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Original

Reversible holography and optical phase conjugation for image formation/correction using highly efficient organic photorefractive polymers

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Abstract

In this work, we report the reversible reconstruction of holographic and distorted transmission images through the four wave mixing (FWM) technique and optical phase conjugation (OPC), an alternative method to adaptive optics, by using highly efficient Photorefractive (PR) polymers fabricated in our laboratories. These PR polymers are based on our synthesized nonlinear chromophore 4-[4-(diethylamino)-2 hydroxybenzylideneamino] benzonitrile (**Dc**). For the PR devices, diffraction efficiencies as high as 90% at 25 wt.% doping level of **Dc** at an external applied electric field (E_{ext}) around 56 V/μm are achieved. The reconstruction implementation is simple, of low cost, all-optical and it is capable of recovering 90% of the original images. The real-time holographic experiments were performed at E_{ext} of just 27 V/μm, which is one of the lowest reported values. Reversible holographic imaging is showed with a rise-time around 0.35 s.

Keywords: Real-time reconstructions; Photorefractive polymers; Optical phase conjugation

1. Introduction

In image formation/detection with codified information, aberration media, such as atmospheric turbulence, perturb the phase and cause intensity scintillation on the detectors. The scintillation reduces the information capacity and increases the bit error rate. Adaptive optics technology can dynamically correct the spatial aberrations in the transmitted beams, which carry the information, and significantly improve the performance (Levine et al., 1998; Li et al., 2005). A typical adaptive optics system includes a wave front sensor for measurement of the aberrations, an actuator for wave front correction, and the corresponding control electronics. Implementation of such a system is expensive and complex. Considerable research efforts have been devoted to develop real-time, low-cost adaptive optical systems, for instance, by using nonlinear optical (NLO) effects by means of the photorefractive (PR) phenomenon through optical phase conjugation (OPC) and multiple wave mixing (MWM) (Joo, Kim, Chun, Moon, & Kim, 2001; Köber, Salvador, & Meerholz, 2011; Li et al., 2005; Simonov, Larichev, Shibaev, & Stakhanov, 2001; Sun & Dalton, 2008; Winiarz & Ghebremichael, 2004). PR dynamic holographic techniques are also of interest for laser communication and information processing since fast, low-cost, and all-optical compensation of wave front distortion can be achieved without expensive actuators (deformable mirrors), sophisticated computation, and complex electronics (Günter & Huignard, 2007; Günter, 2000; Köber et al., 2011; Levine et al., 1998; Li et al., 2005; Sun & Dalton, 2008).

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OPC is one of the most important phenomena in PR materials. Full theoretical treatment of the OPC can be found elsewhere (Yeh, 1993). Briefly, when a plane wave front passes through an inhomogeneous medium with refractive index $n(x,y,z)$, it distorts the wave front. If the wave is now reflected backwards by an ordinary mirror and again passes through the medium, the distortion of the wave front accumulates. In contrast, if the wave is reflected from a phase-conjugated mirror creating the phase-conjugated replica, distortion is canceled, and the wave front is reconstructed. Some of the potential applications include transmission of undistorted images through optical fibers (or through the atmosphere), refreshing of holograms for long-term optical storage, optical interferometry, beam cleanup, and image processing (Sun & Dalton, 2008). In a classic geometry (FWM), phase conjugation occurs when two counter propagating pump beams overlap in a PR material and create a phase-conjugated replica of a third incident beam (Sun & Dalton, 2008; Yeh, 1993).

PR compounds need to possess simultaneously photosensitivity, photoconductivity and electro-optic (EO) properties. These materials are ideal for potential applications in real-time optical processing because they provide a medium for reversible and nonlocal volume holography (Blanche et al., 2010; Günter & Huignard, 2007; Günter, 2000; Köber et al., 2011; Moon, Choi, & Kim, 2013; Sun & Dalton, 2008), for instance, recently the use of PR polymers for demonstration of holographic three-dimensional telepresence was reported (Blanche et al., 2010). The pioneer report on organic polymer-based PR composites by Ducharme, Scott, Twieg, and Moerner (1991) generated an intensive research with these materials, and in 1994 appeared the first report of nearly 100% diffraction efficiency (η) by Meerholz, Volodin, Kippelen, and Peyghambarian (1994). In these PR devices, a spatial optical excitation (interference pattern) produces, through a sensitizer, a number of mobile holes/electrons, which drift under an external applied electric field E_{ext}, and are subsequently trapped on the dark regions of the interference pattern (Oh, Lee, & Kim, 2009). The resulting space charge electric field, E_{sc}, alters the refractive index of the polymer blend through the electro-optic effect (Kukhtarev, Markov, Odulov, Soskin, & Vinetskii, 1978; Oh et al., 2009). Reorientation of the nonlinear (NL) chromophores, under the combined effects of E_{sc} and E_{ext}, leads to a modulated birefringence, further enhancing the refractive index modulation (Günter & Huignard, 2007; Günter, 2000; Sun & Dalton, 2008). The resulting index pattern has the same period as the interfering light that generates the photo-carriers, but its phase is shifted. This phase shift is an evidence of the PR effect and leads to an energy exchange between the two coherent beams that generate the light grating. For PR polymers, however, a strong external electric field is necessary for charge photogeneration, high hole/electron mobility and orientational birefringence (Maldonado et al., 2007; Ostroverkhova & Moerner, 2004; Zhao et al., 2011). Regarding this fact, in the literature, few reports of highly efficient PR polymers at fields lower than 60 V/μm are found (Hendrickx et al., 1998; Joo et al., 2001; Kippelen et al., 1998; Maldonado et al., 2009; Tay et al., 2008; Thomas et al., 2004), so, the reduction of E_{ext} values is a very important

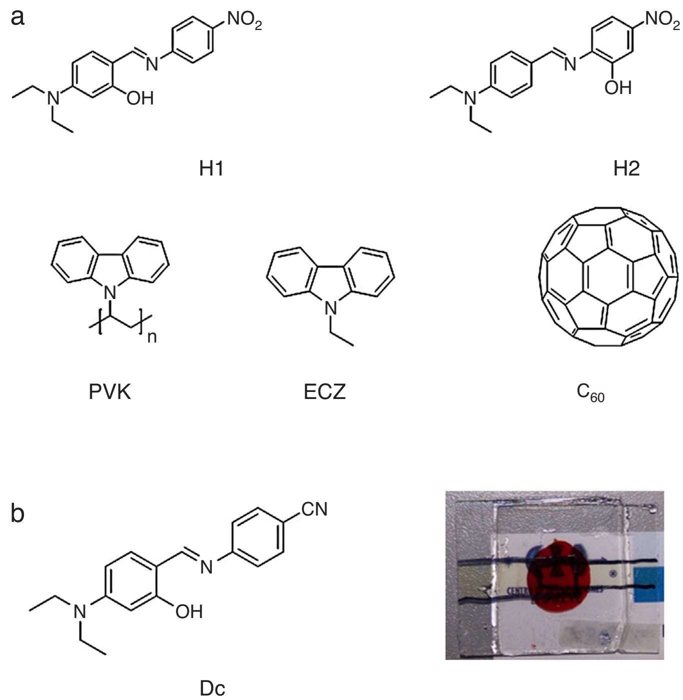

Fig. 1. (a) Molecular structure of our previously used nonlinear molecules **H1** and **H2** (Maldonado et al., 2009), the polymer matrix PVK, the plasticizer ECZ and the sensitizer fullerene C_{60}. (b) Molecular structure of the NL **Dc** chromophore used in this work and a photograph of a PR polymer device doped with **Dc**.

feature to take into account in the development of novel organic PR materials and for the realization of technological applications.

Optimization of the PR effect in organic materials generally involves the synthesis of *push-pull* molecules (chromophores) (Marder, Kippelen, Jen, & Peyghambarian, 1997; Moon & Kim, 2009; Würthner, Wortmann, & Meerholz, 2002) with strong linear and microscopic NLO properties, i.e., the permanent dipole moment μ, the polarizability anisotropy $\Delta\alpha$ (birefringence contribution), and the first hyperpolarizability β (EO contribution) (Marder et al., 1997; Moon & Kim, 2009). Recently, we have reported very high diffraction efficiencies at low applied electric field on PR compounds based on the dipolar arylimine chromophores **H1** and **H2** (Maldonado et al., 2009), see Figure 1, obtaining 87% and 75% at just E_{ext} = 48 V/μm and 32 V/μm, respectively; likewise, using the chromophore **Dc**, from the same family, diffraction efficiencies as high as 90% and 82% were achieved at just E_{ext} = 56 V/μm and 63 V/μm, respectively (Herrera-Ambriz et al., 2011). Our PR polymers based on **Dc** were also recently employed in a laser ultrasonic receiver (Zamiri et al., 2015) as contactless and adaptive interferometers, which are used widely for materials characterization (Davies, Edwards, Taylor, & Palmer, 1993; Zamiri et al., 2014).

In this work, by using our PR polymers based on **Dc** NL chromophore synthesized in our labs, reversible holographic transmission images and reconstruction of distorted figures by OPC under the FWM technique are reported. These reversible reconstructions were performed at one of the smallest E_{ext} values reported in the literature: 27 V/μm. Typical response time