

## Methods and Applications of Optical Holography

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After invention of holography by Dennis Gabor in 1947 it is widely used in various areas. The development of new holography methods made it suitable for new industrial and scientific applications: printing, security and authentication, sensors, data storage, particles analysis, etc. This review will focus mainly on the development of the optical holography and its application for security and authentication. Other methods and applications such as measurements, particle analysis and data storage are discussed as well.

**Keywords:** holography, dot-matrix hologram, security and authentication.

### 1. INTRODUCTION

Dennis Gabor invented holography in 1947 [1] (Nobel Prize in 1971). It was dedicated for microscopy as was indicated in the article “Microscopy by Reconstructed Wave fronts” [2]. Gabor introduced the term of holography using two Greek words: ‘Holos’ – whole and ‘Graphe’ – writing. These two words mean that the recorded holographic image of the object contains whole optical information about the object – amplitude and phase information of the light scattered from the object. The word ‘Holos’ was used to distinguish the holography from photography, since in photography information of amplitude of the light is recorded only. Typically the hologram is a three-dimensional image reproduced from interference pattern recorded by coherent light beams and holography is a process of writing or reconstructing a hologram.

At the time when Gabor invented holography there was no coherent sources of light developed yet. Nikolai Bassov, Alexander Prokhorov and Charles Townes invented the laser in 1960 (Nobel Prize in 1964) and first ruby laser was developed [3]. The first practical holography methods were developed by Yuri Denisyuk in the Soviet Union [4] and by Emmett Leith with Juris Upatnieks in US [5] (Nobel Prize in 1964). Leith and Upatnieks succeed to overcome side effects (zero order and twin image) in Gabor’s “in-line” holograms using an “off-axis technique” borrowed from their work “off-side reading radar” [6]. Several types of holograms were developed at this time using different methods in holography. Denisyuk developed white-light reflection hologram and his hologram was the first one viewable in the white-light. Leith’s and Upatnieks transmission holograms was viewed illuminating them with the coherent (laser) light. First transmission holograms invented by Bennton in 1968 [7] were viewable in the white light also.

Despite that the Gabor’s inventing was originally dedicated to microscopy a lot of holography application was in different areas such as art, decorating, packaging,

advertising and entertainment. For example Benton invented transmission rainbow holograms during his research in holographic television at Polaroid Research Laboratories. The development of new holography methods made it important to various industrial and scientific applications: printing, security and authentication, sensors, data storage, particles counting and manipulation, etc. In this review we will focus on the development of optical holography methods and its application in security, authentication, measurements and data storage.

### 2. BASIC PRINCIPLES OF HOLOGRAM RECORDING AND IMAGE RECONSTRUCTION

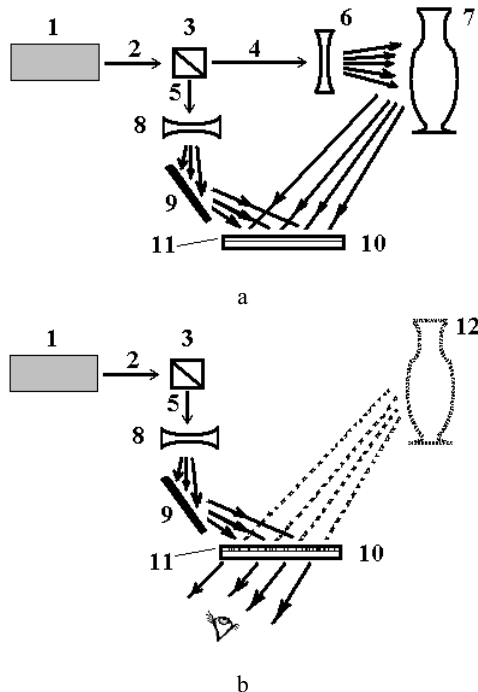
For clarity of how the image in hologram is recorded and reconstructed, an example off simplified “off-axis” process for 3D transmission hologram formation is described below. Optical setup for transmission hologram recording process comprises of the source of coherent light, optical table, recording media and optical-mechanical components. Recording media should have sufficient resolution, for example the silver halide emulsion layer or photoresist layer on glass plate can be used for hologram recording process.

In Fig. 1 the principle optical scheme for transmission hologram recording and reconstruction processes is presented. Here the beam splitter 3 is used to split primary laser beam 2 in two beams: object beam 4 and reference beam 5 (Fig. 1, a). Object beam 4 illuminates the object 7 through the concave lenses 6. Expanded reference beam 5 is directed by mirror 9 to thin photosensitive layer 11 on the surface of glass plate 10. Light scattered from the surface of the object 7 overlaps with reference beam on the surface of the layer 11. There the pattern of interference of reference beam and scattered light is recorded for appropriate time. After developing in liquid developer the plate is dried in air thus finishing hologram formation.

For hologram image reconstruction the similar optical setup is used (Fig. 1, b). The reference beam 5 illuminates hologram and undergoes diffraction in recorded interference pattern in layer 11. Diffracted light creates the

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virtual image 12 of recorded object. The image 12 can be viewed (Fig. 1, b) at the same direction in which scattered object beam propagated towards plate during hologram recording process (Fig. 1, a). Different parts of object can be viewed at different viewing angles while changing position of the viewer creates parallax effect and a three-dimensional image is perceived.



**Fig. 1.** Optical scheme for 3D transmission hologram recording and image reconstructing process (a top side view): a – hologram recording using splitted laser beam, b – image reconstruction illuminating developed hologram with reference beam (1 – laser, 2 – primary laser beam, 3 – beam splitter, 4 – object beam, 5 – reference beam, 6, 8 – concave lenses, 7 – object, 9 – mirror, 10 – glass plate, 11 – photosensitive layer)

The main disadvantage of this type of hologram is the necessity of coherent light source for hologram image reconstruction. Various methods were developed to overcome this limitation – some of them are mentioned in the Introduction. On the other hand, the necessity of coherent source for image reconstruction is not a disadvantage in some areas of holography application, a good example for this is the holographic data storage - data recording and reading processes are realized using the same laser beam. In the following section development of the main methods and application of holography for security and authentication will be described.

### 3. HOLOGRAPHY FOR SECURITY AND AUTHENTICATION

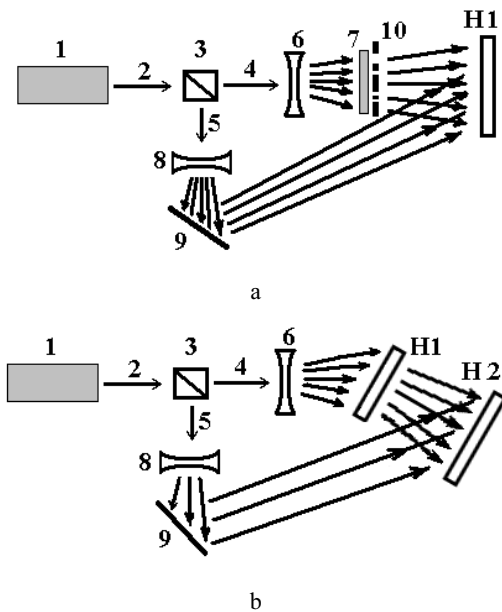
Security and authentication is most common area for holography and diffractive optics applications: The increase in demand on security is dictated by steady growing rating of counterfeiting and piracy. Analysis carried out by Organization for Economic Co-operation and Development (OECD) showed that amount of counterfeit and pirated products in 2005 was about USD

200 billion [8] and in 2007 reached USD 250 billion [9] in the world market. Various types of holograms and Optically Variable Devices (OID) and Optically Variable Image Devices (OVID) are widely used to improve security of documents for anticounterfeiting and for brand authentication [10, 11]. Holograms and OVIDs have clear advantages in this area due to several reasons and first is the esthetic: most of the holograms or OVIDs are designed to make positive impression to viewer and can be exploited for advertising purpose. The second reason is that they are easy recognizable by inexperienced user – that allows almost every user to identify them without any equipment – so called “first line inspection”. The third reason is that manufacture of holograms and OVID is complicated, it requires expensive equipment and well-trained personnel to run the process and it is limiting factor for potential forgery. And the final reason is that most types of holograms are relatively cheap at the mass production.

Most impressive appearance of security holograms is the image presented by white-light 3D reflection holograms. They can be viewed in ambient light and represents true three-dimensional image of recorded object. Viewed from different sides it shows different parts of recorded object. Most common example of 3D hologram application for authentication is a hologram label on the backside of Nokia’s cell phone battery. Viewed from the different angles it shows different number of dots on the Nokia Original Enhancements logo sides. The description of exact sequence of dots appearance in the original hologram label is given on the Nokia’s website for end-user convenience [12]. Here three goals are achieved in single hologram: spectacular image, easy identification and increased protection due to complicated and expensive manufacturing process. Since invention of the first 3D holograms by Denisjuk, Leith and Upatnieks [4, 5], new techniques were invented for improved and more sophisticated 3D holograms [13, 14]. Nevertheless mostly traditional reflection 3D holograms are widely used for security and authentication and in some cases they are combined with different types of holograms or OVD [15]. Nowadays development of 3D holography is focused on holographic media that can be erased and rewritten [16] and on new methods for 3D TV [17–19].

One of the popular type holograms used for anticounterfeiting is 2D/3D hologram [20]. These holograms are recorded in two steps: at first the images of flat two-dimensional transparent objects 10 are recorded through diffuser 7 on hologram H1 using reference and object beams (Fig. 2, a), afterwards the hologram H1 is developed. At the next step the hologram H1 is illuminated with the object beam 4 and images reconstructed from the hologram H1 are recorded on the surface of hologram H2 (Fig. 2, b). When the hologram H2 is illuminated with white-light the images of recorded objects appear at the different depth with regard to the surface of the hologram creating perspective effect. Changing viewing angle in horizontal plane makes images to overlap or separate from each other creating parallax effect. Both effects create an impression of three-dimensional image. The term of 2D/3D hologram commonly used for this type of hologram is due to the fact that hologram creates a 3D image impression though the 2D objects are used for hologram recording.

Relative simplicity of recording process and impressive appearance determined popularity of 2D/3D holograms.

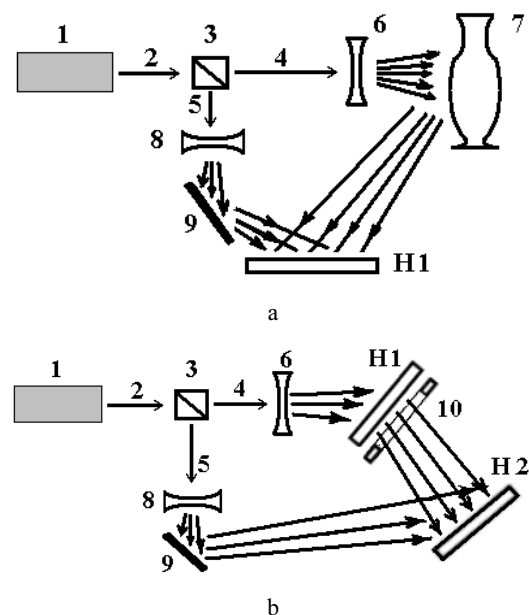


**Fig. 2.** Recording processes of 2D/3D hologram (a top side view): a – flat two-dimensional object is recorded in hologram H1; b – reconstructed image from the primary hologram H1 is recorded in secondary hologram H2 (1 – laser, 2 – primary laser beam, 3 – beam splitter, 4 – object beam, 5 – reference beam, 6, 8 – concave lenses, 7 – diffuser, 9 – mirror, 10 – transparent 2D object, H1 – primary hologram, H2 – secondary hologram)

Transmission “rainbow” holograms [7] are viewable in the white-light and presents brighter image when compared with 3D reflection holograms. After invention by Benton, the recording process of rainbow hologram is almost unchanged although some improvements were developed [21, 22]. In the process developed by Benton at first the 3D transmission hologram H1 is recorded (see Fig. 3, a). In the second step the developed hologram H1 is used to record second hologram H2 through the narrow horizontal slit 10 (see Fig. 3, b). During recording process of hologram H2 the horizontal slit suppresses information in vertical plane. Therefore no three-dimensional effects are visible when hologram H2 is viewed at different angles in vertical plane. Instead of it the bright image of recorded object is presented in different colors: from red through orange, yellow, green blue, indigo and violet, the same sequence as in real rainbow. Such a colorful, iridescent image was the reason for term “rainbow” hologram. If the hologram is viewed at different angles in horizontal plane, the object of one color is visible and it represents all three-dimensional effects (perspective, parallax and overlapping objects). United States Banknote Company (USBC) was first commercial user of embossed rainbow holograms in 1980 and rainbow holograms were the first application of holography for bank credit card security introduced by MasterCard International, Inc. in 1983.

The most common type of holograms used for authorization of products and against document forge is so called dot-matrix hologram. As the term implies the hologram surface consists of array (or matrix) of dots. Dot-

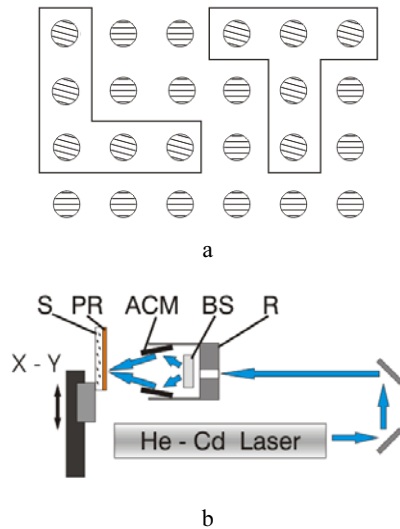
matrix method is based on surface relief structures and diffractive optics technology therefore belongs to DOVIDs (Diffractive Optically Variable Image Devices). Dot matrix method also falls into group of holograms designed and produced using computer software therefore the image of non-existent virtual object can be created as well as image of the real object. The background for this method was made by invention of single laser beam data recording devices [23, 24], so called “dot-matrix printers” [25, 26] and a digital ink-printing device [27]. Later the Laser Interference Lithography (LIL) was employed for image formation – the interference pattern of two laser beams intersecting in small area (so called dot or pixel) was used for three-color dot-matrix image recording process [28]. In this technique every dot contains diffraction grating and is recorded separately in sequential order one after another covering most of the hologram surface. When hologram is viewed in white-light the color of each pixel in the image is predetermined by the interference angle between reference and object beams used in recording process therefore image of the recorded object appears with various effects of movement and shape changes. In 1990 the holographic diffraction grating patterns method was invented [29] where the diffraction grating is employed as laser beam splitter and each dot have variable grating pitch, shape, orientation angle and adjusted exposure time. Most of today’s dot-matrix hologram equipment is based on this approach [30]. Modification to this technique was made later introducing reference beam modulation and various laser beam splitters [31, 32].



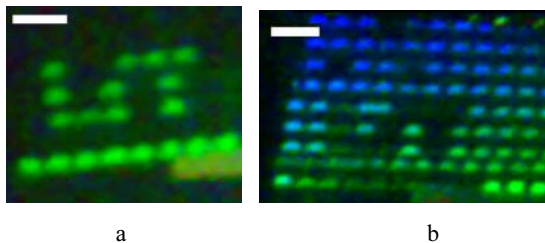
**Fig. 3.** Transmission “rainbow” hologram (a top side view): a – an image of three-dimensional object is recorded in hologram H1; b – reconstructed image of hologram H1 is recorded on a hologram H2 through the narrow horizontal slit (1 – laser, 2 – primary laser beam, 3 – beam splitter, 4 – object beam, 5 – reference beam, 6, 8 – concave lenses, 7 – object, 9 – mirror, 10 – narrow horizontal slit, H1 – primary hologram, H2 – secondary hologram)

The simplified approach for recording process of dot-matrix hologram can be used where the diffracting grating pitch is constant and angle of graining orientation is

variable (Fig. 4, a) [33–35]. In this case the optical scheme can be either symmetrical (Fig. 4, b) [35] or asymmetrical [33]. Reconstructed image depends on viewing angle, dot's placement and orientation angle of diffraction grating. When simplified dot-matrix hologram is viewed in white-light at different angles in vertical plane it represents image of different colors. Alternatively, main object and background can be viewed separately (Fig. 5, a and b) if hologram is viewed at different angles in horizontal plane.



**Fig. 4.** A simplified approach for recording process of dot-matrix hologram (a top side view): a – variable grating orientation angle, b – top view of symmetrical optical setup (X-Y – translation stage, S – substrate, PR – photoresist layer, ACM – aluminum-coated mirrors, BS – beam splitter, R – motorized rotation stage) [35]



**Fig. 5.** Simplified dot-matrix hologram viewed at different angles in white-light: a – the main object; b – background [35]

A simplified dot-matrix hologram manufacturing process is cost-efficient and it served well for its popularity. But it also has a major drawback, namely reduced security features. The demand on optical security level is growing steadily and the most convenient way to be at the cutting edge of it is to combine different hologram origination methods in one hologram. Security features of simplified dot matrix hologram can be increased combining it with rainbow hologram [36]. For the same reasons dot matrix holograms were recorded employing Electron Beam Lithography (EBL) instead of LIL process [37,38]. Further increase in security of dot-matrix hologram was achieved combining both EBL and LIL methods together as described in [39]. It should be noted that the EBL process requires complicated equipment and appropriate knowledge thus employing it can reduce

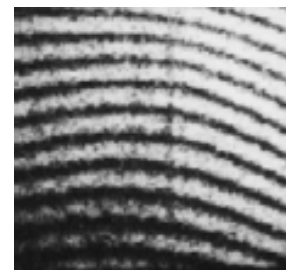
potential forgery however it is also quite expensive approach for hologram manufacture.

In 1965 the digital methods for optical filtering were invented [40–42]. Developing this method led to invention of CGH (Computer Generated Hologram) employing binary mask to record two-dimensional [43, 44] and three-dimensional objects [45, 46] viewed in coherent light. The CGH is based on numerical computation of virtual wavefront therefore requires substantial computing resources. For improved security the Electron Beam Lithography is used for CGH recording process [47]. It should be noted that CGH method also possesses ability to record image of nonexistent objects. It is well known that laser beam has Gaussian profile of intensity and some times such beam shape is disadvantage [48]. Due to precisely calculated reconstructed wavefront of CGH it is widely used for desirable spatial intensity profile configuration of a laser beam [49].

Another type of computer generated OVD is KINEGRAM® introduced by a company “OVD Kinegram” [50]. In 1986 the first KINEGRAM® was used for ID document – Saudi Arabian Passport protection. Later, in 1988, the first world banknote was protected using KINEGRAM® when Austria issued the 5000 Schilling banknote. When viewed in white-light KINEGRAM® represents two-dimensional images with kinematics, color and contrast changing and other effects [51].

#### 4. HOLOGRAPHY FOR MEASUREMENTS, PARTICLE ANALYSIS AND DATA STORAGE

Holography methods and techniques described above are mostly applied in security printing. At the same time holography applications for various measurement methods were developed as well. In 1965 Robert Powell and Karl Stetson published their work on holographic interferometry [52] for real-time vibration analysis of diffuse objects. This method is based on 3D hologram image recording process (see Fig. 1, a) and enables precise measurements (accuracy – tenth of  $\mu\text{m}$ ) of displacements of rough objects.



**Fig. 6.** Holographic interferometry (double exposure technique): interference fringes of thermally treated holographic plate. Reprinted with permission from [54]

Three main techniques are used for that purpose: double-exposure, time-average and real-time techniques. In the first approach – double-exposure technique, the image of the object is recorded two times on the same holographic plate. At the first step the image of untreated object is recorded and secondly, the second image is recorded after the object was treated mechanically,

thermally etc. When the hologram is reconstructed in coherent light it generates two wavefronts – one from image of object in primary state and another from image of object after treatment [53, 54]. The interference of both wavefronts produces fringes on reconstructed 3D image of object (Fig. 6). The spacing between fringes depends on wavelength of used laser and displacement value while pattern of fringes indicates the displacement vector of surface during treatment therefore precise value of object displacement can be calculated.

Time-average technique is dedicated for the analysis of vibrating objects [52, 55]. It uses long exposure of vibrating object during hologram recording process. In the interference pattern of reconstructed image the bright fringes corresponds to the nodal lines of vibrations and the amplitude of vibrations is calculated from fringes number [56].

For real-time technique the image of object in primary state is recorded on hologram plate. After recording process the hologram is developed and placed in the same place as it was during recording process. The placement of developed hologram has to be precisely the same (in order of  $\lambda/2$  of used wavelength), therefore usually the hologram is developed without removing it or the media with self-developing abilities is used [57]. The developed hologram is illuminated with the reference beam and the object is illuminated with object beam. Light reflected from the object interferes with light of reconstructed image and when object is moved or distorted the interference pattern appear on image. From the interference pattern the defects that are hidden inside object can be detected [57].

Another application of holography in measurements is holography for particle analysis used for particles sizes, placement and movement measurements. At its early stage HIPV technique (Holographic Particle Image Velocimetry) was used in analogue form where hologram was recorded on holographic film or plate [58]. In mid 1990s the digital processing of holographic film was implemented [59, 60]. Later the film was replaced with electronic image sensor [61] eliminating the wet chemical processing step. However true digital HIPV was developed only after the appropriate algorithms were implemented to replace the cumbersome optical reconstruction through the numerical reconstruction algorithms [62–64]. HIPV is particularly interesting for high-speed phenomena analysis as in fluid mechanics, for example Soulez et al. [65] demonstrated new approach for analysis of diameter, position and movement of particles from 3.5  $\mu\text{m}$  to 50  $\mu\text{m}$  in size with position precision of about 1  $\mu\text{m}$ .

Holographic data storage is most promising approach as high-density data recording and reading method. With development of computers and Internet the demand for data storage is increasing steadily: replacement of the floppy disks with CD devices was followed by implementation of DVD and Blu-ray Disc<sup>TM</sup>. The next candidates in this area are “near field” recording devices and optical holography [66]. In the near-field recording devices the NA (Numerical Aperture) exceeds one and spot sizes are squeezed down to hundreds of nanometres. Such approach requires placement of the optical head in close proximity to recording media due to short focusing

distance and it is serious drawback if media replacement option is required. It should be noted that all the methods listed above employs sequential data recording system i.e. each bit of data is recorded individually on the surface of the media. Holographic optical data storage is capable to record data in parallel mode – stacks of bits are recorded at the same time thus increasing data transfer rate significantly. Another advantage of holographic data storage is that data is recorded in the volume of media thus data density can be much higher. Developing of holographic data storage started in 1960s when P.J. van Heerden published his work "Theory of Optical Information Storage in Solids" [67] and predicted storage capacity of the order of  $10^{12}$ – $10^{13}$  bits per  $\text{cm}^3$ . Nevertheless the real development started in 1980s when compact lasers and appropriate I/O devices become available in the market. The first fully operational holographic data storage systems were described in mid 1990s [68–70]. System presented by IBM Almaden Research Center demonstrated a data rate of 1 Gbit/s and a BER (raw Bit-Error Rate) as low as  $2.4 \cdot 10^{-6}$  was demonstrated. The iron-doped lithium niobate ( $\text{LiNbO}_3$ ) crystals as media and Kodak CCD  $1536 \times 1024$  array of 9  $\mu\text{m}$  detector pixels were used [70]. Today's systems also uses  $\text{LiNbO}_3$  crystals as recording media [71] and polymers as well [72, 73].

## 5. CONCLUSIONS

Since invention of holography various holography methods were developed exploiting its unique features. Capability to record the phase information of the light is the main difference distinguishing it from traditional photography. This exceptional feature made holography suitable for various industrial and scientific applications. Nowadays numbers of different holography methods and their combinations are widely used in document security and authentication along with others OVDs. Development of computers and new powerful numerical algorithms made possible holography to be used for particle analysis. Analysis of holography development showed that in upcoming years holography application in industry will cover new areas such as data storage and 3D displays.

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