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Spatially parallel picosecond optical data storage using persistent hole burning

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Picosecond real-time recording and reading of spatially parallel optical data was demonstrated. The technique is based on the time and space holography in media which exhibit persistent hole burning at low temperatures. Picosecond temporal profiles of three optical beams representing three characters, P, H, and B, were stored in a polymer film doped with dye molecules.

1. Introduction

Development of new techniques and materials for optical parallel data processing is of great importance for the construction of high-capacity optical communication systems and for ultrafast optical computing. In this communication, we propose and demonstrate ultrafast writing and reading of spatially parallel optical data using a holographic information storage technique in persistent hole burning (PHB) materials. PHB in low-temperature dye-doped polymers has been intensely studied mainly for the application to multiple-wavelength data storage [1,2]. Holes of up to 10^3 can be burned in the broad inhomogeneous absorption band, in addition to the high spatial density of the optical memory devices. The writing and the reading speed of this technique, however, are very limited because of difficulties in fast burning and probing of spectrally narrow holes.

Time and space holography in PHB media has been proven to be effective for the storage of ultrafast spatial optical data [1–6]. Using the same materials as used in the frequency-domain PHB memories, ultrafast writing and reading of spatially parallel subpicosecond optical data is possible by this technique. In this technique, a short "reference" optical pulse, write pulse, is used for the recording of temporally modulated spatially parallel data in a PHB medium. By applying another short pulse, read pulse, to the sample to read out the data, a replica of the data pulse is emitted from the sample. Since the writing and the reading processes proceed in real time, subpicosecond recording and restoring of spatially parallel optical data is possible.

In the time and space holography technique, the temporal shape of the signal beam is stored in the inhomogeneous absorption band as a spectral interference pattern between the signal beam and short-pulsed reference beam [7]. The resulting frequency-domain hologram records the amplitude and the phase of the signal beam as a Fourier transform of the temporal shape of the electric field of the signal beam. Spatial information is stored at the same time in the same manner as in ordinary holograms in frequency-nonselective media, where the amplitude and the phase of the signal beam are stored in the spatial domain in the medium as an interference fringe pattern with the unidirectional reference beam. Thus the temporal and the spatial information storage in PHB media is a logical extension of the usual (spatial) holography, and the processes can be formulated in a unified way as is presented in the following. Being a holographic technique, it has a great advantage in invulnerability to partial damages to the media. It should also be noted here that the time and space hologram in a PHB medium has the full capacity of the high information density of the PHB memory.

2. Theory

Time and space holography in PHB media can be analyzed by extending the formulation of the photon echo memory [7,8] or the accumulated photon echo [9] to allow the signal pulse to have the information in the spatial dimension. In accumulated photon echo experiments, two pulses with a time delay between them, t_{12}, generate a frequency-domain periodical modulation in the excited and the ground state population in the wide inhomogeneous distribution of the transition frequency of the chromophore. The population grating in the excited state decays rapidly (nanoseconds to picoseconds) because of the excited state relaxation. The grating in the ground state, however, can be accumulated on a much longer time scale if the chromophore has a so-called bottle-neck state with a long relaxation time. In organic dye molecules, usually the lowest triplet state is the bottleneck state and accumulates the ground state population grating. In materials which exhibit persistent hole burning, however, some fraction of the population grating is stored persistently in the media as spectral holes. Thus the accumulation time can be virtually infinite. The power spectrum of the sum field of the reference write pulse and the signal pulse is stored as a spectral hole in the medium. The stored information can be recovered by another short read pulse applied after a long time, as long as months in principle. Another advantage of the time and space holography using persistent hole burning, which is sometimes called photochemically accumulated stimulated photon echo (PASPE) [4], is that it does not require strong optical nonlinearity.

We assume here that the field of the write pulse, E_W, has a propagation direction unit vector $\boldsymbol{n}_0$, and that the temporal duration is short enough as

$$E_W(\boldsymbol{r},t)=\theta_W\,\delta(t-t_1-\boldsymbol{n}_0\cdot\boldsymbol{r}/c)\times\exp[-i\omega_0(t-t_1-\boldsymbol{n}_0\cdot\boldsymbol{r}/c)]\,, \tag{1}$$

where t_1 is the arrival time of the write pulse, c is the velocity of light, and ω_0 is the central angular frequency of the light. The signal beam arrives at the sample after the write pulse with an arbitrary temporal and spatial shape as

$$E_S(\boldsymbol{r},t)=\int d\boldsymbol{n}\,E(\boldsymbol{n},t-t_2-\boldsymbol{n}\cdot\boldsymbol{r}/c)\times\exp[-i\omega_0(t-t_2-\boldsymbol{n}\cdot\boldsymbol{r}/c)]\,. \tag{2}$$

The power spectrum of the sum field E_W+E_S in the sample is

$$\begin{aligned}S(\boldsymbol{r},\omega)&\propto\left|\int dt\,\exp(i\omega t)\,[E_W(\boldsymbol{r},t)+E_S(\boldsymbol{r},t)]\right|^2\\&=|\theta_W|^2+\left|\int d\boldsymbol{n}\,F(\boldsymbol{n},\Delta\omega)\exp[i\omega(\boldsymbol{n}\cdot\boldsymbol{r}/c)]\right|^2\\&\quad+\theta_W\int d\boldsymbol{n}\,F^*(\boldsymbol{n},\Delta\omega)\\&\quad\times\exp[i\omega(t_1-t_2+(\boldsymbol{n}_0-\boldsymbol{n})\cdot\boldsymbol{r}/c)]\\&\quad+\theta_W^*\int d\boldsymbol{n}\,F(\boldsymbol{n},\Delta\omega)\\&\quad\times\exp[i\omega(t_2-t_1+(\boldsymbol{n}-\boldsymbol{n}_0)\cdot\boldsymbol{r}/c)]\,,\end{aligned} \tag{3}$$

where

$$F(\boldsymbol{n},\Delta\omega)\equiv\int dt\,\exp(i\Delta\omega t)\,E(\boldsymbol{n},t)\,, \tag{4}$$

and

$$\Delta\omega=\omega-\omega_0\,. \tag{5}$$

The hole burned in the sample has the same shape as that of the power spectrum provided that the homogeneous linewidth of the chromophore is narrow enough compared with the modulation structures in the power spectrum, and that the inhomogeneous distribution of the absorption frequency is flat through the spectral region of the excitation light. The first condition is equivalent to the requirement that in the time domain the time interval between the write pulse and the signal pulse should be shorter than the dephasing time, T_2, of the chromophore.

The read pulse, which is also assumed to be a delta-function pulse as

$$E_R(\boldsymbol{r},t)=\theta_R\,\delta(t-t_3-\boldsymbol{n}_0\cdot\boldsymbol{r}/c)\times\exp[-i\omega_0(t-t_3-\boldsymbol{n}_0\cdot\boldsymbol{r}/c)]\,, \tag{6}$$

arrives at the sample at time t_3 ($t_3>t_2$) with the same propagation direction, $\boldsymbol{n}_0$, as that of the write pulse. After time t_3, each chromophore starts free precession, which causes light field emission. The emitted field is proportional to

$$\int d\omega\,\theta_R\exp[-i\omega(t-t_3-\boldsymbol{n}_0\cdot\boldsymbol{r}/c)]\,S(\boldsymbol{r},\omega)\,. \tag{7}$$

The component of the emitted field with the same propagation direction as that of the signal beam is obtained by substituting only the last term of eq. (3) into eq. (7) as

$$E_E(\boldsymbol{r}, t) \propto \theta_R \theta_W^* \int \mathrm{d}\boldsymbol{n}\, E(\boldsymbol{n}, t-t_3-t_2+t_1-\boldsymbol{n}\cdot\boldsymbol{r}/c) \times \exp[-\mathrm{i}\omega_0(t-t_3-t_2+t_1-\boldsymbol{n}\cdot\boldsymbol{r}/c)] \,. \qquad (8)$$

This expression shows that the emitted light is a time-delayed replica of the signal beam.

3. Experiment

In the experiment, signal beams of three different directions representing three ASCII codes for P, H, and B were used for the recording of spatially parallel data in the PHB medium. Each character was coded binarily in the temporal shape of one of the three picosecond beams. Simultaneous reading of the three spatially parallel temporally-coded data were observed using a streak camera coupled with a CCD photodetector, which could acquire the two-dimensional time and space profile of the read-out signal.

The sample used for the recording of the time and space hologram was a polymethylmethacrylate (PMMA) film doped with Oxazine 720 at a concentration of 0.9×10^{-4} mol/kg. The absorbance of the sample at the laser wavelength (641 nm) was about 0.5. The sample was immersed in liquid helium and kept at 1.6 K during the experiment.

The schematic of the experiment is shown in fig. 1. Picosecond optical pulses for the experiment were generated by a synchronously mode-locked dye laser (Coherent, Model 774) pumped by a cw mode-locked Nd:YAG laser (Coherent, Model 76-s). The dye laser was operated without the saturable absorber jet which is included in the commercial set. The repetition rate, the pulse width and the wavelength were 76 MHz, 5 ps, and 641 nm, respectively. The laser output was attenuated and divided into the reference beam and the three signal beams. The average power of each beam was about 10 μW. The delay time of each signal pulse with respect to the reference write pulse could be varied independently. These beams were loosely focused to a focal area of 3 mm^2 on the sample. Three signal beams were aligned on a horizontal plane. After passing the sample, they were focused onto the entrance slit of a synchroscan streak camera (Hamamatsu, C3681-01) by a spherical and a cylindrical lens. The distance between the signal beams was about 1 mm at the entrance slit. In the reading process, the signal beams were blocked, and the emitted light in the direction of the signal beams was observed by the streak camera.

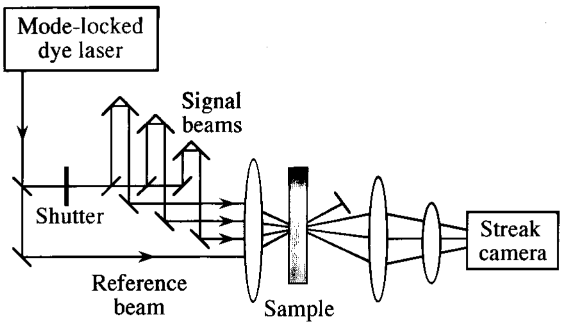

Fig. 1. Experimental schematic of writing and reading optical data by the time and space holography.

The ASCII codes for P, H, and B were written in the sample bit by bit in each signal beam. Since all the three binary codes, P, H, and B, have two 1's, which were coded as pulsed peaks, and six 0's, which were coded by the absence of pulses, only two exposures were enough. Writing by the three signal beams was performed simultaneously, which resulted in two simultaneous exposures to the three signal beams. This writing procedure was adopted only for ease of the experiment. In actual memory devices, all the parallel codes can be written in real time if picosecond temporally coded pulses are prepared. The sample was irradiated by the laser pulse train for 10 s for writing of one bit, which corresponds to the fluence of 3 mJ/cm^2. The stored data were read after the writing process by applying only the read pulse, which was the same as the write pulse, and the emitted light was detected by the synchroscan streak camera. The integration time for the detection was 10 s. In some organic PHB materials, the efficiency of persistent hole burning reaches over 10% [10]. Therefore, if we prepare a high power laser pulse, writing with a single set of the signal and the write pulses is possible.

The contour plot of the emitted data is shown in fig. 2. The time origin is at the time when the read pulse was applied, and the spatially wide signal at time zero is due to the scattering of the read pulse.

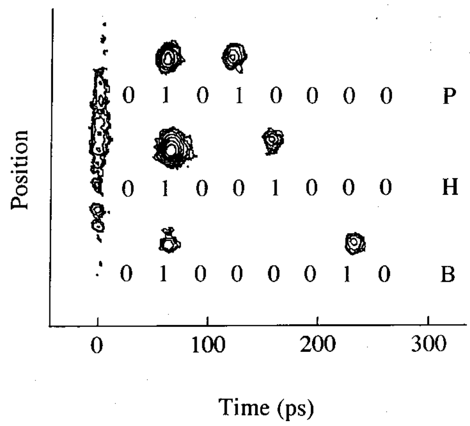

Fig. 2. The streak-camera contour plot of the binary data for "PHB" restored from the time and space hologram.

The binary codes for P, H, and B are shown in the figure. Each peak in this contour plot corresponds to "1" of the binary code and absence of peaks to "0". The temporal width of each peak is about 10 ps, which is determined by the temporal resolution of the streak camera, instead of the actual pulse duration. The time interval between each bit was about 33 ps. The variation in the intensity of peaks, which is not intentional, is due to imcomplete overlap of the signal and the reference beams at the sample.

4. Conclusion

It was shown that picosecond spatially parallel, temporally coded optical data can be stored and recovered in persistent hole burning media in real time. The possible duration of the data is limited by the dephasing time of the sample, which is estimated to be several hundreds of picoseconds at 1.6 K. The bit rate per each beam direction can be increased up to several THz, which is limited by the inhomogeneous width of the absorption spectrum. The capacity of this technique in the spatial domain is proportional to the area of the sample, and the limit is about 1 bit per 10 μm^2, which is determined by the diffraction of the light. For the full utilization of the possible capacity of this holographic memory, the development of the generation and detection technique of subpicosecond pulse train is desired. The development of new PHB materials with a higher burning efficiency and a higher operation temperature is also required for the future employment of this technique.

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References

[1] W.E. Moerner, ed., Persistent spectral hole burning: science and applications (Springer, Berlin, 1988).
[2] O. Sild and K. Haller, eds., Zero-phonon lines and spectral hole burning in spectroscopy and photochemistry (Springer, Berlin, 1988).
[3] A.K. Rebane, R.K. Kaarli and P.M. Saari, Pis'ma Zh. Exsp. Teor. Fiz. 38 (1983) 320; [JETP Lett. 38 (1983) 383].
[4] P. Saari, R. Kaarli and A. Rebane, J. Opt. Soc. Am. B 3 (1986) 527.
[5] A. Rebane, Optics Comm. 65 (1988) 175.
[6] A. Rebane and J. Aaviksoo, Optics Lett. 13 (1988) 993.
[7] T. Mossberg, Optics Lett. 7 (1982) 77.
[8] M. Mitsunaga, M.K. Kim and R. Kachru, Optics Lett. 13 (1988) 536.
[9] W.H. Hesselink and D.A. Wiersma, Phys. Rev. Lett. 43 (1979) 1991.
[10] H. Suzuki and T. Shimada, Appl. Phys. Lett. 59 (1991) 1814.