, high-resolution grating printer were introduced in the last decade [1]. The author's own classification of diffraction gratings in visual applications and features of new technologies of grating recording will be described in more detail in Section 5.

2. Classical holographic techniques

Classical holographic techniques have an important feature in common such that they may record an image of an existing object only. Holograms are able to record in each point the whole information of how a given object looks from that point. They can be classified using several criteria. For the purpose of this study, we will follow such a way of image reconstruction in which hologram categories to be shortly described below are reconstructed with monochromatic light transmission holograms, white light transmission holograms and white light reflection holograms.

2.1. Coherent light transmission holograms

This type of hologram is typically recorded in a two-beam set-up where one beam forms light reflected or transmitted by an object and the second is an undisturbed expanded reference beam coming directly to holographic plate. Both beams impinge on the holographic plate from the same side. The recording is relatively easy and resulting image can be of good quality when reconstructed using monochromatic light. If white light is used, then the image becomes unsharp and often only irregular rainbow is visible. This type of hologram may not be used to record true-colour images.

Laser transmission holograms are rarely used in visual applications, except exhibition holograms, but even for these purposes white light reflection holograms are used more often. The laser transmission hologram is, however, an entry point (so-called H1 hologram) to record two other types in 2-step recording processes.

2.2. White light transmission holograms

Invented by Steve Benton, these are often called rainbow holograms. They are usually recorded from H1 hologram with a slit eliminating vertical parallax and making the hologram suitable for white light reconstruction. Due to the flat structure of recorded information such holograms are easy to obtain in mass-production and cheap, so they are very often used in visual applications where large quantity of 3D images is required.

Rainbow holograms may also be used to record 2D images either in the hologram plane (2D hologram) or in one or more planes outside the hologram plane (2D/3D holograms). Such rainbow holograms are relatively easy to record and even though they do not record an image of truly 3D object they have high visual appeal and are often used commercially.

White light transmission holograms can be used to record true colour images, however, three H1 holograms recorded using three different wavelengths are necessary for that purpose. The rainbow hologram reconstructs properly recorded true-colour image under strictly observed illumination conditions, otherwise colours become wrong.

2.3. White light reflection holograms

Often called volume holograms, they are recorded either directly from an object using one beam illuminating the object after passing through a thick (10 – 100 μm) photosensitive layer (Denisyuk set-up) or from H1 hologram in a two-step process. Volume holograms are also called "Bragg holograms" because the diffracting structure is a modulated Bragg grating. This means that when reconstructing the recorded image with the use of white reflection hologram, only the wavelength which fulfils the Bragg condition is selected, thus monochromatising the incoming light.

White light reflection holograms have the best 3D object reconstructing properties of all kinds of holograms and are very often used especially for exhibitions, valuable objects archiving and holographic portraiture. However, they are very difficult and expensive in mass-production, and thus are not manufactured in large quantities.

3. Holographic stereograms

Holographic stereogram is often called multistereogram to differentiate it from a stereopair. It is often very difficult to distinguish between classical hologram and the holographic stereogram because both can record an image of 3D object. However, while the hologram contains extremely large number of views of recorded object the stereogram usually contains from few to some tens of views, thus containing much less information than hologram. The in-plane resolution of stereogram is also usually much lower, up to 100 dpi.

On the other hand, there is no need to have an exact scale object for making stereogram; it is sufficient to have a set of views of the object either in the form of video sequence or a set of properly rendered views of digital model. This means that any 3D object, small or large, real or virtual, may be recorded by means of stereogram, being thus ideal for visual applications.

Holographic stereograms are usually recorded in the white light transmisssion form to allow mass-production. It is possible, however, to record stereograms in the form of an analogue to laser light transmission hologram, which enables the recording of volume holograms from transmission stereogram master.

The major disadvantage of stereograms is their limited resolution and number of views, which makes them unsuitable for applications requiring high resolution, such as document authentication.

4. Computer generated holograms

In today's holographic business many DOVDs, where computers are used in the measuring process, are referred to as CGHs. This refers to computer driven stereograms and dot matrix DOVDs where computers control the whole mastering process. However, for optical scientists involved in holography, they are not CGHs. For physicists, the term "computer generated hologram" means a diffractive structure strictly calculated (usually point by point) and accurately recorded to diffract light in the desired way [12]. Frequently, a CGH is able to form 2D or 3D images focused outside of the hologram plane. The CGH's surface profile or transmission should be a result of the wavefront calculation rather than the result of interference of two (or more) laser beams or analytic description of diffraction grating fringes.

The CGHs have been known for some 30 years and many scientific experiments have been performed to record good quality 3D images using several coding techniques. However, their quality has not been acceptable for visual applications. The HoloMax®, a CGH based optical technology of DOVD mastering, recently introduced offers high quality origination of CGH's for visual applications and other uses. Even that technology, however, is far from exploiting the whole potential of CGHs. This results mainly from the fact that strict and straightforward calculation of the wavefront necessary to reproduce a high quality 3D scene is enormous, even for present-day computers. In addition, modern laser printers which allow 1500 lines/mm resolution are not accurate enough to strictly record calculated structures.

Different features, aspects and perspectives of CGH based DOVDs classified by the author on the basis of available CGH recording technologies will be discussed in the following subsections.

4.1. Optically recorded CGHs

In the optical technology of CGH mastering (developed by the author and known under the name "HoloMax"), a holographic structure is first calculated using a special form of the Fourier transform iterative algorithm [4]. Grey scale map of CGHs structure is then displayed using an SLM in an optical set-up, photoreduced and recorded on a photosensitive material. Due to diffractive limitations, recording is not very accurate and the profile of resulting fringes is approximately sinusoidal. The optical behaviour of such DOVD, however, meets the expectations of DOVD designers, with all the optical effects present and the graphical resolution of CGH based optical DOVD reaching up to 20000 dpi. Features which lend themselves to optical recording with the use of CGHs are described in more detail below.

4.1.1. Flat cinematic CGH-based DOVDs

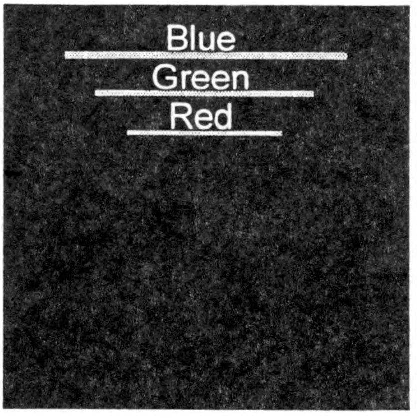
The most important part of any security DOVD is the high quality optically variable 2D graphics. Normally, diffraction gratings are used to record this type of drawing with cinematic effects. However, the use of CGHs for that purpose offers much wider, in fact unlimited, range of optical variability effects [6]. Different part of DOVD, not only appears/disappears like a grating, but may also change colour or appear several times with different colours. It is also possible to make flat cinematic DOVD containing hidden information associated with optically variable effects [4]. There is no rose without a thorn, however, any part of DOVD visible in more than one orientation, is significantly darker than a simple grating – energy must be conserved. This disadvantage is probably much less important than the distinguishable optical behaviour of CGH based DOVDs.

4.1.2. 3D images recorded using CGHs

A three-dimensional image constitutes the most characteristic feature of holography and a lot of people cannot imagine a "hologram" without 3D image. With traditional techniques it was difficult to combine high quality 3D images with high resolution, sophisticated flat graphics. The CGHs do it easily, combining "true colour", high-resolution 3D images with very high resolution, extremely sophisticated 2D optically variable graphics [7]. The 3D objects are recorded in the form of multistereogram with 20–50 views of the object as standard and a 3D image sampling resolution from 300 to 1200 dpi.

To calculate a CGH representing 1D colour view of a 3D scene, the following procedure is used. As the first step we take the set of colour views of recorded objects from the hologram plane. It can be a series of rendered images (in the case of a virtual 3D scene) or a set of digitised photographs (for real objects). Each image represents a view of an object from one direction. Basic colour views from one point in the hologram plane are composed of basic colour components from points at the same locations on subsequent images. In the second step, these three views are placed as three rows in the matrix representing the Fourier plane of the calculated CGH. Vertical positions of those rows correspond to spatial frequencies of diffraction gratings, which restore basic colours under predefined white -light-illumination conditions (Fig. 1). Horizontal position of pixel in the row represents direction of the view. The whole matrix represents amplitude to be restored from the CGH while a phase may be chosen freely. This means that the classical IFTA algorithm may be used to calculate the pure phase CGH [5], [6]. Finally, a set of CGHs of views taken from a matrix of points in the hologram plane is calculated this way (Fig. 2), forming the whole stereogram map. The visual quality of 3D image recorded using optical CGHs is much better than the quality of classical holographic multistereograms and slightly better than the quality of stereograms recorded using high-resolution gratings (described later on).

The only disadvantage of recording 3D images using CGHs is the complexity and time of calculations. It may take several hours to calculate CGH of 1″ square 3D scene.



▲

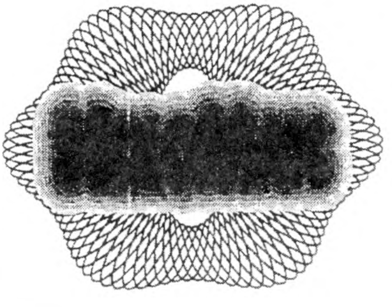
Fig. 1. Fourier transform of CGH forming one stereogram pixel; rows correspond to basic colours.

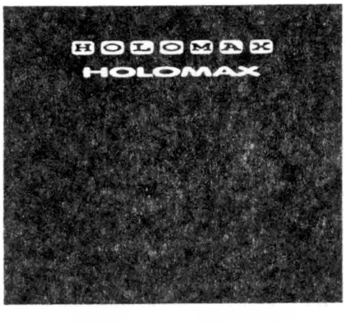
Fig. 2. CGH stereogram pixel to be recorded.

4.1.3. Hidden information coding using CGHs

It is possible to use a matrix of Fourier CGHs and DOVDs with hidden elements [4] – [6]. Matrices of CGHs may contain various elements distinguishable with the naked eye and/or available for machine readers. A modified iterative Fourier transform algorithm is used for kinoform calculations. Resulting CGH maps are used to print DOVDs on a HoloMax CGH printer.

The DOVD characterized by both visible cinematic effects and a hidden element distributed all over the element surface is built on the basis of an image shown in Fig. 3. Different CGHs are assigned to different colours of the basic image. In CGHs, we record Fourier spectra of maps of directions from which different colour areas are visible. Each colour is visible within a certain range of viewing angles. All of them are shown in Fig. 4. The term "map of directions" denotes a representation of spatial frequencies coded in a certain area of the DOVD. In most of the spatial frequencies





▲

Fig. 3. Graphic design of the OVD that contains several hidden elements assigned to different colours of the design.

Fig. 4. Spatial frequencies visible in the Fourier spectrum of the whole OVD.

no light is present, which corresponds to dark areas on the map of directions shown in Fig. 4. Some areas, such as outlines of the word HOLOMAX in Fig. 3, diffract light into narrow ranges of spatial frequencies. As a result, single letters from Fig. 4 form the corresponding maps of directions. Other areas are visible in a wide range of angles (similarly as in 2D rainbow holograms), therefore their respective maps of directions consist of horizontally long structures (*i.e.*, the whole word HOLOMAX in Fig. 4).

4.2. Non-optically recorded CGHs

Computer generated holograms are structures calculated with submicron accuracy and only approximately accurate recording enables one to exploit their whole potential. This means that microlithography-recording techniques are definitely the best way of recording CGH. Scientists have already used e-beam lithography to make various types of CGH, also for commercial applications like holographic optical elements. However, no commercial DOVDs based on CGHs were mastered using microlithography.

Electron beam or other microlithography recording techniques not only allow us to make more precise CGHs similar to optically recorded ones, but also make it possible to obtain several new types of CGHs where precise profile recording is essential. These types include (but are not limited to) asymmetric cinematic effects, new types of hidden and machine-readable features or sharp, full-parallax 3D images.

The new sophisticated types of CGH will however require a lot of computational power and microlithography machinery capable of handling far greater amount of data than in standard microelectronic circuit masks recording. It means that such an origination will be extremely expensive, so again the use of non-optically recorded CGH will be restricted to top security applications.

5. Diffraction gratings

Diffraction gratings, *i.e.*, periodic structures usually composed of parallel lines, have been known for centuries for their ability to diffract light and decompose white light into a rainbow band. This "optically variable" behaviour attracted attention of people looking for highly visible, eye-catching and difficult to copy features for different applications, especially for document and product authentication, promotion and product wrapping.

The concept of carrier frequency photography, developed in the 19th century, may be considered as a basic inspiration for creating most of the modern types of grating based DOVDs, in which different areas of graphical design are represented by different diffraction gratings. Such a DOVD contains easily visible, flat, bright and eye-catching image, which cannot be readily reproduced, thus forming a good anticounterfeiting measure [13]. Obviously, the DOVD's resistance to imitation attempts depends mainly on its resolution, quality of design, and quality of its mastering and production. Various types of grating based DOVDs have highly different visual properties, anticounterfeiting features and different ability to form 3D images. The approach to grating based DOVD classification taken by the author, with emphasis on 3D capabilities, is presented in the following subsections.

5.1. Optically recorded diffraction gratings

These types of gratings contain fringes being a result of interference of two coherent beams of light. The density of grating fringes may vary from ca. 500/mm to ca. 2000/mm. They have approximately sinusoidal profile of fringes that cannot be exactly controlled because of the diffractive limitations and the complexity of the photosensitive material development process. The contrast of fringes may slightly vary from point to point as a result of laser beam non-uniformity and noises in optical set-up. Brightness and overall optical quality of optically recorded diffraction gratings may be very high and the effective (practically useful) resolution of graphical design vary depending on an exact way of recording.

5.1.1. Holographic gratings based on DOVDs

Two-beam interference pattern recording is the standard way of making diffraction gratings for different applications. Two expanded beams of laser light interfere on the photosensitive plate recording the grating over a relatively large area. When used for DOVDs, recording is performed with the aid of additional mask, so only intended areas are exposed. There are usually several exposures, with different masks and grating parameters resulting in DOVD containing up to some 10 gratings. It is usually not reasonable to increase the number of different gratings too much, because the misalignment errors with exposures of smaller grating areas are more significant. The recording time is relatively short, but preparation of masks and the setting-up may take quite a lot of time, especially in the case of more sophisticated DOVDs with a lot of different gratings.

The overall quality of such a DOVD may be very high, but its useful resolution is severly limited, so is the range and smoothness of optical effects. However, when used together with other DOVD mastering techniques, classical grating may be really good counterfeit deterrence feature in product security applications. Optically recorded gratings may be used for 3D objects recording only as simple stereopair.

5.1.2. Dot-matrix DOVDs

A relatively new, but already widely available, diffraction grating mastering technology uses computer driven machinery to subsequently record small diffraction gratings (from 12 μm to 0.5 mm), resulting in useful design resolution from 50 to 2000 dpi. As each grating pixel is recorded separately, the fringes are not continuous between neighbouring dots, which makes the dots easily visible using the lens or microscope and differentiates dot matrix DOVDs from other types of grating based DOVDs. The discontinuity of fringes also makes highest resolution images a bit noisy and limits the possibility of increasing the graphical resolution.

Some new technologies derived from dot-matrix partially overcome this disadvantage introducing additional information recorded within each dot.

Dot-matrix origination technology is quite flexible as many different diffraction gratings may be exposed on DOVD allowing for quite fine 2D cinematic effects. It is also possible to record low-resolution (in both geometrical design and number of views sense) 3D stereographic images using the new type of dot-matrix systems and software. 3D-image recorded can actually contain up to 8 views of the object so its quality is significantly lower than that of traditional rainbow holograms, stereograms, and, especially, computer generated holograms.

Dot-matrix DOVDs are mainly used for 2D graphics recording, in particular, for promotional, packaging and sometimes for low security purposes.

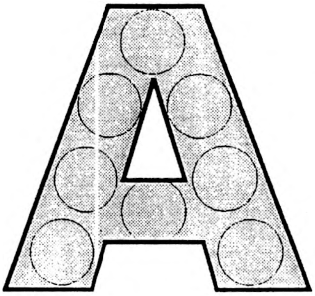
5.1.3. High resolution, optically recorded digital gratings

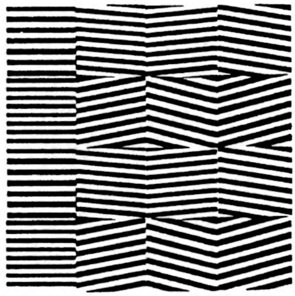
This new DOVD mastering technology has been developed by the author and co-workers and marketed by his company Polish Holographic Systems (PHS) under a "KineMax" trademark. The main feature of this technology is that several optical interference fields are recorded at the same time in different areas and give a multimode of gratings. A pitch and direction of fringes in each grating is accurately specified in design. All gratings are recorded within areas defined with resolution up to 6000 dpi, but resolution cells are not separated, they form continuous recording over relatively large areas.

Due to high design resolution and precise control of the parameters of gratings the technology allows efficient recording of 3D objects, hidden information in Fourier type holograms, and achromatic elements. The 3D objects can be recorded as "true colour" multistereograms composed of up to 30 views with 3D-image resolution of the order of 400 dpi. This makes their quality comparable to that of good holographic stereograms, moreover multistereograms have significantly higher image resolution. For grating-based multistereograms digital image data are prepared in the same way as for CGHs. However, instead of calculating CGH the basic pixel is composed of a set of diffraction gratings with spatial frequencies corresponding to directions of subsequent views and fringe contrast being responsible for the given point-direction combination amplitude. To record a "true-colour" multistereogram three sets of gratings corresponding to basic colours are recorded. The specific way of 3D pixel preparation developed by the author constitutes the know-how which belongs to PHS company.

The process mentioned above does not contain any Fourier transform calculations, and thus can be performed directly by grating recorder in line with recording. It is also possible, unlike in the CGH based stereogram, to scale 3D image without any additional calculations.

The Fourier hologram type hidden information is recorded in a somehow similar way. The 2D image to be recorded in hidden form is decomposed into limited number of dots – preferably not more than 20 (Fig. 5). Then a set of gratings is calculated, each grating with spatial frequency corresponding to co-ordinates of one point of 2D image. All gratings are next combined to form one pixel of a hidden





▲
Fig. 5. 2D image to be recorded in hidden form and its decomposition into dots.

Fig. 6. Pattern of gratings reproducing hidden info in Fourier plane.

information area (Fig. 6). As the arrangement of all gratings in the set can be chosen freely, it is possible to arrange them into a simple graphical microelement, which adds a new security feature to the DOVD design. This way of creating hidden elements using diffraction gratings only was developed by the author.

5.2. Non-optically recorded diffraction gratings

This family of DOVD originating technologies is in general characterized by the fact that microlithography engraving technologies, usually taken from microelectronics industry, instead of light interference are used for DOVD recording. Microlithography technologies are extremely accurate, but very expensive and time consuming, so these types of DOVD are usually available for high security applications only where cost is much less important than anticounterfeiting value.

Extremely precise recording technology allows us to achieve very high graphical design resolution (up to 25000 dpi), microscopic features visible using microscopes only and to use special fringe profiles impossible to record optically. The properly designed fringe profiles may have a look quite different and easily distinguishable from optically recorded DOVDs. All these features are obviously extremely advantageous in security applications, because they highly reduce the risk of making good, optical imitation of such DOVDs.

Because of very high cost of necessary equipment (from several hundred thousands of dollars for most primitive, old machinery to a few millions for modern equipment), microlithography based DOVD recording technologies are not widely available. This fact, together with special optical properties of DOVDs possible to achieve with these technologies, makes them the most appropriate for top optical security applications.

Using non-optial gratings for 3D image recording is theoretically possible (like high-resolution optically recorded digital gratings), but practical realisation is not easy, mainly due to severe limitations of microlithographic machinery not designed for such a purpose. Simple classification of non-optical gratings was prepared by the author with respect to their visual properties.

5.2.1. Binary gratings

This is the simplest of non-optical diffraction grating technologies. During the recording a binary profile is produced, which is the simplest profile possible to achieve with electron-ion lithography. The binary profile optical properties (lower brightness, higher noise) are significantly worse than properties of sinusoidal profile obtained in optical technologies, without an advantage of distinguishing look, specific only to more complex fringe profiles. Also the behaviour of thermoplastic foils embossed using a shim with binary profiles is quite unpredictable, with the final optical properties of DOVDs produced being highly dependent on foil type and embossing parameters. This disadvantage limits the suitability of binary gratings for visual applications, however, the very high resolution specific to microlithography recording is still present.

5.2.2. Blazed gratings

Diffraction grating with blazed profile is the simplest example of structure impossible to realise with optical means with highly distinguished look. Such a grating diffracts incident light mostly into one direction, making it very bright in one illumination/observation set-up and dark in all others, especially after rotation at 180 degree, where optically recorded sinusoidal grating would also be bright. Blazed profile requires (just like all other more sophisticated profiles) either multiple electron beam exposures or exposure with variable beam energy, both being much more difficult to do than simple binary exposure.

5.2.3. Curvilinear and other generalized gratings

Curvilinear gratings consist of fringes being smooth curves rather than straight lines like in common diffraction gratings. This causes special visual behaviour depending on the curve parameters. In a more general case, the shape, directions and pitch of grating fringes may be variable, enabling the manufacturing of DOVDs with very sophisticated and distinguishing optical behaviour. The best known examples of DOVD based on generalised gratings are probably Pixelgram® and Excelgram® by CSIRO from Australia.

5.2.4. Subwavelength gratings

This type of non-optically recorded gratings is characterised by typical grating pitch much less than wavelengths of visible light and precisely controlled profiles, calculated on the basis of strict solutions of the Maxwell equations set. Subwavelength gratings exhibit an optical behaviour completely different from that of all other diffraction gratings – the colour of directly reflected (not diffracted!) beam of white light is changing with an angle of incidence and an angle of rotation of such a grating in its plane. This effect is extremely difficult (practically impossible) to achieve using optical methods.

Subwavelength gratings are extremely difficult to emboss and apply with required level of accuracy, so they are not used too often in spite of their very promising security features.

6. Conclusions and perspectives of DOVD development

In this paper, after a brief description of classical holographic techniques, we have presented CGH and diffraction grating based DOVDs and their suitability to visual applications, especially in 3D object recording. In the part devoted to CGHs we have described the most important features of HoloMax, the only existing technology of mastering high quality CGH for visual applications. Then different kinds of diffraction gratings, with an emphasis on their 3D recording properties were shortly described according to author's own classification.

It has been shown that both CGHs and our technology of high-resolution optical grating recording enables high quality 3D object recording. The CGHs offer higher resolution than grating based DOVDs, slightly better image quality and some additional highly sophisticated features. However, for 3D object recording CGHs need a lot of complex calculations which must be repeated for every change of scaling. High-resolution optical gratings may be used to record 3D images without any additional calculations and these images can be scaled in any desired way.

It is always difficult to predict the future, nevertheless, it seems that combination of CGHs and grating based DOVDs into one optical diffractive device with synergetic potential is inevitable. Both techniques have their strengths and combining them is the only way to have really secured DOVD. For example, "Visa dove" is a nice and well-recognised DOVD, but is not perceived as a secure one because a lot of holograms are able to make similar holograms. Replacing it by a more detailed 3D CGH, combined with high resolution grating guilloche, microtext, and CGH containing machine-readable feature would make this DOVD more secure and maintain its high visual appeal.

Acknowledgments — I wish to thank Prof. Tomasz Szoplik from Warsaw University for encouraging me to carry on my work on DOVDs and CGHs.

References

[1] STĘPIEŃ P., Proc. SPIE **3973** (2000), paper 24.
[2] LOHMANN A.W., PARIS D.P., Appl. Opt. **6** (1967), 1739.
[3] LESEM L.B., HIRSCH P.M., JORDAN J.A., IBM J. Res. Dev. **13** (1969), 150.
[4] STĘPIEŃ P., GAJDA R., SZOPLIK T., Opt. Eng. **35** (1996), 2453.
[5] STĘPIEŃ P., GAJDA R., Proc. SPIE **2659** (1996), 223.
[6] STĘPIEŃ P., GAJDA R., MARSZALEK A., Proc. SPIE **3314** (1998), 231.
[7] STĘPIEŃ P., *Computer generated stereograms*, presented at Conf. *Diffractive Optics*, Jena, Germany, 1999.
[8] LEE R.A., Proc. SPIE **1509** (1991), 48.
[9] LEE R.A., *Security diffraction grating with special optical effects*, Australian patent application No. PL1316, 1993.
[10] ANTES G., *Document having an optical-diffraction authenticating element*, Swiss patent No. 5820/82, 1982.

[11] MOSER J.-F., *Document protection by optically variable graphics (Kinegram)*, [In] *Optical Document Security*, [Ed.] R. L. Van Renesse, Artech House, Boston and London, 1994, Chap, 9. pp. 169–185.
[12] BRYNGDAHL O., WYROWSKI F., *Digital holography — computer generated holograms*, [In] *Progress in Optics*, Vol. XXVIII, [Ed.] E. Wolf, North-Holland, Amsterdam 1990.
[13] SZOPLIK T., STĘPIEŃ P., BURSKI M., Proc. SPIE **2659** (1996), 181.

Received May 22, 2000
in revised form August 10, 2000