Polarization Holography

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Polarization holography has the unique capacity to record and retrieve the amplitude, phase, and polarization of light simultaneously in a polarization-sensitive recording material and has attracted widespread attention. Polarization holography is a noteworthy technology with potential applications in the fields of high-capacity data storage, polarization-controlled optical elements, and other related fields.

polarization-sensitive material | holographic recording | photopolymer | photoinduced birefringence | first_page settings azopolymer materials

1. Introduction

Improvements in the capacity and reliability of data storage systems are urgently needed. One potential optical information storage technology uses a holographic approach in which recorded data are distributed throughout the volume of a thick medium with high density. Optical holographic recording technology can record information in a three-dimensional space versus traditional two-dimensional storage methods and offers a small volume, large capacity, and high density. In 1994, Heanue et al. first used holographic recording technology to realize the storage of digital images and compressed video data [1]. This high-density and large-capacity storage technology has attracted widespread attention.

In holographic data recording, the entire information contained in the light is stored at once as an optical interference pattern within a photosensitive optical material. Holographic storage technology usually uses the interference of light to record the interference fringes and uses the diffraction of light to reproduce the information of the recorded light. Holographic storage recording is achieved through the interference of two coherent laser beams irradiated at the same position in the photosensitive material. Figure 1 shows that the light emitted by the laser is divided into two beams: One beam carries data information through the spatial light modulator as information light, and the other beam is used as the reference light. When the information needs to be read, the hologram is irradiated with the same beam as the reference light to cause diffraction. The information can be reconstructed, and the initial image of the information can be read through the diffracted light [2]. As a recording medium, photosensitive materials greatly affect the holographic recording ability. Traditional holographic storage technology, however, considers only the phase and intensity information of light and ignores the polarization information. Polarization holography can employ waves with two different polarizations to record polarization states on the polarization-sensitive materials.

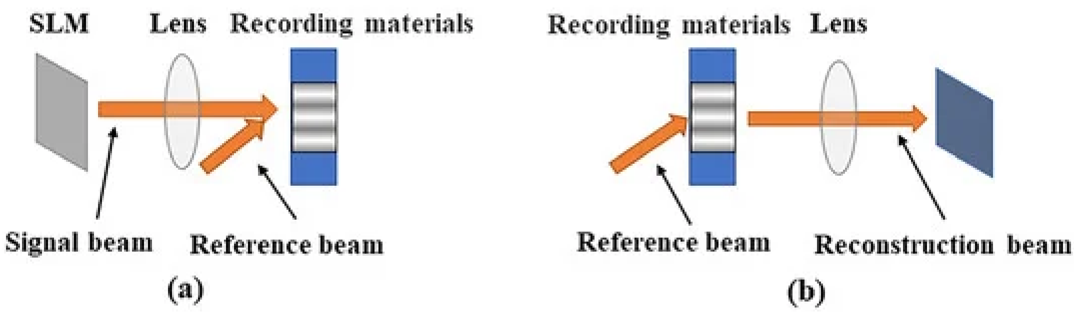

Figure 1. Principle of the holographic recording and reading process: (**a**) holographic recording process; (**b**) holographic reconstruction process, SLM, spatial light modulation.

2. Polarization Holography

The polarization properties of light and its anisotropy process in propagation increase as the degree of freedom, which can be controlled; this is called the polarization state. In 1965, Lohmann first proposed a method to record the polarization state of light with two orthogonal polarized beams [3]. In 1968, Foumey et al. described an experimental method to record and reproduce the polarization state of light, which verified Lohmann's theory [4]. Holography that can record the polarization information of light is called polarization holography. Polarized holography is different from traditional holography, which can modulate the recording and reproduction of information using the polarization state. As presented in Figure 2, two orthogonally polarized waves interfere, forming an interference field with the periodic change of the polarization states.

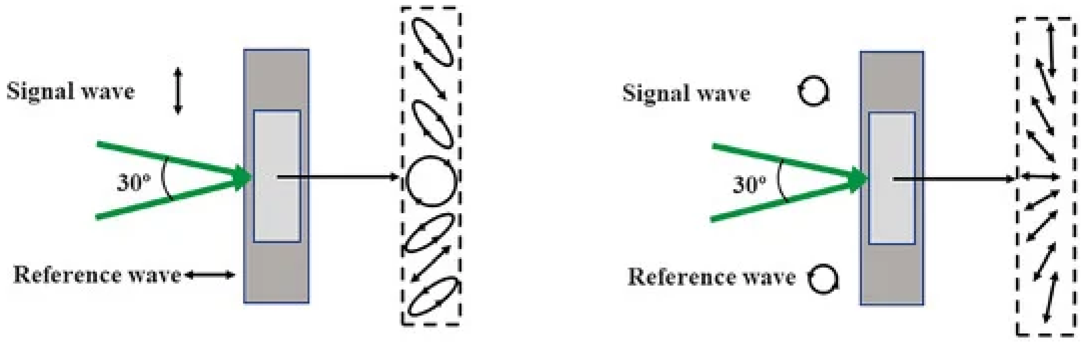

Figure 2. Interference field with the periodic change of the polarization states caused by two orthogonally linear polarized waves or two orthogonally circularly polarized waves.

Since the concept of polarization holography was proposed, in 1974, Kakichashvili first gave a theoretical proof using the photoinduced anisotropy of polarization-sensitive materials for polarization holographic recording [5]. This was the first time the holographic method that uses the Weigert effect (photoinduced birefringence) to record the polarization state of the light field in a photosensitive material was presented. The interaction of the polarized light field with the photo-anisotropic material records the polarization state of the light field. Ordinary holographic recording materials cannot meet the requirements of polarized holography. This discovery caught the attention of researchers from polarization holographic recording to choose appropriate polarization-sensitive material. In 2009, Nikolova et al. adopted the Jones matrix to describe the recording and reproduction process of polarization holography, but the theory was established under the condition that two polarization interference lights were approximately parallel, which limited the development of this theory [6]. Because of recording condition restrictions, polarization holographic recording has not been widely studied and applied. In 2011, Kuroda et al. proposed a tensor-based polarization holographic theoretical model, which is applicable when two polarization interference lights are at any angle, which has wide universality [7]. Polarization holography technology is used mostly in polarization multichannel multiplexing, vector beam storage, polarization modulation and encoding, and optical component production. It has broad application prospects. For holographic data storage, polarization multichannel multiplexing will increase the one-dimensional polarization variable, as depicted in Figure 3. This means that holographic three-dimensional storage can be upgraded to four-dimensional systems, which effectively improves the storage density. With the development of polarization holography, polarization holography materials have also been continuously developed and optimized. To realize the real practical application of polarization holography theory, excellent polarization-sensitive materials are indispensable.

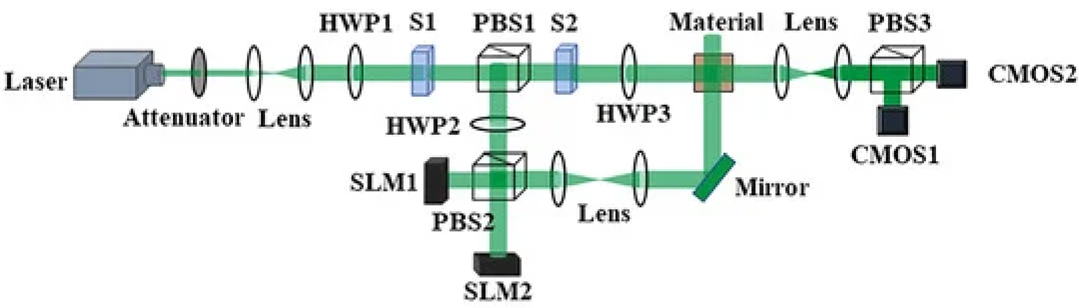

Figure 3. Polarization multichannel multiplexing device: S, HWP, PBS, SLM, and COMS are the shutter, half-wave plate, polarization beam splitter, spatial light modulation, and complementary metal oxide semiconductor sensor, respectively.

3. Polarization-Sensitive Material

In the development of polarization holographic storage technology, the most vital thing is to find suitable polarization-sensitive materials. Polarization-sensitive materials include organic materials and inorganic materials. Inorganic materials, such as photorefractive crystals, have a high diffraction efficiency and a short response time. These materials have harsh production conditions and high costs, however, which limits their marketability. They are not suitable for permanent storage of information because they can be erased [8][9]. Recently, metasurfaces also showed their superior capability in controlling the phase, amplitude, and polarization states of light [10][11]. Metasurfaces, which consist of an array of function-driven artificial meta-atoms, can be designed to exhibit highly anisotropic responses such that their interaction with electromagnetic fields is strongly polarization sensitive [12][13][14][15]. Although they have not been used in the study of polarization holography, some other materials have been found to be sensitive to polarization. Some special nanostructures with large field enhancements exhibit obvious polarization dependence, such as nanoscale gaps and nano-gold dimers [16][17]. The structural chirality of molecules gives rise to optical chirality. Ali Rafiei Miandashti et al. experimentally and theoretically observed photothermal chirality in gold nanoparticle helicoids [18]. In colloidally prepared gold helicoids, a polarization dependence was found in circular differential absorption and the maximum temperature of a small cluster of helical nanoparticles. There are many types of organic materials, and more attention has been given to photorefractive polymer materials, azopolymer materials, photochromic materials, and photopolymer materials.

An excellent volume holographic recording material needs to have the following characteristics: (i) The material should have sufficient optical quality to ensure that the loss of the beam during reading and writing is extremely small, and the surface of the material should have optical flatness to avoid distortion during the imaging process. The scattering rate of the material is extremely low, and for holographic storage, it needs to have sufficient thickness to achieve a high storage density. (ii) The recording wavelength of the material should match the wavelength of the laser, and it should be sensitive to light waves in the wavelength range. (iii) The material should be processed without traditional holographic processing, such as heat treatment or solvent processing, to reduce costs. (iv) For long-term recording, the material must be nonvolatile, that is subsequent holographic recording and reading will not destroy the recorded hologram. (v) The material must be able to maintain long-term stability within a certain temperature and humidity range to achieve sufficient storage life.

4. Conclusions

We report on the basic optical design of polarization holographic recording, as well as corresponding system demonstrations. Polarization holographic recording offers the best prospect for holographic data storage, including the fabrication of artificial anisotropic elements and polarization control. This includes the physical principles and high performance of polarization-sensitive media.

We present an overview of reported work on the polarization-sensitive materials and discuss three types of typical polarization-sensitive material in detail. We examine the key contributions of each work, and many of these suggestions have improved the different polarization-sensitive materials discussed in this work. Clearly, many materials have provided promising polarization-sensitive capacities and are being developed for polarization holographic application. We emphasize photopolymers in this review, as they offer many advantages and are widely used as holographic data storage media. In particular, we discuss the polarization-sensitive mechanism of the PQ/PMMA material, which offers an in-depth understanding of comprehensive improvements in different photopolymers.

Various approaches are summarized to improve performance in the field of polarization-sensitive holographic recording materials. Such improvements include (i) the introduction of the liquid crystal structure that betters the manipulated material polarization-sensitive properties; (ii) the introduction of nanoparticles that increase the absorption and promote effective photoconversion of photosensitive molecules; (iii) optimization of the photosensitizer composition structure and polymer composite substrate that improves the photoinduced birefringence of polarization-sensitive materials. The development of polarization holographic recording in optical holographic storage, optical element production, and other related fields needs continuous improvements.

References

1. Heanue, J.F.; Bashaw, M.C.; Hesselink, L. Volume holographic storage and retrieval of digital data. Science 1994, 265, 749–752.
2. Dhar, L.; Curtis, K.; Fäcke, T. Holographic data storage: Coming of age. Nat. Photonics 2008, 2, 9–11.
3. Lohmann, A.W. Reconstruction of vectorial wavefronts. Appl. Opt. 1965, 4, 1667–1668.
4. Fourney, M.E.; Waggoner, A.P.; Mate, K.V. Recording polarization effects via holography. JOSA 1968, 58, 701–702.
5. Kakichashvili, S.D. Method for phase polarization recording of holograms. Sov. J. Quantum Electron. 1974, 4, 795.
6. Nikolova, L.; Ramanujam, P.S. Theory of polarization holography. In Polarization Holography; Publishing House: Cambridge, UK, 2009; pp. 24–87.
7. Kuroda, K.; Matsuhashi, Y.; Fujimura, R.; Shimura, T. Theory of polarization holography. Opt. Rev. 2011, 18, 374.
8. Bittner, R.; Meerholz, K.; Steckman, G.; Psaltis, D. Dark decay of holograms in photorefractive polymers. Appl. Phys. Lett. 2002, 81, 211–213.
9. Cheng, N.; Swedek, B.; Prasad, P.N. Thermal fixing of refractive index gratings in a photorefractive polymer. Appl. Phys. Lett. 1997, 71, 1828–1830.
10. Choi, C.; Lee, S.Y.; Mun, S.E.; Lee, G.Y.; Sung, J.; Yun, H.; Yang, J.H.; Kim, H.O.; Hwang, C.Y.; Lee, B. Metasurface with nanostructured Ge2Sb2Te5 as a platform for broadband-operating wavefront switch. Adv. Opt. Mater. 2019, 7, 1900171.
11. Ye, W.; Zeuner, F.; Li, X.; Reineke, B.; He, S.; Qiu, C.W.; Liu, J.; Wang, Y.; Zhang, S.; Zentgraf, T. Spin and wavelength multiplexed nonlinear metasurface holography. Nat. Commun. 2016, 7, 11930.
12. Kats, M.A.; Genevet, P.; Aoust, G.; Yu, N.; Blanchard, R.; Aieta, F.; Gaburro, Z.; Capasso, F. Giant birefringence in optical antenna arrays with widely tailorable optical anisotropy. Proc. Natl. Acad. Sci. USA 2012, 109, 12364–12368.
13. Jiang, S.C.; Xiong, X.; Hu, Y.S.; Hu, Y.H.; Ma, G.B.; Peng, R.W.; Sun, C.; Wang, M. Controlling the polarization state of light with a dispersion-free metastructure. Phys. Rev. X 2014, 4, 021026.
14. Arbabi, A.; Horie, Y.; Bagheri, M.; Faraon, A. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission. Nat. Nanotechnol. 2015, 10, 937–943.

15. Sung, J.; Lee, G.Y.; Choi, C.; Hong, J.; Lee, B. Single-Layer Bifacial Metasurface: Full-Space Visible Light Control. Adv. Opt. Mater. 2019, 7, 1801748.

16. Herzog, J.B.; Knight, M.W.; Li, Y.; Evans, K.M.; Halas, N.J.; Natelson, D. Dark plasmons in hot spot generation and polarization in interelectrode nanoscale junctions. Nano Lett. 2013, 13, 1359–1364.

17. Ramos, D.; Malvar, O.; Davis, Z.J.; Tamayo, J.; Calleja, M. Nanomechanical plasmon spectroscopy of single gold nanoparticles. Nano Lett. 2018, 18, 7165–7170.

18. Rafiei Miandashti, A.; Khosravi Khorashad, L.; Kordesch, M.E.; Govorov, A.O.; Richardson, H.H. Experimental and Theoretical Observation of Photothermal Chirality in Gold Nanoparticle Helicoids. ACS Nano 2020, 14, 4188–4195.