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Holography in frequency selective media II: Controlling the diffraction efficiency

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A novel hologram storage technique based on recently reported causality effects in spectral hole-burning media [1] is presented. Simultaneously sweeping the phase and frequency of CW recording light produces holograms with new diffraction properties. In particular the distribution of the light in the different diffraction orders becomes asymmetric and can be easily controlled by the direction of the phase shift. The line shape of phase and frequency swept holograms can be designed in a way which yields many advantages for optical data storage. Compared with normal holograms recorded at a single frequency the maximum diffraction efficiency has been increased by a factor of 5.

1. Experiment and setup

The experimental setup is shown in fig. 1. A tunable frequency-stabilized CW laser beam (Coherent 899-29 autoscan dye laser) is split into an object and a reference beam which illuminate the sample with a relative angle of only 1.5°. To fulfill the condition for thin holograms requires the spacing of the hologram fringes (25 μm) to be on the order of the sample thickness (65 μm). This small angle is achieved by introducing a 50/50 beamsplitter plate in front of the sample. Both beam paths have approximately the same length (±0.5 cm) to reduce phase shifts of the hologram fringes during a frequency shift. A mirror in the object beam path is mounted on a piezo-transducer and can be moved several wavelengths in both directions under computer control. The sample consists of a thin (65 μm) chlorin doped polymer film (polyvinylbutyral) with a size of 2.5×2.5 cm^2 and an optical absorbance of 1.5 at the absorption maximum at 634 nm. The sample is immersed in liquid helium in an Oxford MD 10 bath cryostat at a temperature of 1.7 K. The properties of these samples are described elsewhere [2]. Behind the sample two photomultipliers detect the light from the symmetrical −1 and +1 diffraction orders. A Sun-4 computer controls all aspects of the experiment.

During recording, the object and reference shutters are open and both beams illuminate the sample with an intensity of 0.6 m W/cm^2. The

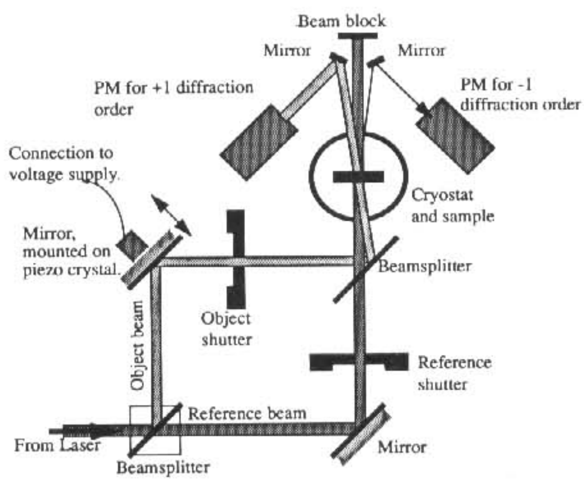

Fig. 1. Setup for the recording and reading of phase and frequency swept holograms. The procedures are explained in the text. The +1 diffraction order is the extension of the object beam through the sample, while the −1 order is symmetrical to it with respect to the reference beam direction.

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laser scanned slowly from lower to higher frequency. Simultaneously the piezo-mounted mirror in the object beam is displaced as a linear function of the frequency change. A decrease of the optical path of one wavelength causes a $+2\pi$ phase shift of the resulting grating at the sample. The total exposure time is typically 10 s, depending on the frequency range used.

During reading only the reference shutter is opened and the light intensity is decreased with a neutral density filter by a factor of 100. The diffraction efficiency is recorded as a function of frequency using two photomultipliers which monitor the diffracted light of the $+1$ and -1 diffraction orders.

2. Results

2.1. Switching between diffraction orders

In fig. 2 the readout signals of the $+1$ diffraction order are shown for three different burning processes. In all cases the burning range is 3.5 GHz and the exposure time 20 s. In the cases a), b) and c), phase shifts of -2π, 0 and $+2\pi$ have been applied.

The diffracted intensity is suppressed in one diffraction order and amplified in the other, depending on the direction of the phase shift used during recording. If no phase shift is applied, then both orders show the usual equal intensity signals as expected for thin diffraction gratings.

The results in the other (-1) diffraction order look identical, if curves (a) and (c) are switched. These experiments demonstrate a new way of controlling the distribution of the hologram signal into different directions during holographic recording with CW laser light.

2.2. Line shape of swept holograms

In fig. 3 two experimental curves are displayed. Curve (a) shows the typical line shape of a hologram recorded at a single frequency [3] while curve (b) shows a phase and frequency swept hologram burned over a frequency range of 1 GHz (twice the homogeneous hole width) with a phase shift of -2π. The exposure time is the same as for the normal hole. The signal is broader

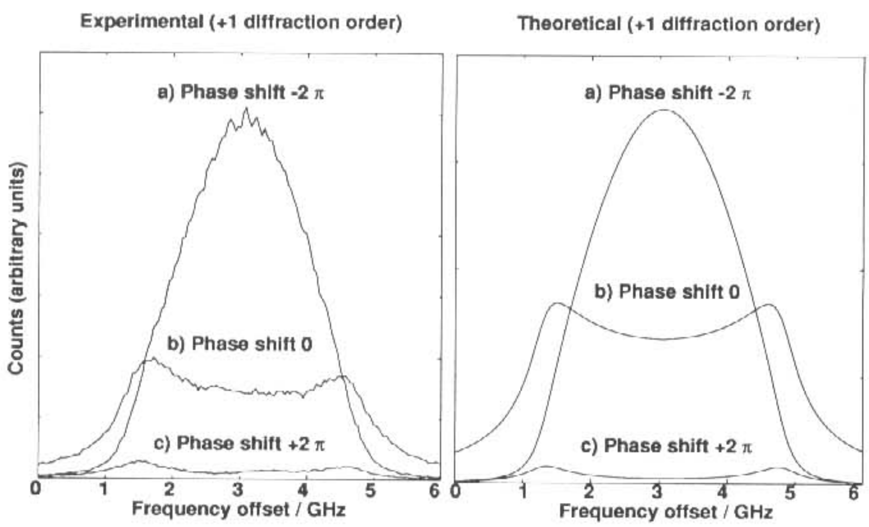

Fig. 2. Comparison of the holographic signal intensities after different phase shifts during recording. All holograms are burnt continuously in a frequency range of 3.5 GHz. Simultaneously different mirror shifts were applied. (a): One wavelength into negative direction, (b): no mirror shift, (c): one wavelength into positive direction. If the other (-1) diffraction order is regarded, the curves (a) and (c) are just switched, while (b) remains the same. On the right-hand side the results of theoretical calculations are plotted.

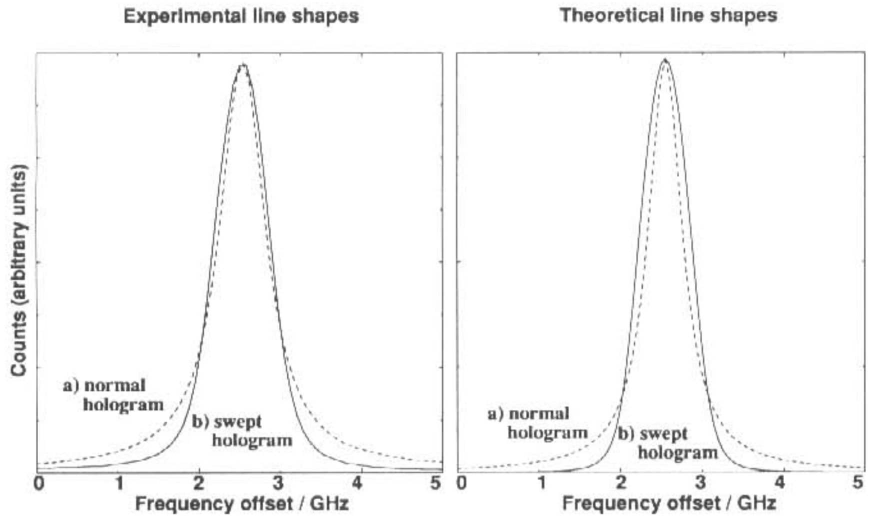

Fig. 3. Comparison of the line shapes of normal holograms with those of phase and frequency swept holograms. Both holograms are exposured for the same time. The normal hologram a) is recorded at a single frequency position while hologram b) is burnt continuously over a 1 GHz range (about two line widths) with a phase shift of -2π. On the right side, theoretical results for these cases are plotted.

near the maximum while the wings decay more steeply. This property is useful for reducing crosstalk between holograms at adjacent frequencies in high density optical data storage [4].

2.3. Increasing the diffraction efficiency

In fig. 4 the maximum achievable efficiency of single-frequency holograms is compared to those

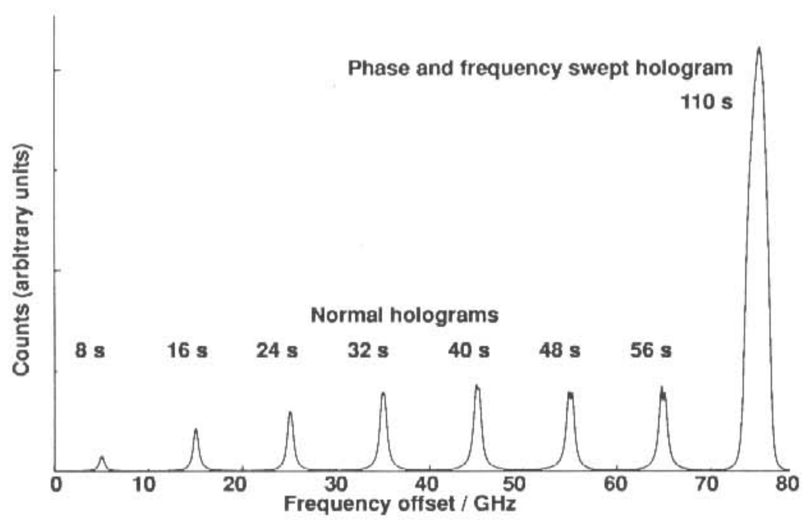

Fig. 4. Maximum efficiencies of normal holograms, compared with those of phase and frequency swept holograms. The first holograms are burnt at single frequency positions with 8, 16, 24, 32, 40, 48 and 56 s exposure time. Saturation with the typical splitting in the middle can already be observed at the 5th hologram (48 s) where the efficiency cannot be increased any more. The hologram on the right side is burnt continuously in a range of 3 GHz, with a phase shift of -2π. The exposure time is enhanced to 110 s and the resulting efficiency is about 5 times larger than the maximum efficiency of the normal holograms.

of phase and frequency swept holograms. The first seven holograms were recorded with linearly increasing burning time (8–56 s), while the right-most hologram is phase and frequency swept, burnt for 110 s over a frequency range of 3 GHz with a phase shift of -2π. The data show that the diffraction efficiency of single-frequency holograms becomes saturated and shows a typical dip in the middle [3]. The phase and frequency swept hologram consumes a greater amount of molecules, but the maximum efficiency is increased by a factor of 5. Here, the frequency sweep gives access to more molecules, while the phase shift ensures constructive interference of the light diffracted from the different gratings.

3. Theory and simulations

The holographic efficiency of a hologram with small grating amplitude is proportional to the square of the modulation of the complex dielectric constant $|\epsilon_1|^2$ [5]. After recording at a single frequency ω_B this modulation is given by ($n_1 - i\alpha_1$ in ref. [6]):

$$\epsilon_1 = \frac{1}{\pi} \frac{1}{\omega_B - \omega + i\left(\frac{\Gamma}{2}\right)}, \tag{1}$$

where Γ is the homogeneous line width.

The phase and frequency sweep of a hologram recorded on the range $[\omega_{B1}, \omega_{B2}]$ with a total spatial phase shift of $\Delta\varphi$ can be taken into account by multiplying of ϵ_1 with a phase factor $e^{i\phi\omega_B}$ and integrating ω_B over the burning range. In our case of a linear phase shift, a dispersion factor ϕ is defined as:

$$\phi = \frac{\Delta\varphi}{(\omega_{B2} - \omega_{B1})}. \tag{2}$$

A positive factor ϕ means an increase of the phase with increasing frequency and is therefore the description for positive mirror shifts. With consideration of this phase shift, the variation of the complex dielectric constant becomes:

$$\epsilon_{1cont}(\omega) = \frac{1}{\omega_{B2} - \omega_{B1}} \int_{\omega_{B1}}^{\omega_{B2}} \epsilon_1(\omega, \omega_B)\, e^{i\phi\omega_B}\, d\omega_B. \tag{3}$$

The calculated curves in figs. 2 and 3 are plots of $|\epsilon_{1cont}(\omega)|^2$, with ϕ calculated from eq. (2) assuming $\Gamma = 500$ MHz. The other diffraction order is described by changing the sign of the dispersion factor ϕ, since negative spatial phase shifts in one diffraction order are positive in the conjugate order.

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