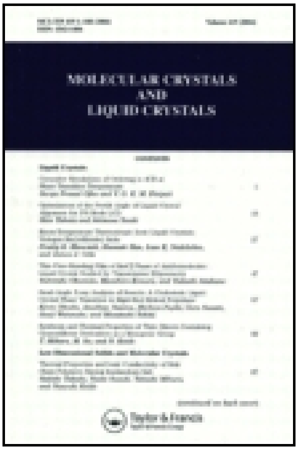

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Spectral Holograms in the Terahertz Range

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To cite this article: J.-L. Le. Gouët , F. Grelet , I. Lorgere , M. Rätsep , M. Tian , M.-L. Roblin & C. Sigel (1996): Spectral Holograms in the Terahertz Range, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 291:1, 295-302

To link to this article: http://dx.doi.org/10.1080/10587259608042759

Mol. Cryst. Liq. Cryst., 1996, Vol. 291, pp. 295–302
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Abstract We review recent works on temporal frequency holograms. The role of white light excitation is stressed. The interferometric data retrieval technique is emphasized. Both the photorefractive crystals and the persistent spectral hole burning amorphous materials are considered as spectral holography media.

INTRODUCTION

In the framework of optical data storage, we have been developing techniques for engraving and retrieving temporal frequency holograms, and for using them as fast optical processors[1-4]. The holographic « plates » that we consider have a spectral size of a few Terahertz. We have encountered this recording spectral width in two different classes of materials. The first class is represented by the persistent spectral hole burning (PSHB) materials that are made up of active centers embedded in an amorphous host matrix. The second class is represented by photorefractive (PR) materials in the counterpropagating-beam configuration[4]. Although their spectral coherence must be preserved over a very broad frequency domain, the holograms have not to be stored with the help of subpicosecond laser pulses. We have been using a white light source to engrave and retrieve them.

STORAGE OF A SPECTRAL PHASE FACTOR: STIMULATED PHOTON ECHO

Let a PSHB sample be illuminated by two pulses, which issue from the same source and that propagate along $\underline{k}_1$ and $\underline{k}_2$ respectively. One can vary the time separation T between the pulses by adjusting their path length difference. The spectral amplitudes of the two fields in the sample can be represented by E(ν) and E(ν)exp(-2iπνT) respectively. Their interference term reads as: S(ν)exp(-2iπνT), where S(ν)= | E(ν) | ^{2} is the energy spectral density of the pulses. Provided T is smaller than the inverse homogeneous width Δ_h^{-1}, this interference structure is engraved over the width Δ_{in} of the absorption band W(ν). The recorded hologram is described by the expression W(ν) S(ν) exp(-2iπνT). The original idea of holography is to store the thorough structure (*holos*: « entire ») of an object field, given a perfectly known reference one. The present process is slightly different since the recorded spectrum S(ν) does not keep any memory of the spectral coherence properties of E(ν). The phase object exp(-2iπνT) is conveyed to the memory material by the carrier field E(ν). The phase object alone is stored while the phase structure of the carrier is lost.

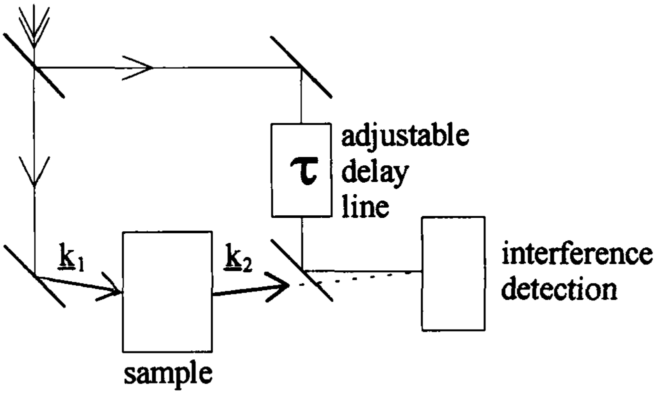

FIGURE 1 Interferometric analysis of the spectral holograms

The sample radiates a field:

$$E_s(\nu)= E_p(\nu)S(\nu)W(\nu)\exp(-2i\pi\nu T) \qquad (1)$$

in direction $\underline{k}_2$, when probed by $E_p(\nu)$ propagating along $\underline{k}_1$. The temporal structure of this signal reflects the spectral shape of the engraved hologram. However, since it coherently spreads over the THz-wide absorption band, the sample response may exhibit subpicosecond features that are not resolved by conventional detectors. In addition, the temporal behavior of the signal is affected by the probe field spectral coherence properties. Interferometric analysis offers an efficient way to recover the originally recorded phase object[5]. The device is sketched on Fig.1. The sample is inserted in one arm of the interferometer. One detects the interference between the signal and a time-delayed replica of the probe field. As a fonction of the delay τ, the contrast of interference fringes reads as:

$$C(\tau) = \int E_s{}^*(\nu).E_p(\nu)\exp(-2i\pi\nu\tau)d\nu \tag{2}$$

Substitution of Eq.1 into Eq.2 leads to:

$$C(\tau) = \int [S(\nu)]^2.W(\nu)\exp[-2i\pi\nu(\tau - T)]d\nu \tag{3}$$

which is rid of the probe field spectral coherence structure. If the source bandwidth is larger than Δ_{in}, $C(\tau)$ exhibits a peak of width Δ_{in}^{-1} that is located at τ=T. As a function of τ, one recovers the temporal shape of the stimulated photon echo that would be generated by a sequence of femtosecond pulses. However, the validity of Eq. 3 is not conditioned by any assumption on the pulse duration. Any source that delivers broadband pulses should work, whether or not pulses are Fourier transform limited. Holograms with different T values can be multiplexed in the sample. In the framework of data storage, each hologram is regarded as a stored information[6] the address of which is represented by T. Interferometry spectroscopy proves efficient to retrieve the stored informations[1]. However, access to data is hampered by the slowness of the optical delay scan. One can improve the random access rate by taking advantage of the processing capabilities of the spectral holograms[3, 7, 8].

RETRIEVAL OF DATA THROUGH SPECTRAL PATTERN RECOGNITION

Let the pulse propagating along $\underline{k}_1$ be shaped by a phase-only filter which converts its spectral amplitude into $E(\nu)f^{(1)}(\nu)$ where $|f^{(1)}(\nu)|^2$=1. Then, the stored hologram reads as: $S(\nu)[f^{(1)}(\nu)]^*W(\nu)\exp(-2i\pi\nu T)$. The readout pulse along $\underline{k}_1$ is assumed to be shaped by the phase factor $f^{(2)}(\nu)$. Then, according to Eqs 1-3, the interferometer detected signal reads as:

$$C(\tau) = \int [S(\nu)]^2.W(\nu)[f^{(1)}(\nu)]^* f^{(2)}(\nu)\exp[-2i\pi\nu(\tau - T)]d\nu \tag{4}$$

The spectral density $S(\nu)$ can be adjusted so that $[S(\nu)]^2$ $W(\nu)$ is constant over the width

Δ_w of the shaping window. Then, at $\tau = T$, the contrast $C(\tau)$ can be expressed as:

$$C(T) \propto \int [f^{(1)}(\nu)]^* f^{(2)}(\nu) d\nu \qquad (5)$$

which is nothing but the scalar product of the shaping factors. This function is optically computed by the combination of the holographic memory and of the interferometer. Let the shaping factors belong to a set of orthogonal functions that satisfy the following property:

$$\int [f_i(\nu)]^* f_j(\nu) d\nu = \delta_{ij}\Delta_w \qquad (6)$$

A signal is detected only if the readout shape factor coincides with the recorded one. The shape factor can be regarded as a data address in the spectral memory[8]. Holograms which are built with different shape factors can be multiplexed in the memory. Each address only responds to the matched readout key. All the stored data are retrieved at the same fixed delay T of the interferometer, in contrast with temporally addressed data. In order to retrieve a data one has to compose its address phase factor. This can be accomplished within a few hundreds microsedonds with the help of a liquid crystal modulator[3]. The optical processing capability of spectral holograms is not specific to PSHB compounds. It can be adapted to PR materials[9, 4], with the additional attractive property of working at room temperature.

SPECTRAL HOLOGRAMS IN PHOTOREFRACTIVE MATERIALS

Let two counterpropagating monochromatic beams, directed along $\underline{k}_1$ and $\underline{k}_2 = -\underline{k}_1$, overlap in a L-thick PR crystal (Fig.2). In this material they form a standing wave that engraves a refractive index Bragg grating of period $c/2n\nu$, where ν represents their common single frequency. The grating spreads over the entire length L of the crystal. After recording, a beam of frequency ν', that is directed to the crystal along $\underline{k}_1$, is diffracted along $\underline{k}_2$ provided $|\nu-\nu'| < c/2nL$, according to the phase matching condition. Bragg gratings engraved at different wavelengths can be multiplexed in the crystal. Data that are recorded in the shape of these gratings are thus selectively retrieved at addresses represented by their storage wavelength[10].

A wavelength multiplexed memory ignores the relative phase-shift of the different gratings: the spectral addresses are mutually incoherent. However a coherent set of gratings is engraved when finite bandwidth pulses are substituted for the monochromatic ones. Let z be the space coordinate along $\underline{k}_1$. Let the origin located at the center of the crystal. The two pulses are split from the same beam, with a time-shift T at z= 0. Their bandwidth is denoted by Δ_p. The grating they engrave at frequency ν is proportional to $S(\nu)\exp[2i\pi\nu(-T+2nz/c)]$. The gratings associated with the different frequencies

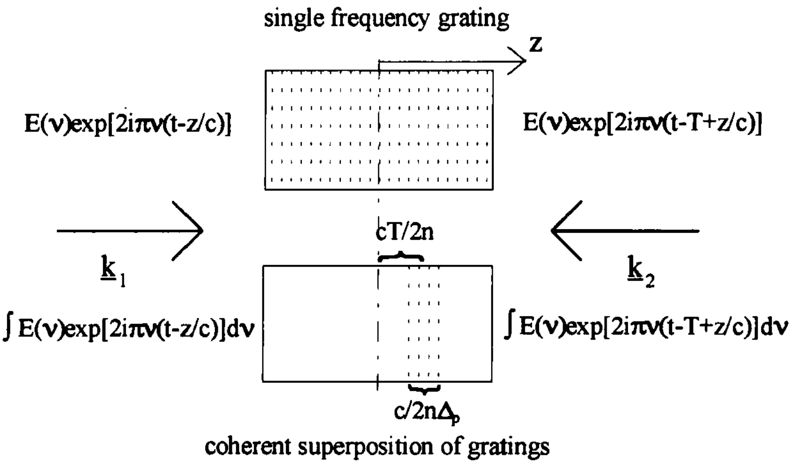

FIGURE 2 Spectral hologram in a photorefractive crystal

combine in a thin spatially modulated structure, the extension of which is $c/2n\Delta_p$. It is located around z=cT/2n. When probed along $\underline{k}_1$ the sample radiates a signal in direction $\underline{k}_2$. Interferometric analysis of the emitted field is again described by Eq. 2. The fringe contrast on the interferometer is:

$$C(\tau) = \int [S(\nu)]^2 . \exp[-2i\pi\nu(\tau - T)]d\nu \tag{7}$$

As in a PSHB material, the parameter T can be considered as a storage address[11]. The spatial position where a data is recorded can be identified with a temporal coordinate. The number of independent addresses is about $2nL\Delta_p/c$. This is the number of non-overlapping elementary gratings that the sample can accomodate. The storage of broad bandwidth fields illustrates the spectral coherence properties that underlie the optical processing capabilities of spectral holograms. The retrieval efficiency of broad bandwidth pulses thus appears as a critical issue in the context of optical processing.

DATA RETRIEVAL EFFICIENCY

The data retrieval efficiency can be characterized by the signal-to-probe field ratio $\eta = |E_s(\nu)/E_p(\nu)|$ (Table 1). In both PR and PSHB materials we consider the recovery of a single narrowband storage as a reference to which we ultimately compare the readout of multiple broad bandwidth pulses. We first examine the local storage of a single data within the absorption band of a PSHB material. The light source bandwidth Δ_p is assumed to be much smaller than the absorption width Δ_{in}. In order to avoid causality effects we assume that the delay T of the two pulses involved in the storage satisfies the condition $\Delta_p T > 1$. The data is engraved at spectral position ν_d over the spectral domain Δ_p. The maximum corresponding value of $|E_s(\nu)/E_p(\nu)|$ is denoted η_{PHB}. In order to stack different data in the material, one assigns each information to a specific address ν_d, while T is kept constant. Then the maximum η value remains equal to η_{PHB} for each recovered data, irrespective of the data number which is $<\Delta_{in}/\Delta_p$. Indeed, different data stand on different molecules. Let us now examine the storage of a single T-addressed data. The data is represented by a spectral hologram that spans the entire absorption band. The maximum η value still equals η_{PHB}. In order to record M T-addressed data within the memory, one has to multiplex M holograms. Each one, that spreads over the same spectral domain, is labeled by a specific value of the frequency period 1/T. Since the same molecules are shared between the M different data, the maximum η value drops to η_{PHB} /M. This reduction occurs when the data are sequentially recorded. A less important reduction factor of $M^{-1/2}$ can be obtained when all the data are simultaneously recorded with random relative phase-shift.

TABLE I Data retrieval. Ratio of the signal to the readout fields. The memory capacity and the number of occupied addresses are denoted N and M.

	ν-addressing	T-addressing
PSHB	η_{PSHB}	η_{PSHB}/M
PR	η_{PR}/M	$\eta_{PR}/(MN)$

As for storage in a PR material, it can be shown that data are restored with the same diffraction efficiency, whether one uses the wavelength multiplexing[10] approach or the more conventional angular multiplexing technique. Let η_{PR} represent the maximum η value when a single monochromatic data is recorded in a PR material. This value is reduced to η_{PR}/M when M data are wavelength multiplexed in the crystal, since the maximum refractive index variation is shared between the different holograms. When data are T-addressed, each information is engraved in the shape of a $c/2n\Delta_p$-thick grating. The the number of addresses N is close to $2nL\Delta_p/c$. Thus, the spatial thickness of a monochromatic data is N times larger than that of a Δ_p-broad recording. It results that, in a PR memory where a single T-address is occupied, the maximum η value is about η_{PR}/N. This dramatic ratio between T-addressing and wavelength multiplexing persists when several data are stored. Indeed, when a data is locally recorded, it is gradually erased by the subsequent storage of additional data at different positions. When T-addressing is used to store M data in a N-address memory, the maximum η value turns out to be about $\eta_{PR}(NM)^{-1}$. Above we considered holograms that are engraved when the pulse along $\underline{k}_1$ is spectrally shaped by the phase factor $f_i(\nu)$. Comparison with wavelength multiplexing leads again to the same 1/N reduction[12]. This questions the adequacy of PR crystals to the storage of broadband spectral holograms. However operation at room temperature is a decisive advantage that can pay for the small size of the signal. In addition, one must keep in mind that η_{PSHB} and η_{PR} can reach quite dissimilar values. While a diffraction efficiency of one hundred per cent can be attained on a refractive index grating stored in a transparent PR material[13], the absorption character of the gratings engraved in a PSHB medium imposes an upper limit of about 0.37 to η_{PSHB}[14]. Further experimental investigation is required to decide between those two classes of materials.

CONCLUSION

With the help of a chaotic light source, we have been able to store and retrieve multiplexed THz-wide spectral holograms in PR and PSHB materials. When the temporal frequency address of the holograms is shaped by a liquid crystal spatial modulator, the random access to any stored page does not exceed 1 ms. In addition to their application to data storage, spectral holograms offer attractive prospects in the field of real time ultrafast optical processing where both PR and PSHB materials could play a role.

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