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PHOTOREFRACTIVE POLYMERS AND THEIR APPLICATIONS IN PHOTONICS

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ABSTRACT

The demand for holographic recording materials has been ever increasing for the past few decades. Photorefractive materials have been studied extensively as candidate recording media. They offer high index modulation with reversible recording that make them very attractive for applications such as three-dimensional holographic displays, adaptive optics, optical data storage and medical optics. Recently, organic photorefractive composites have drawn significant attention due to their high performance, compositional flexibility and low cost associated with their fabrication, presenting an alternative to traditionally studied non-linear crystals such as $LiNbO_3$. In this article, we describe basic concepts of holography and summarize latest developments in photorefractive polymer research. Possible applications of photorefractive polymers are also reviewed.

Keywords: Holography, photorefractive polymers, optics, photonics, polymers, materials.
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FOTOREFRAKTİF POLİMERLER VE FOTONİKTE UYGULAMALARI

ÖZET

Holografik teknolojiler için uygun kayıt ortamı ihtiyacında son yıllarda büyük bir artış gözlenmektedir. Muhtemel kayıt ortamı olarak fotorefraktif materyaller üzerine yoğun çalışmalar yapılmaktadır. Yüksek kırıcılık indeksi modülasyonu ve geri-çevrilebilir kayıt özelliklerinden dolayı fotorefraktif materyaller üç-boyutlu holografik göstergeler, adaptif optik, optik data kaydı ve tıbbi optik gibi uygulamalarda oldukça ilgi çekmektedirler. Yakın geçmişte, organik fotorefraktif kompositler yüksek performans, bileşimsel esneklik ve düşük maliyet gibi özelliklerinden dolayı dikkat çekmiş, ve geleneksel olarak çalışılmış $LiNbO_3$ gibi inorganik kristallere alternatif olma durumuna gelmişlerdir. Bu makalede temel holografi kaideleri, fotorefraktif polimerilerdeki son gelişmeleri özetlenmekte, bu materyallerin optik ve fotonik teknolojilerinde muhtemel uygulamaları tartışılmaktadır.

Anahtar Sözcükler: Holografi, fotorefraktif polimerler, optik, fotonik, polimerler, malzeme.

1. INTRODUCTION: PHOTOREFRACTIVE POLYMERS AND HOLOGRAPHY

The word holography means "total recording" and refers to the total wavefront reconstruction of images recorded in a medium [1]. The use of holography in art and entertainment dates back to its discovery by Dennis Gabor in 1948, which brought him the Nobel price in Physics in 1971,

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however it is only in the last couple of decades that we have started to see holograms being used for technological purposes. Today, holography has found a variety of daily use applications, ranging from optical data storage to holographic security overlays, medical imaging, optical communication and to 3D displays. The early holograms were recorded using radiation from a mercury lamp, and it was only until the discovery of a highly coherent light source, the laser, many of these holographic applications have been possible.

To record a hologram, we usually need a highly coherent light source that is split into two beams, one illuminating the object we want to image and the other (called the reference beam) illuminating the recording material (Fig.1-a). When the object beam is brought to the recording medium, both beams interfere and create a light pattern that includes the optical (amplitude and phase) information from the object and reference beams. If the material is sensitive to light, this interference pattern can be recorded as a change of the material properties such as transmission or index of refraction. If needed, this hologram can be reconstructed with the help of the reference beam and imaged back to a detector, such as a CCD camera or the human eye (Fig.1-b).
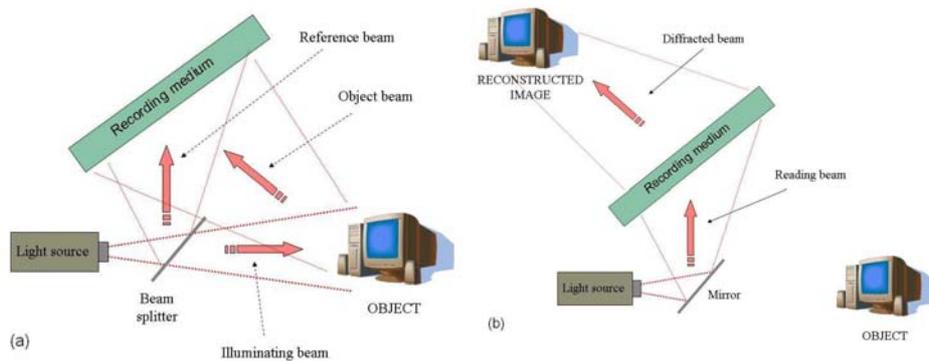
Figure 1. Holographic recording and retrieval. (a) Phase and intensity information from the object is recorded to the recording material by the help of writing beams. (b) When needed, the hologram can be retrieved (read) through uniform illumination of the recording material.

Although holography is theoretically well understood, the recording materials area is relatively underdeveloped. Early recording materials were mostly based on absorption (transmission modulation) such as silver-halide films. Today, there is a fierce competition in this field and many candidate materials are proposed. Some of the most interesting materials are photopolymers, liquid crystal compounds, birefringent films and photorefractive materials. Although different applications may present different requirements, a good holographic recording material in general should have the following properties [2]:

- High diffraction efficiency: The diffraction efficiency is the ratio of the light power diffracted by the hologram to the incident light power. In order to fully reconstruct images, different spatial frequencies existing in an image should be recorded and reconstructed with high efficiency. This requires the diffraction efficiency for a single spatial frequency to be high enough, at least several orders higher than the noise floor. Usually, the higher the diffraction efficiency, the higher is the amount of holograms that could be recorded in the material.
- High photosensitivity: The desired diffraction efficiencies should not require using high optical power.
- Fast response: For dynamic applications the recording speed is a serious requirement. The response time of a hologram is defined is the time to record the hologram, and it can range from microseconds to hours depending on the material.

- Reversible recording: The possibility to erase and re-write the holograms is essential for dynamic applications such as real-time image processing, beam clean-up and holographic displays.
- Fixing: After recording, holograms should persist without significant decay. This is especially important for holographic storage and display applications.
- Non-destructive readout: For reversible recording materials, the reconstruction process is partially destructive: the reading beam used in reconstruction process erases the hologram. Non-destructive reading is desired to store the holograms longer and keep the signal levels constant.
- Operating wavelength: The holographic material should operate (be sensitive) at the desired wavelength. For many applications sensitivity at the visible wavelengths is enough, while for others such as optical communication applications infra-red (IR) sensitivity is necessary. Although there are many holographic materials are available at visible, IR operating materials are very rare.
- Low cost: The end product based on holography should be competitive with the current technologies in terms of cost.

Over the recent years there has been increased interest in the reversible holographic materials. These materials can serve as the key components in many technologies such as optical communication, optical computing, data storage and real-time image processing that require dynamic and reversible recording. Among possible candidates, photorefractive materials[3-4] seem to be the most interesting. Their diffraction efficiency can reach to almost 100% with considerable speed and sensitivity. The cost associated with their fabrication can be very low, such as in the case of organic based photorefractive materials (polymer composites). This article is dedicated to an important class of photorefractive materials, namely photorefractive polymers. Before we go deeper into the details of photorefractive materials and associated technologies, let us spend some time on understanding the photorefractive effect.

2. PHOTOREFRACTIVE EFFECT

Photorefractive effect refers to the light induced, non-uniform refractive index change in photorefractive materials[2-4]. Photorefractivity is a multi-step process that involves a variety of distinct phenomena. To better visualize this, let us consider two coherent laser beams intersecting inside a material, creating an interference pattern (Fig.2). If the material is absorbing at the laser wavelength, free electron-hole pairs are created and the charge density replicates the light pattern formed by the interfering beams. This is the first step in photorefractive effect. After their initial creation, the photo-generated charge carriers are free to drift and diffuse macroscopic distances throughout the material. Every now and then these charges run into local defects (potential wells) in the material and become trapped at these sites. Eventually, these trapped charges accumulate in the dark regions of the light pattern until a steady state is reached, creating a "space-charge field". The space-charge field is defined as the local electric field generated by the non-uniform charge distribution in the material. The space-charge field that can reach up to 40V/µm in some materials creates a refractive index change through electro-optic effect. This index change is in the form of a 3-D volume hologram, which replicates the interference light field and acts as a phase grating if a probe (reading) beam is incident onto this hologram. Strong diffraction (up to 100%) of the reading beam can be observed; given phase matching conditions are satisfied.

The creation of an index grating by interference of light in the photorefractive material allows the real-time encoding, storage and retrieval of the optical information. Information can be stored in the form of spatial and/or phase modulation of one of the writing beams (called the object beam) and the other beam acts as a coherent reference. The changes in the phase and intensity of the object beam are translated to the space charge field dynamically, but there is a delay that is determined by the response time of the material. Although the first photorefractive

materials were very slow (hours), materials with very fast (microseconds) response times were recently demonstrated[2-5].
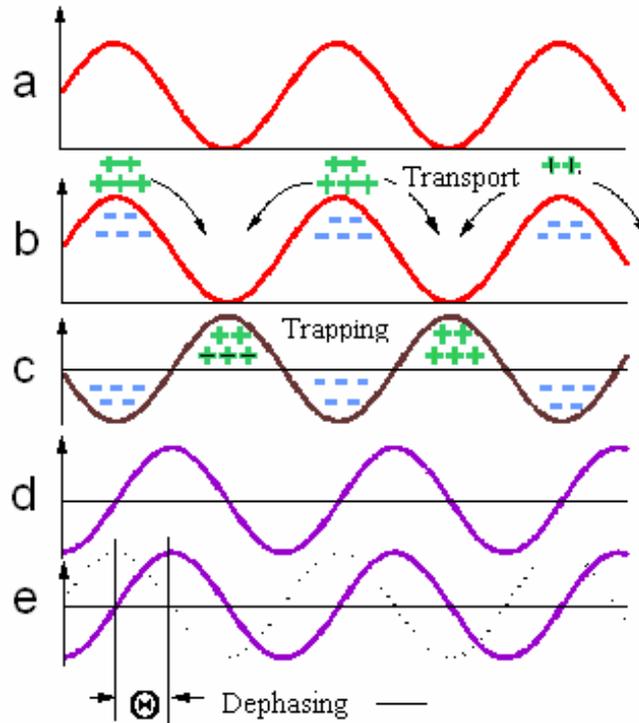
Figure 2. Formation of the photorefractive hologram. (a) Interference of light creates a sinusoidal light pattern. (b) Charges generated in the bright regions migrate to the dark regions in the light pattern. (c) The charges (holes) become trapped in the dark regions, creating a charge density pattern. (d) The electric field (space-charge field) created by the charge density difference. (e) The index grating created is de-phased from the original light pattern.

3. MATERIALS: INORGANIC CRYSTALS OR ORGANIC COMPOSITES

Photorefractive (PR) effect was first observed by Ashkin in 1961 in the non-linear inorganic crystal Lithium Niobate ($LiNbO_3$) which is widely used on optical communication technologies[6]. Initially it was considered as an unwanted "optical damage", but soon after it was realized that this new effect could be very useful in holographic applications. The first publications on PR effect in inorganic crystals include a variety of amazing applications from optical data storage to real-time beam clean-up in photonics, from target tracking to beam steering in military technology, and from imaging through scattering media to optical coherence tomography in medical optics. However, non-linear crystals such as Lithium Niobate come with a high cost, they are hard to fabricate and in many cases it is too hard to tune their optical properties, which have widely prevented the implementation of these applications in daily use.

       Recently, photorefractive polymers have emerged as a new class of holographic materials[7]. These organic based materials exhibit superb photorefractive characteristics while maintaining all the advantages of being plastics: they are robust, cheap and compositionally very

flexible[2,5]. Their optical properties can be tuned by simply changing the weight ratio of various components and mixing them. They can be doped with different optical chromophores (dyes) to tune their wavelength sensitivity. Large area films can be fabricated easily by conventional techniques such as melting, casting and injection molding[8]. The cost associated with their fabrication ranges around a few tens of dollars, being considerably low cost compared to their inorganic counterparts.

4. PHOTOREFRACTIVE POLYMER COMPOSITES

Photorefractive effect in polymers was first discovered in 1991 by Mourner et al, [7] and since then there has been a considerable amount of research dedicated into these materials[5]. First photorefractive polymer showed a diffraction efficiency around 1% with several hours of response time. A few years later very fast [9] and highly efficient [10] materials were developed. Although different recipes exist, the most common (and successful) approach to organic photorefractive composites so far employs the following functional components[2]:

1)   Sensitizer: Optical dyes with absorption feature in the preferred wavelengths are used to sensitize the composite. The optical dye absorbs photons and creates electron-hole pairs in exchange. A considerable research has been dedicated in the development of organic sensitizers for photorefractive composites. As a result, several dyes covering a wide spectrum from 500 nm to 980 nm have been developed and used in photorefractive polymers[5, 11, 12]. Such a dye with very high quantum efficiency is C60 (fullerene), which gives excellent results in the red. Although other dyes that operate further in the IR exist, their use has not been successful due to energetical mismatch between the dye and the photoconductive polymers used for charge transport. Thus, longest operation wavelength in a photorefractive polymer composite employing single-photon absorption has been 980 nm so far (Fig.3).
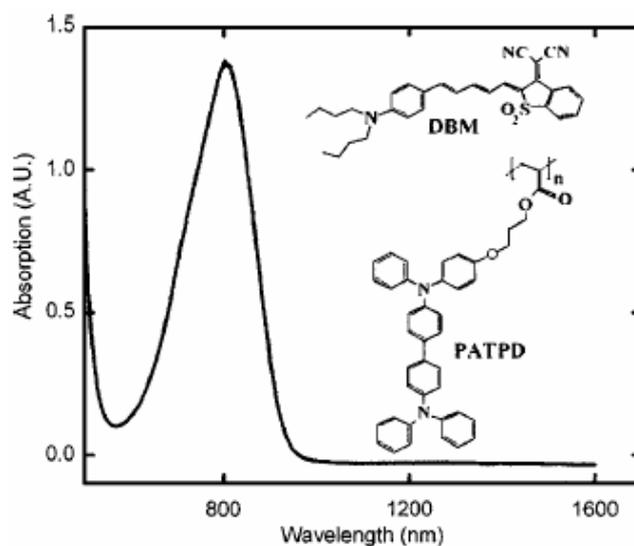
Figure 3. The absorption spectrum of a photorefractive polymer operating at 980 nm through single photon absorption and at 1550 nm through two-photon absorption (Ref. 11, 12). The main absorption feature at 800 nm is due to the dye DBM. The hole transport polymer PATPD is also shown.

2)   Charge transport polymer: The charges generated in the sensitizer are transferred to a conducting polymer backbone and they are free to move along the polymer until they are trapped in a defect site (called a "trap"). The conductivity in a normally insulating organic material can be understood by the "electron hopping model"[13]. The outer orbitals of the molecules that make up the polymer can be represented by electronic wavefunctions that partially overlap between neighboring molecules. The charge carrier has a finite possibility to exist in these sites, and therefore can "hop" between neighboring sites to travel across the polymer. The conductive polymers such as PVK have long been used in xerography and a variety of commercial polymers are available. Usually, a large photo-to-dark conductivity is desired to maximize the transport of photo-generated charges. Also, the LUMO level of the polymer needs to be separated properly from the HOMO level of the sensitizer to allow for charge transport to the polymer (Fig.4). Usually, the charges that are transported in the organic conductors are holes, due to their much larger conductivity compared to electrons. Therefore, it is necessary tune the energetical levels with respect to the holes rather than the electrons.
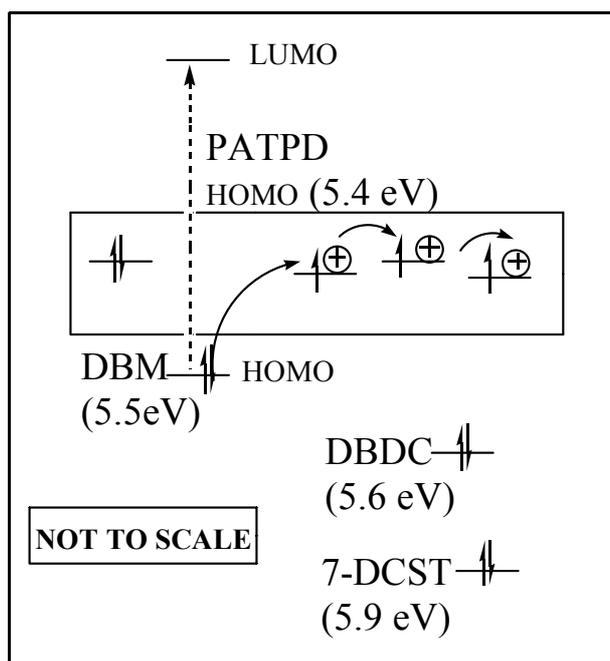
Figure 4. Energy levels of the functional components in a photorefractive polymer composite (Ref. 10). The HOMO level of the sensitizer (DBM) needs to be higher than the LUMO level of the conducting polymer (PATPD) for charge transport to be possible. The energy levels of the non-linear chromophore (7-DCST) and plasticizer (ECZ) are also shown.

3)   Trapping agent: The photogenerated charges migrate across the polymer until they are trapped within irregularities in the polymer. These traps are readily available in organic compounds. However, for certain applications it may be necessary increase the trapping rate.
4)   Non-linear chromophore: The main diffractive power of photorefractive polymer composites is based on hyperpolarizibility non-linearity (birefringence). Polymer composites are doped with non-linear chromophores such as 7-DCST (Fig.5) to increase this effect. These

chromophores exhibit large permanent dipole moments and they can rotate and align with an applied electric field if the composite has its glass-transition temperature (T_g) near room temperature. The collective alignment of the rod-shaped chromophores results in a large index change (Δn) for s and p-polarized light. This index change can reach up to 10^{-2} in many composites, resulting in very large diffraction efficiencies. However, it is necessary to apply a high DC voltage across the polymer samples to align the chromophores. The electric fields necessary for the alignment of chromophores range around 30 to 90 V/μm, resulting in several kV's for 100 μm thick films.
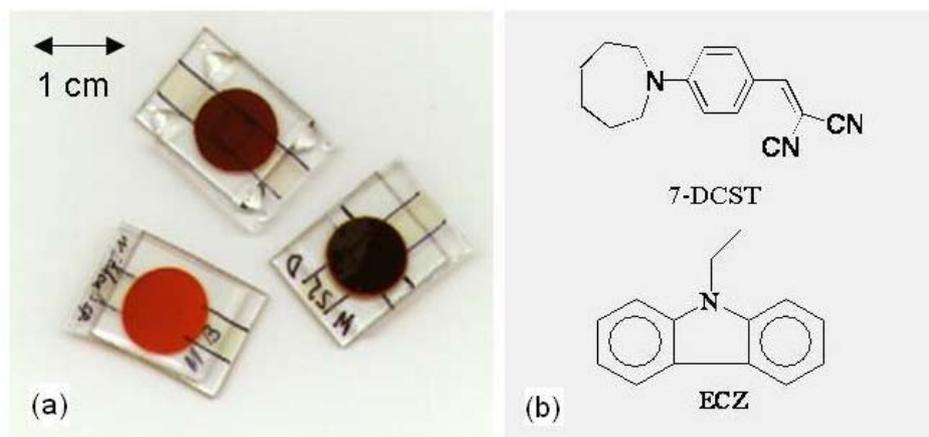
Figure 5. (a) Photorefractive polymer thin-film devices. (b) Chemical compositions of non-linear chromophore 7-DCST and plasticizer ECZ.

5) Plasticizer: Photorefractive polymers may include plasticizers (i.e. ECZ, Fig.5-b) to reduce their T_g to around room temperature to allow for the orientation of the non-linear chromophores.

The components described above are mixed in various ratios to form a composite. One example is a very successful composite[14] operating in the red (633 nm)

PATPD: 7-DCST: ECZ: C60 (39.3/40/20/0.7 wt. %)

Here PATPD is the hole transport polymer, 7-DCST is the birefringent chromophore, ECZ is the plasticizer and C60 is the sensitizer at 39.3, 40, 20 and 0.7 weight percents, respectively. This composite is melted and sandwiched between ITO coated glass substrates and then sealed with glue (Fig.5-a). The ITO layers serve as electrodes to apply a DC bias across the film. The polymer composite is melted at temperatures around 200 °C and pressed between the substrates to form a uniform film. The melt is forced to cool rather rapidly by placing the device in contact with a metal plate. This supercooling prevents the composite to become crystalline. The result is a amorphous composite with very good optical and mechanical properties. These devices can be stored under standard laboratory conditions for several months and even years without any phase separation and degradation.

5. CHARACTERIZATION

The thin-film devices made of the polymer composite can be characterized by various techniques. One of the main tools in measuring the diffraction efficiency and response time is the four-wave mixing (FWM) technique[2]. In FWM, the photorefractive device is placed in an interferometer in

which two coherent laser beams (writing beams) intersect in the polymer film (Fig. 6), creating a photorefractive hologram in the form of a phase grating. The writing beams are usually s-polarized and the reading beam is p-polarized due to polarization dependence of the electro-optic effect[15]. Voltage is applied across the film with the help of ITO electrodes. A reading beam counter-propagating with one of the writing beams is incident onto the region where the writing beams interfere, and it is diffracted by the photorefractive hologram in the direction of the other writing beam if phase matching condition is satisfied. This diffracted beam is separated by a beam-splitter, and its intensity is measured by a photodetector. The ratio of the diffracted beam power to the incident beam power gives the diffraction efficiency (Fig 7-b). From the diffraction efficiency, the index modulation can be found using the following formula[16]:

$$\eta = \exp(-\alpha L)\sin^2(\frac{\pi \Delta n L}{\lambda})$$
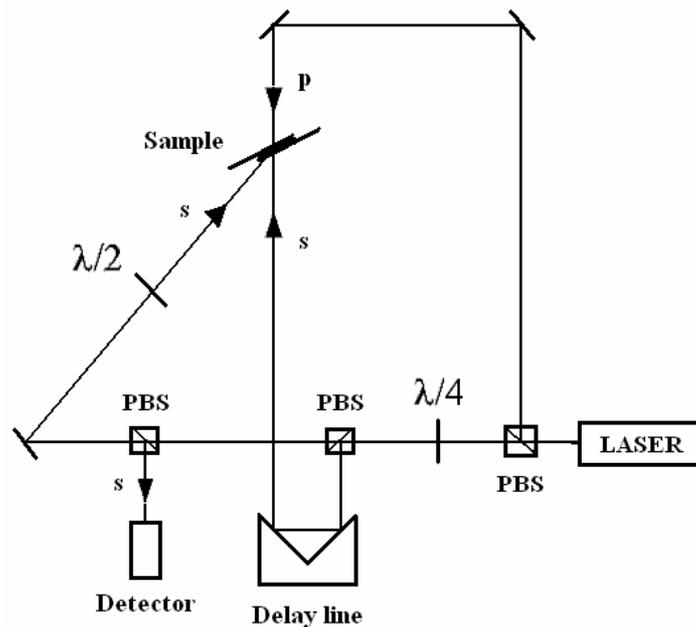
Figure 6. Four-wave mixing setup. The s-polarized writing beams from a laser intersect in the polymer film forming a photorefractive index grating. The p-polarized reading beam incident on the grating is diffracted in the writing beam direction, separated by a polarizing beam-splitter and is measured by a optical detector. A delay line is used in one of the writing beam arms in order to ensure temporal coherence of writing beams in the sample position.

Here η is the diffraction efficiency, α is the linear absorption coefficient, Δn is the index modulation, L is the thickness and λ is the wavelength. The diffraction efficiency over-modulates at a certain index modulation due to the sin-squared behavior as seen in Figure 7-b.
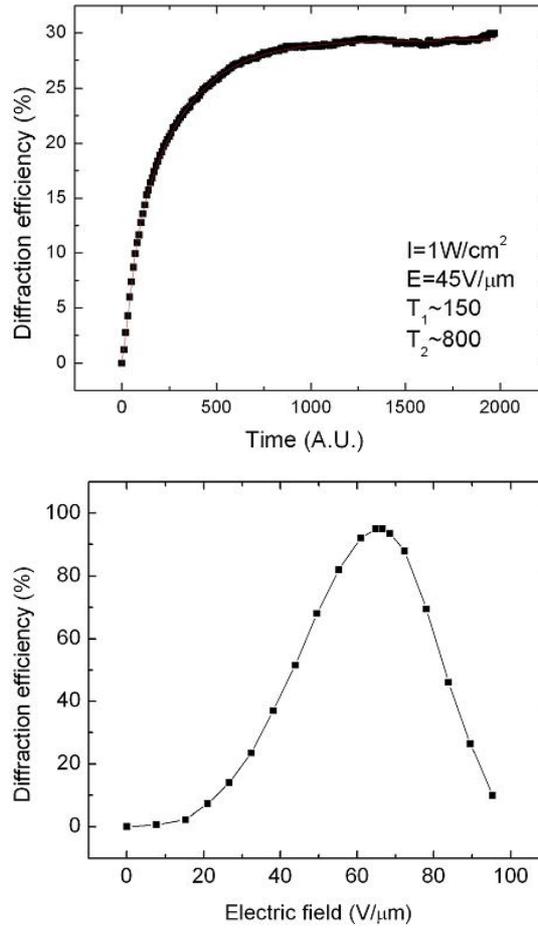
Figure 7. (a) Diffraction efficiency as a function of time. The writing beams are turned on at t=0 and the build-up of the diffraction efficiency is observed. The data fits to a bi-exponential function with time constants T_1 and T_2. (b) Diffraction efficiency as a function of applied field. The diffraction efficiency over-modulates at 60V/μm.

When one of the writing beams is blocked, the unblocked writing beam uniformly irradiates the sample, which results in the erasure of the photorefractive grating. The response time of the polymer can be measured by unblocking this beam and observing the grating build-up in time (Fig 7-a). The diffraction efficiency grows as a function of time with the following expression[16]:

$$\eta = A\sin^2\{B\cdot[1-m\exp(-t/t_1)-(1-m)\exp(-t/t_2)]\}$$

which gives two time constants, a fast (t_1) and a slow (t_2) component. Here m is the modulation depth and A and B are normalization constants.

When the photorefractive hologram builds up an interesting effect is observed: the writing beams exchange energy during build up and one of the beams is amplified in the expense

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of the other. This is called two-beam coupling[17, 18] (TBC) and is the trade-mark of the photorefractive effect. The energy exchange between writing beams happens only when the index gratings written by these beams are non-local (out of phase with respect to the initial light pattern). Photorefractive gratings are the only non-local phase gratings known, therefore the TBC gain is usually sought after to prove the photorefractive nature of the gratings studied. The magnitude of the TBC gain is related to the strength of the index grating created and its shift from the light pattern. Polymers with TBC gains as large as 400 cm^{-1} have been demonstrated[19].

Other tools for characterizing photorefractive polymer composites are photoconductivity[8, 20, 21] and ellipsometry[22-24] measurements. Photoconductivity measures the increase in the conductivity of the material after irradiation. Usually, a large ratio of photo-to-dark conductivity is desired to increase the speed of the grating build up. In best samples, this ratio can be as high as three orders of magnitude. Ellipsometry measures the orientational non-linearity (birefringence) of the composites. It is simply a transmission experiment where the polymer sample is placed between crossed polarizers. The change in the transmission is recorded as a function of the applied voltage. As the chromophores orient, the incident linearly polarized light changes its polarization, which indicates the magnitude of the birefringence induced in the material.

6. STATE-OF-THE-ART

Soon after their first discovery, photorefractive polymers have shown tremendous improvement in almost all areas described in the previous sections. With the use of birefringent chromophores, diffraction efficiencies up to 100% have been shown at a variety of wavelengths[21, 22]. Development of photoconducting polymers like PVK and PATPD has resulted in sub-millisecond response times. IR sensitivity has long been a major goal for optical communication and medical imaging applications. Unfortunately, suitable organic sensitizers above 1 μm do not exist. The lack of sensitizer at the telecommunication wavelengths have has forced researchers to find innovative ways around this problem, such as use of two-photon absorption (TPA)[25, 26]. The use of TPA sensitization has resulted in several composites operating at 1550 nm[11, 27]. TPA sensitization also has the major advantage of non-destructive readout when relatively low intensity continuous wave reading beams are used. Fixing of the photorefractive holograms is achieved by using thermal fixing techniques[28]. Holograms have been stored in the dark (without any writing beams) up to several hours with the help of conventional thermo-electric coolers[29]. For high T_g materials CO_2 laser heating have been used to thermally fix holograms at the room temperature[30]. The combination of IR sensitivity, non-destructive readout and fixing can lead to several exciting technologies such as optical memories and 3-D holographic displays. Some of the important composites from the literature are summarized in Table 1, and a few recent review articles exist[5].

7. APPLICATIONS OF PHOTOREFRACTIVE POLYMERS

7.1. Adaptive optics:

As we have mentioned earlier, the photorefractive polymers are superb holographic recording materials. The reconstructed image using a hologram is the phase conjugate of the original image. This phase conjugating property of holography makes possible the adaptive optical (AO) correction of aberrated images[34-37]. AO correction has recently been successfully used for eliminating the atmospheric aberrations from optical telescope images. Holographic AO systems employing photorefractive polymer films offer a low cost, all-optical alternative to the current technology, which employs a complicated combination of wave-front sensors, deformable mirrors

and a large amount of electronics. Several experimental demonstrations have shown the ability of photorefractive polymers for high-order, dynamic aberration correction (Fig.8)[12, 14, 38].

Table 1. PR properties of high-performing organic composites operating at different wavelengths

Composite	Wavelength	Diffraction efficieny	Response time	Reference
E7 on PVK/TNF (83/17)	514.5	40%	10 ms	31
PSX/DB-IP-DC/TNF (69/30/1)	633	92%		
PATPD/DBDC/ECZ/C60 (49.5/30/20/0.5	633	60%	10 ms	14
PATPD/7-DCST/ECZ/DBM (54/25/20/1)	975	65%	35 ms	11
PATPD/7-DCST/ECZ/DBM (49/40/10/1)	1550*	40%	35 ms	27
2BNCM/PMMA/TNF[1] (90/9.3/0.7)	676	80%	83 ms	32
IDOP-20/DPP/TNFM (69/30/1)	780	83%	133 ms	33

* Sensitized through two-photon absorption
[1] Amorphous glass

Recently, free-space optical (FSO) communication has attracted interest as a solution to the so called "last-mile problem" in fiber optical networks. FSO systems employ a laser beam that is directed from one station to another in the atmosphere. They offer mobile, low-cost and high-speed communication in a variety of environments from university campuses to battle fields. Unfortunately, the atmospheric turbulence sets serious limits in the amount of information that could be sent with a laser beam[39]. The FSO laser beam follows a horizontal path, in which the atmospheric turbulence is larger than a vertical path such as in a telescope. Employing electronic AO systems would be too costly, therefore impractical in FSO systems. The use of photorefractive holograms in FSO has been proposed[14] and there are intensive research efforts in this direction. Initial demonstrations performed at the University of Arizona on a FSO system that employs a photorefractive polymer based AO system are encouraging.

7.2. 3D Holographic Displays

3D imaging has long been dreamed of, and recently a few commercial products have became available to the market[40]. The current technology for 3D imaging employs photopolymers for image reconstruction in which the holograms are permanent. Although photopolymers offer excellent dynamic range and sensitivity, the fixed nature of the holograms do not allow for dynamic applications where one could update the images in time, such as in a TV. There is considerable amount of research going in the direction of updateable 3D imaging (3D-TV). The large dynamic range (Δn), real-time recording, availability of large area films with low cost make the photorefractive polymers the strongest candidate as recording medium. For example, the 3D displays employing polymers developed as a result of the collaboration between the University of Arizona, Nitto-Denko Technical and Zebra Imaging offer single pulse writing of hundred of multiplexed holograms. These holograms can be fixed for a long time, and can be erased to update the images when necessary. Although there are several technical issues to be addressed,

3D displays made of photorefractive polymers for military applications (3D maps) may become commercially available in the next few years.
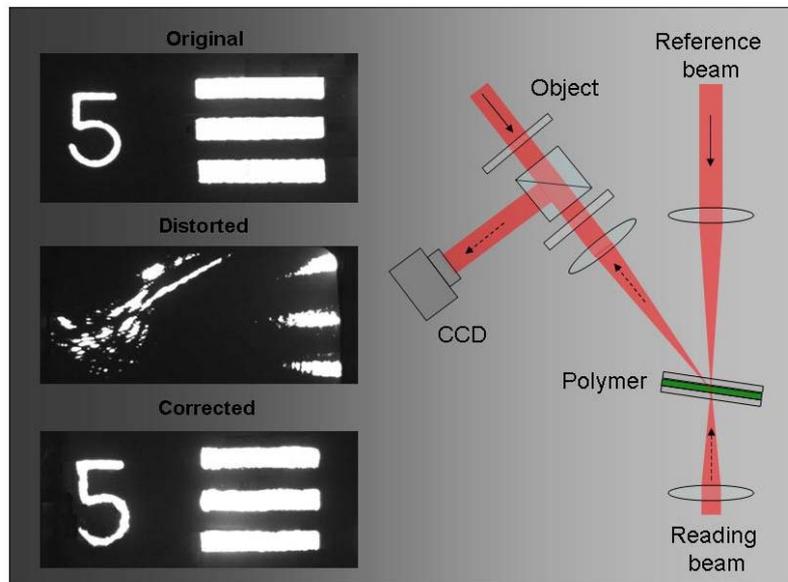
Figure 8. Adaptive optical correction of an aberrated image through read-out of the photorefractive hologram (beam clean-up). The object beam carrying an image, number five from a resolution target, is aberrated by passing through a phase plate. After recording of this aberrated image to the photorefractive material, a probe beam illuminates the hologram, diffracts in the object beam position and passes through the aberrator. This second pass of the phase conjugated reading beam allows for the removal of the aberrations.

7.3. Optical Data Storage

The demand for higher density storage in information technology pushes the research into other directions such as 3D volume holographic storage. Several commercial products employing photopolymers are available [41] and the amount of stored data can reach to terabytes for a single CD sized disc. Photorefractive polymers have long been considered for data storage where dynamic recording applications are important. Experimental demonstrations have shown that the storage rates for certain photorefractive polymers can be as high as photopolymers, with the additional advantage of re-writebility[42, 44]. Recent demonstrations of TPA recording, non-destructive readout and thermal fixing bring photorefractive polymers closer to the data-storage applications.

7.4. Medical Imaging

The ability of eliminating unwanted information in an image through holography makes it possible to use photorefractive polymers for medical optics. Imaging through highly scattering media [21] has been demonstrated with photorefractive polymers. The unwanted scattered light can be eliminated by use of optical-phase conjugation, and images of different tissue sections

without damaging the organism can be taken by use of photorefractive holography. Materials with improved sensitivity may serve well in a variety of medical applications[45].

Among different 3D medical imaging technique, Optical Coherence Tomography (OCT) has been an exciting field of research for the last decade. This technique is based on the interferometric imaging of deep tissue sections. There is a very successful commercial product in the market that is used to detect dermatological anomalies such as skin cancer[9]. The current technology in OCT imaging relies on pixel-by-pixel imaging of the whole tissue, which requires a long time to image a small area. Holographic OCT allows imaging the whole area in a single shot, making the time required for imaging much shorter. Several holographic OCT systems employing photorefractive materials have been demonstrated in the past[46].

Covering all the possible applications of photorefractive polymers is beyond the scope of this article. There is a large number of applications we have not mentioned here such as beam steering and target tracking for military applications, spatial soliton formation, coherent combination of lasers, interferometric sensors, neural networks and optical computing. The interested reader may consult several books [2-4, 34, 35] and recent review papers [5] dedicated to physics and applications of photorefractive materials.

8. CONCLUSION

Photorefractive polymers are promising holographic materials. They offer the combination of high-performance, flexible design and low cost being the preferred recording materials for a variety of applications. There is a large number of opportunities for researchers and industry in this very important class of optical materials. The development of photorefractive polymers has been impressive and the first commercial products based on photorefractive polymers may be available in the next few years.

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