Holographic applications based on photopolymer materials

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Abstract

Photopolymer materials are widely used in many holographic applications because of their advantages. This paper reviews the various holographic applications which either require the high index modulation including optical demultiplexer, color-display filter, and polarization-selective element, or need the stability and long life such as holographic memory and security card system.

1. Introduction

Holography is a method of reproducing a three-dimensional image of an object by means of a hologram, which is the photographic plate or film recorded light wave patterns. These patterns are the intersection of two coherent light beams. One coming from object is called the object beam, and the other is the reference beam. When the hologram is illuminated with the reference beam, it produces a light beam essentially identical to the object beam, which is used in its recording. Historically, in 1947, the principle of holography was invented by scientist Dennis Gabor, who afterward was awarded the Nobel Prize in Physics for that discovery. However, it took a further two decades before the technology was developed to put this principle into practice. With the advances in laser and material technologies, the holography industry is growing rapidly. There is a wide variety of current and potential applications for holography. The use of holographic three-dimensional images is probably the most familiar application. These images are typically used on credit cards and for product advertisement and promotion. In these applications, holograms add both eye appeal and security. Holographic images are also used in nondestructive material testing. Holographic optical elements can be made in large thin films for use in solar lighting control and solar energy collection, and they can be made very small for use in optical communication systems. Narrow-band holographic mirrors may also be useful for laser eye protection or for filter in display system. Optical computing, pattern recognition, and very-high-density information storage are other potential applications of holography.

Many holographic applications require the high performance that is possible only with "phase" holograms, in which the original interference pattern is recorded as a refractive index variation. One of them is photopolymer [1, 2]. The interest in using photopolymers for holography increased when DuPont developed a family of photopolymers that present nearly ideal holographic properties including high reliability, large thickness for volume application (up to 100µm), high index modulation (0.06 for the film HRF-700), dry processing, reasonable shelf life [3], and low price that is very important in the case of large volume production. Nowadays, many research attempts on creating the better
photopolymer materials with the aim of satisfying the requirements of the holographic applications in many fields. In this paper, some holographic applications based on photopolymer materials are overviewed.

2. Photopolymer characteristics

The photopolymerizable systems generally can be classified into either liquid compositions or dry films. In this section, however, the structure, the composition, and the recording mechanism of DuPont photopolymer, a typical dry film system that is used in the holographic applications mentioned afterward, are presented. Descriptions of other systems can be found in other documents such as Ref. [1]; these are outside the scope of this paper.

The holographic photopolymer film has a three-layer structure shown in Fig. 1. The emulsion of photopolymer layer is sandwiched between a 50-µm Mylar base and a thinner cover sheet of Mylar. The cover sheet can be peeled off easily. On the other hand, the Mylar base cannot be removed before the polymerization is complete. Prior to exposure, normally, the cover sheet is removed leaving the tacky photopolymer on its Mylar base. The tacky photopolymer is then hand laminated onto a glass plate by means of the rubber roller to prevent air bubbles from being trapped at the photopolymer-glass interface. This preparation process may be performed under a red safelight because the films have very poor sensitivity in the red region.

![Figure 1. Photopolymer structure](image)

The general composition of photopolymer material typically consists of polymeric binders, monomers, and plasticizers, along with initiating systems including photoinitiators, chain transfer agents, and sensitizing dyes [4, 5]. The binder acts as the support matrix containing the other film components. The monomers serve as refractive index “carrier”. The choice of monomer and binder affects the physical properties of the film and the magnitude of the index modulation (\(\Delta n\)) recorded in the film. The sensitizing dyes absorb light and interact with the photoinitiators to begin photopolymerization of monomers. The proper choice of components allows tailoring of material and holographic properties to specific applications or end uses.

A mechanism based on monomer diffusion best describes the formation of refractive index modulation. During holographic recording, the film is placed within an interference pattern formed by the intersection of two laser beams. The interference pattern consists of a sinusoidal variation of bright and dark fringes due to constructive and destructive interference. In the bright fringes, the sensitizing dye absorbs light, interacts with the initiators, and creates free radicals. The polymerization, which is the combination of monomers with those radicals, then occurs. As monomer is converted to polymer in these regions, fresh monomer diffuses in from neighboring dark regions, thus setting up concentration and density gradients that result in refractive index modulation. During the
exposure and polymerization processes, the initial highly viscous composition gels hardens, diffusion is suppressed, and further increase in the index modulation of the recorded hologram is arrested. At this point, a hologram exists in the film, which is easily viewable. The holographic image consists of polymer-rich regions that monomer diffused into and binder-rich regions that it diffused away from, with some residual un-reacted monomer distributed throughout, as shown in Fig. 2. After holographic exposure, the film is subjected to a UV cure to fix the image. Finally, if needed, a post baking enhances the refractive index of the polymer and thus the diffraction efficiency.

**Figure 2.** Process of the index modulation in photopolymer

The photopolymer can record holograms with nearly 100% diffraction efficiency. Figure 3 shows an exposure curve for two plane wave transmission grating in the 38-µm thick film with the intensity of 3.0mW/cm² for each recording beam. A small delay has been observed during which the growth of the grating seems to be inhibited. This latent period is due to the presence of oxygen molecules in the material that inhibit the photochemical reaction of the polymerization. Under the high recording intensity, the index modulation grows up rapidly until most monomer is depleted. Continuing exposing the photopolymer, the exposure process comes into the saturation status, which the diffraction efficiency is not changed much.

**Figure 3.** Diffraction efficiency of the photopolymer depends on the exposure time

Other distinct advantages of the photopolymer enumerated are extended shelf life before and after imaging, high photo speed, higher index modulation, and broader spectral sensitivity. Further, they can be thermally processed (heating at about 100ºC for 20-60
minutes and then cooling to room temperature) to obtain higher efficiency and bandwidth. The final holograms are insensitive to humidity and temperature and can be conveniently mounted onto paper, glass or plastic, or even be embedded in acrylics. The ease of use and simple processing requirements allow these materials to be amenable to mass production of holographic optical elements.

3. Holographic applications

With these advantages, photopolymer materials are utilized in many holographic applications including those which need a single grating with high diffraction efficiency such as optical demultiplexer, polarization-selective device, or display filter and those which multiplex multi-holograms on the same volume position. In this section, they are described briefly as typical applications of photopolymer.

3.1 Holographic optical demultiplexer

In the DWDM system, optical demultiplexer is one of the key components [6]. The performance of these devices determines the overall system capacity. In the initial systems, dielectric filter technology was the preferred method. However, as the channel spacing decreased and channel count increased other technologies such as fiber Bragg gratings (FBG) and arrayed waveguide gratings (AWG) became applicable. Today, these and other technologies are competing for advanced applications. Optical demultiplexer based on holographic volume grating is a potential device [7]. One of the significant advantages of this type is that only a single grating is required, all the channels are operated on in parallel. Its simple and compact structure that consists of a collimating lens, a volume grating, and an output lens is shown in Fig. 5. The polychromatic light going out from the input fiber impinges on the grating at the Bragg angle after being collimated by the collimating lens. Because of the dispersion property inherent to the volume transmission grating, the channels are separated angularly.

The output lens turns these angularly separated waves into spatially focused points where the fibers are placed. The fiber separation versus wavelength is given by

$$\Delta d = \frac{F\Delta \lambda}{\Lambda \cos \theta}$$

where $\Lambda$ is the grating period, $\Delta \lambda$ is the channel spacing, $\theta$ is the incident angle, and $F$ is the focal length of the output lens.

![Figure 5. Structure of a demultiplexer based on the photopolymer volume grating](image_url)
It should be noticed that the holographic transmission grating has a large wavelength selectivity under which all of channels can operate with high diffraction efficiency or low insertion loss. For example, if the grating of 1.05-µm grating period is recorded in the HRF-150-38 photopolymer of 38-µm thickness, it will have about 73-µm wavelength selectivity, enough for 80 channels of 0.4-nm channel spacing with acceptable channel uniformity. When the holographic grating is uniform, the spectral response of a channel is similar to sinc function. However, in the case of an apodized grating whose diffraction efficiency profile is Gaussian, for instance, the spectral response has Gauss shape, as shown in Fig. 6. It is obvious that with apodized grating, the side lobes are suppressed about 15 dB, and therefore, the interchannel crosstalk is reduced. The price paid for that suppression, of course, is the high insertion loss due to the lower diffraction efficiency at the outer part of the Gaussian grating.

![Figure 6. Spectra of two output channels with 0.4nm channel spacing for (a) Uniform grating and (b) Gaussian apodized grating](image)

The performance of the apodized grating working as a 42-channel demultiplexer is drawn in Fig. 7. The channel characteristics have been measured in the flat region (1540-1557 nm) of the EDFA (Erbium Doped Fiber Amplifier) source. For all 42 channels, the interchannel uniformity of 1.5 dB is achieved. Two adjacent fibers are separated by 122.5-µm distance providing the wavelength spacing between each channel of 0.4 nm. Especially, the interchannel crosstalk level is about -30 dB.

![Figure 7. Spectral response of 42-channel demultiplexer with 0.4 nm channel spacing.](image)
3.2 Holographic polarization-selective element

Polarization-selective elements (PSEs) play significant roles in several applications such as optical switching networks, optical interconnection networks, and magneto-optical pick-up heads [8]. Those devices are moving towards compactness and integrated structure. For example, in a magneto-optical storage system, a pick-up head, a component employed to receive and analyses the polarizing variation of the reading beam, should be light weight, high efficiency, and stable operation. Conventional PSEs made of anisotropic materials do not satisfy these requirements. They have bulky dimensions and high loss. Another approach that can be considered is the use of holographic volume grating as a polarizing beam splitter. Recorded in a thin film of photopolymer, the grating is not only small in size but also good extinction ratio and low loss.

The principle of the polarization selecting capability of holographic grating is pointed out by the coupled wave theory. It states that the grating strength for p-polarized component is the product of that of s-polarized component and the cosine of the angle between the readout and the signal wave. The diffraction efficiencies when Bragg condition is satisfied are written as

\[ \eta_{s,p} = \sin^2 \nu_{s,p} \]  

(1)

where the grating strengths, \( \nu_s \) (for s-field) and \( \nu_p \) (for p-field) are given by

\[ \nu_s = \frac{\pi L \Delta n}{\lambda \left[ \cos \theta_R \cos (\theta_S - 2\psi) \right]^{1/2}} \quad \text{and} \quad \nu_p = \frac{\pi L \Delta n}{\lambda \left[ \cos \theta_R \cos (\theta_S - 2\psi) \right]^{1/2}} \cos (\theta_S - \theta_R). \]

Here, \( \Delta n \) is the index modulation, \( L \) is the grating thickness, \( \lambda \) is the reconstruction wavelength, \( \theta_R \) and \( \theta_S \) are the reconstruction and diffracted angles measured in the material, respectively, and \( \psi \) is the slant angle of the fringe plane with respect to the normal to the surface of the recording medium. For the simplest case, when the unpolarized light impinges on a volume grating, the diffracted beam will be s-polarized if it is perpendicular to incident beam.

Figure 8 shows a possible structure of a PSE for a dense magneto-optical pick-up head system. It simply has a holographic polarizing beam splitter (H-PBS), a holographic input grating (HIC), and a dove prism coupler. The HIC turns the perpendicularly incident unpolarized beam to 45 degree, which is the Bragg angle of H-PBS. Hence, the diffracted beam is normal to the transmission beam, and those are coupled out by the dove prism coupler. If the H-PBS has high diffraction efficiency for s-field, the transmission beam will be p-polarized. In other words, the PSE with high-extinction ratio will be obtained.

![Figure 8. Structure of a polarization-selective element (top view)](image-url)
The fabrications of the HIC and the H-PBS on photopolymer are straightforward by recording them in series. There is a practical problem with the HIC due to the shrinkage of the photopolymer after UV exposing [9]. It rotates the fringes in the HIC, therefore change the direction of the diffracted beam, and then make it not match the Bragg angle of H-PBS well. However, it can be complemented by changing the angle of the recording beams. Since the photopolymer has the stability of the shrinkage amount, it is suitable for mass production. This is an advantage of the photopolymer over dichromated gelatin.

The polarization properties are depicted graphically in Fig. 9. It can be observed that the extinction ratios of signals in diffraction channel ($\eta_B$ / $\eta_P$) and in transmission channel ($\tau_P$ / $\tau_S$) are approximate 91 and 11, respectively. Although its properties are not as good as those of a conventional PSE based on the spatial varying optical anisotropy, this device can still be successfully applied to magneto-optical pick-up systems.

![Figure 9. Polarization properties of the PSE](image)

3.3 Holographic color filter

Color filter or spectral filter can be found in many applications such as displays and optical spectrum analyzers. They block undesired spectrum while transmit the others, or they deflect the polychromatic light to different directions depending on wavelengths.

![Figure 10. Principle structure of reflective color LCD](image)
Holographic color filters (HCF) have been widely used [10, 11]. Figure 10 shows an application of HCF in color LCD. Based on the photopolymer materials with dry process, the volume phase holograms have high efficiency and can be mass-produced. As known, for a volume grating, the wavelength with respect to the angle at which it is most diffracted obeys the Bragg condition given by \( \lambda = 2\Lambda \sin \theta_0 \).

The filtered wavelength range can be changed by increasing fringe spacing using color tuning films or by the deliberate shrinkage/swell of the grating [12]. In the former, after being recorded and UV fixed, the hologram is laminated to the color tuning film (CTF). Then, that laminated film is baked in a forced-air convection oven at 100ºC for 30 min. By the diffusion of monomers from the CTF into the holographic recording film (HRF), the hologram’s playback wavelength is shifted and retained permanently. The process creating the color filter matrix using CTF is shown in Fig. 11. A note is that the diffusion lengthens the grating period, which makes the playback wavelength longer.

Figure 11. Fabrication of the color filter matrix using CTF

In the second method, the recorded grating is pressed by a mask during the heating so that the grating period is shrunk until the preferred refracted wavelength is reached, as shown in Fig. 12(a). This technique does not much change the diffraction efficiency and the bandwidth either. The experimental results for OmniDex 706 photopolymer sketched in Fig. 12(b) present these advantages. In addition, the processing time is short, and the pixel size can be very small. However, after the embossing force is released, the restoration of the grating period can happen along with time.

Figure 12. (a) Principle and (b) experimental result of press-based color tuning method
3.4 Holographic data storage and digital holographic security card system

Describing the holographic applications of the photopolymer will not complete if the holographic memory is ignored [13]. Unlike both magnetic and conventional optical data storage technologies, where individual bits are stored on the surface of a recording medium, the holographic data storage allows data to be kept throughout the volume of a medium. In holographic data storage, an entire page of information is stored at once as an optical interference pattern within a thick, photosensitive optical material. A large number of these interference patterns can be superimposed in the same thick piece of media and accessed independently, as long as they are distinguishable by the direction or the spacing of the grating. Such separation can be accomplished by changing the angle between the object and reference wave or by changing the laser wavelength. The data recording and reading schemes in the holographic data storage are drawn in Fig. 13. The data to be stored are imprinted onto the object beam with a pixelated input device called a spatial light modulator (SLM). The theoretical limits for the storage density of this technique are around tens of terabits per cubic centimeter. In addition to high storage density, holographic data storage promises fast access times.

Photopolymers are worthy of consideration as a volume holographic material because beside several attractive advantages as mentioned above, photopolymer can store data forever [3, 14]. Once recorded, the grating will not be volatilized by the readout process. Therefore, with the property of ROM like that, photopolymer-based holographic memory can be served in applications where data is stored permanently. Especially, when an individual portrait, a fingerprint, or other biometric information is digitally encoded, optically encrypted, and holographically stored in photopolymer, a potential security memory used for authentication purposes such as passport, credit card, or other ID cards would be realized. This is a promising replacement for embossed holograms that can be easily counterfeited due to the rapid advances in computer, CCD technology, image-processing hardware and software, and copier. Figure 14 shows the block diagrams of encryption and decryption processing of a digital holographic security card system. The encoded information of the card holder is divided into pages, each of which optically modulated by the SLM, and recorded in photopolymer attached on the card. The multiplexing scheme can be shift or angular. The reference wave is encoded by a random phase code to optically encrypt the holograms. In the reader, the random phase code must be exactly same as one that used in the recording process to decrypt and reconstruct the stored data.

**Figure 13.** Holographic data storage system: (a) Recording and (b) reading
Using holographic memory, a single page of 8kbit can be recorded. Figure 15(a) is a reconstructed image with the right phase code. The estimated raw BER of the system is around $3.6 \times 10^{-4}$. In the case of the incorrect key, only random like noise is obtained as shown in Fig. 15(b). Consequently, the optically encrypted holograms, which normally are transparent for human eyes, now become clear for the conventional devices. Therefore, they are very difficult to be copied and counterfeited, and the information cannot be accessible by unauthorized person.

**Figure 14.** Block diagrams of (a) encryption and (b) decryption processing

**Figure 15.** Reconstructed images (a) with and (b) without correct phase code
3. Conclusion

Presentation in this paper is an overview of photopolymer material and its holographic applications. Utilizing advantages of photopolymer, these applications have reached some good results, which cannot be obtained with other materials. However, problems are non-stop appearing, and many attempts should be given to solve them. The photopolymer should be more sensitive and higher index modulation to support various applications. Interconnection, waveguide, beam shaping are topics in which photopolymer can be used, and many high-performance devices would be realized.

Reference