Enhanced diffraction efficiency and amplitude coupling in photorefractive materials

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Abstract

We show that feedback-controlled holographic recording in photorefractive materials produce, in general, optimized running holograms where the diffraction efficiency and the amplitude coupling (energy coupling or light amplification) achieve their maximum possible values. Absorbing materials produce a departure from this optimum condition, the higher the absorption the larger the departure. Experimental and simulated results using photorefractive $Bi_{12}TiO_{20}$ crystals at different laser wavelengths do confirm our theoretical predictions.

1 Introduction

Most applications of photorefractive materials require high diffraction efficiency (η) or large amplitude coupling (determined by the exponential gain coefficient Γ) or both. Unfortunately, materials having fast response, that are suitable for image and signal processing, usually exhibit comparatively low η and low Γ too. It is possible to increase η by adequately applying an external electric field on the sample at the cost of a higher noise and a comparatively lower Γ [1]. It is still possible to further increase η and also Γ by producing running holograms. The latter are generated, in the presence of an externally applied field, under the action of an adequately moving pattern of fringes of light projected onto the sample as indicated in Fig.1. An optimum value does exist for the speed v of the moving pattern of fringes, depending on the experimental conditions and the material's properties, that simultaneously maximizes both η and Γ with increasing values for increasing applied field. Such optimal condition is achieved when the pattern-of-fringes speed matches the response time of the material in which case a resonance is produced. We have already shown citeFrejlich:90OLerra that in the presence of an applied electric field and under the action of a negative feedback loop a kind of running hologram is produced that gets automaticaly adjusted to to the resonance speed condition whatever the experimental and material parameters involved.

2 Theory

The expressions for the irradiances of the reference and the signal beams behind a photorefractive sample ($I_R(z)$ and $I_S(z)$, respectively) for a running (with speed v) hologram in a two-wave mixing experiment are [2, 1]

$$I_R(z) = I_R^0 \frac{1+\beta^2}{\beta^2 + e^{\Gamma z}} \qquad I_S(z) = I_S^0 \frac{1+\beta^2}{1+\beta^2\, e^{-\Gamma z}} \tag{1}$$

$$\Gamma = -\frac{2\pi n^3 r_{\text{eff}}}{\lambda \cos\theta'} \Im\{E_{\text{eff}}\} \qquad E_{\text{eff}} = \frac{E_0 + iE_D}{(1+K^2L_D^2 - iKL_E)(\omega_R + i\omega_I - iKv)} \tag{2}$$

$$\omega_R = \frac{1}{\tau_M}\frac{(1+K^2l_s^2)(1+K^2L_D^2) + Kl_E KL_E}{(1+K^2L_D^2)^2 + K^2L_E^2} \qquad \omega_I = \frac{1}{\tau_M}\frac{KL_E - Kl_E}{(1+K^2L_D^2)^2+K^2L_E^2} \tag{3}$$

where I_R^0 and I_S^0 are the input values, $\beta^2 \equiv I_R^0/I_S^0$, z the coordinate along the sample's thickness. The applied field is E_0, the diffusion-arising field is E_D, the complex pattern-of-fringes modulation coefficient is m, the average index of refraction is n, the effective eletro-optic coefficient is r_{eff}, the recording light wavelength is λ and $2\theta'$ is the angle between the interfering beams inside the crystal. All other are material parameters defined in the references. The diffraction efficiency in this case is

$$\eta = \frac{2\beta^2}{\beta^2+1}\frac{\cosh(\Gamma d/2) - \cos(\gamma d/2)}{\beta^2\, e^{-\Gamma d/2} + e^{\Gamma d/2}} \quad \text{with} \quad \gamma \equiv -\frac{2\pi n^3 r_{\text{eff}}}{\lambda\cos\theta'}\Re\{E_{\text{eff}}\} \tag{4}$$

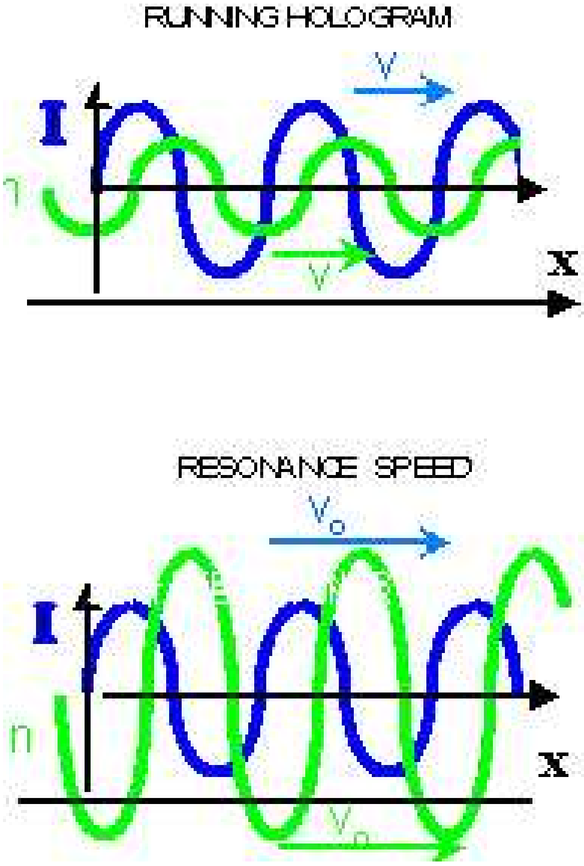

Figure 1: *Schematic description of running hologram generation in photorefractives. A moving pattern-of-fringes (dark sinusoidal) onto the sample produces a synchronously moving volume hologram (grey sinusoidal) that reaches a maximum amplitude at a resonance speed.*

with d being the thickness of the sample. From Eq.(2) it stems that the maximum amplitude of the effective space-charge field modulation is achieved for the resonance speed

$$Kv_0 = \omega_I \tag{5}$$

For the case of $\eta \ll 1$ Eq.(4) simplifies to

$$\eta \propto |E_{\rm eff}|^2 \tag{6}$$

in which condition the relation in Eq.(5) also leads to a maximum in η. From the plot of $\Re\{E_{\rm eff}\}$ in Fig.2, $\Im\{E_{\rm eff}\}$ in Fig.3 and $|E_{\rm eff}|^2$ in Fig.4, as functions of Kv, it is possible to realize that, at the resonance speed, $\Re\{E_{\rm eff}\}$ is very close to zero whereas $\Im\{E_{\rm eff}\}$ and $|E_{\rm eff}|^2$ are close to their maxima. This means that both $\eta \propto |E_{\rm eff}|^2$ and $\Gamma \propto \Im\{E_{\rm eff}\}$ are maximum at resonance.

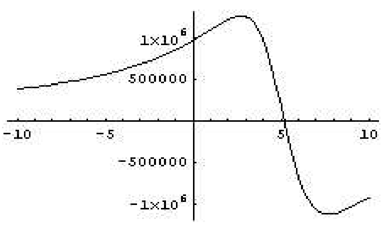

Figure 2: *Computed real part of* $\Re\{E_{\rm eff}\}$ *with* Kv *in rad/s in the horizontal axis, and the hypothetical parameters:* $L_D = 0.20\mu m$, $l_S = 0.02\mu m$, K=*10*μm^{-1}, $E_0 = 10kV/cm$ *and* $\lambda = 514.5nm$.

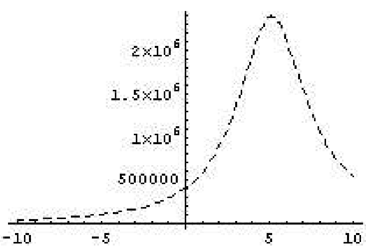

Figure 3: *Computed imaginary part of* $\Im\{E_{\rm eff}\}$ *with* Kv *in rad/s in the horizontal axis and same parameters as in Fig.2.*

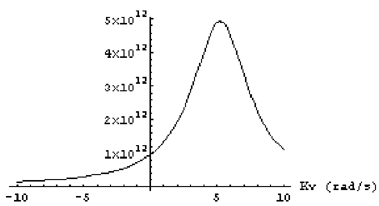

Figure 4: *Plot of* $|E_{\rm eff}|^2 \propto \eta$ *for the same parameters as in Fig.2*

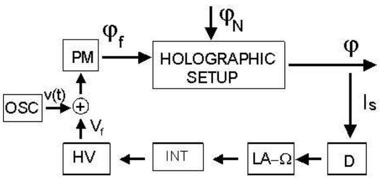

Figure 5: *BLOCK-DIAGRAM OF FRINGE-LOCKED RUNNING HOLOGRAM SETUP: same as for Fig.??* *with the addition of an integrator* **INT** *at the output of the lock-in amplifier*

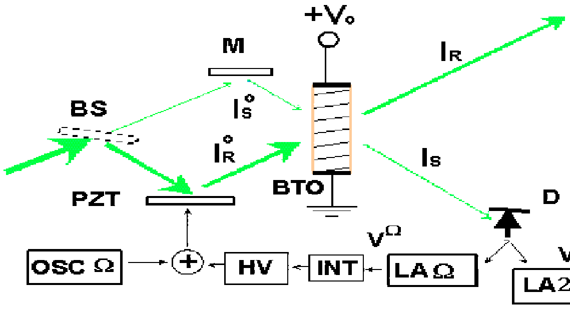

Figure 6: *SELF-STABILIZED HOLOGRAPHIC SETUP:* **BS** *beamsplitter,* **M** *mirror,* **PZT** *piezoelectric-supported mirror,* **OSC** *oscillator,* **D1** *photodetector,* **LA-Ω** *and* **LA-2Ω** *lock-in amplifiers tuned to Ω and 2Ω respectively,* **INT** *integrator,* **HV** *high voltage source,* **BTO** *BTO crystal, V_A applied voltage.*

2.1 Feedback-controlled running hologram

The theory of feedback-controlled (also known as fringe-locked) running hologram has been already described in the literature [3]. Its operation is illustrated in the block-diagram of Fig.5 and the in setup of Fig.6 An oscillator **OSC** (angular frequency Ω) acting on a piezo-electric supported mirror **PZT** produces a phase modulation in one of the interfering beams so that temporal harmonic terms in Ω appear at the output irradiance behind the crystal. The first harmonic (I^{Ω}) is filtered out from the irradiance ($I_S(d)$) at the crystal output and used as error signal in the feedback loop that includes an integrator **INT** and a high-voltage source **HV** acting on the **PZT** in order to produce the correcting phase-shift in the setup. It is possible to show [4] that using I^{Ω} as error signal means to keep $\Re\{E_{\text{eff}}\} = 0$ which substituted into Eq.(2) allows one to compute the speed v of the hologram (and of the associated recording pattern-of-fringes)

$$Kv = \frac{1}{\tau_M} \frac{(E_0/E_D}{E_0^2/E_D^2 + 1)K^2 L_D^2 + 1} \tag{7}$$

that is the speed of the fringe-locked running hologram. Moreover, as deduced from Figs.2-4, the feedback condition $\Re\{E_{\text{eff}}\} = 0$ is practically equivalent to the resonance running hologram condition where η and Γ are maximum. This means that fringe-locked running holograms do actually produce optimized running holograms.

3 Experiment

In order to confirm these theoretical predictions a fringe-locked and a plain running hologram experiment were carried out on a photorefractive $Bi_{12}TiO20$ crystal using the 514.5 nm wavelength laser line in Fig.7 and using the 633nm wavelength in Fig.8. The continuous curve represents the running hologram whereas the single dot indicated by the arrow is the feedback-controlled data. We see that in Fig.7 the fringe-locked experiment is far from the optimum position, because of the high absorption of this crystal at 514.5 nm. In Fig.8 instead, the feedback-experiment is much closer to the maximum of η and Γ because the absorption coefficient is much smaller at 633nm. We conclude that the lower the absorption, the closer fringe-locked running holograms approaches optimum conditions.

4 Conclusions

We have demonstrated, both theoretically and experimentally that feedback-controlled running holograms are just optimized running holograms where the condition for maximum η and Γ (amplitude amplification) are automatically achieved, at least for low absorbing materials. The relevance of this technique for image and signals processing becomes therefore evident.

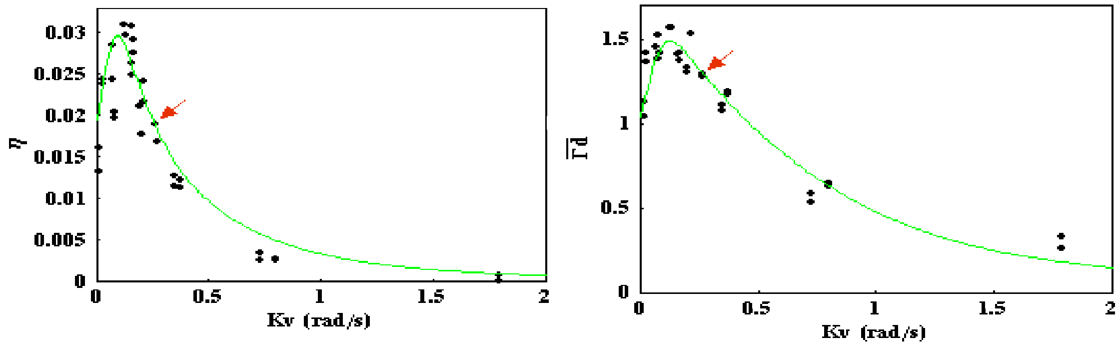

Figure 7: *η (left) and Ωd (right) as a function of Kv for the 514.5nm, $E_0 \approx 6.6kV/cm$ and $K \approx 12\mu m^{-1}$ with $\alpha \approx 1000m^{-1}$. The arrow indicates the fringe-locked data.*

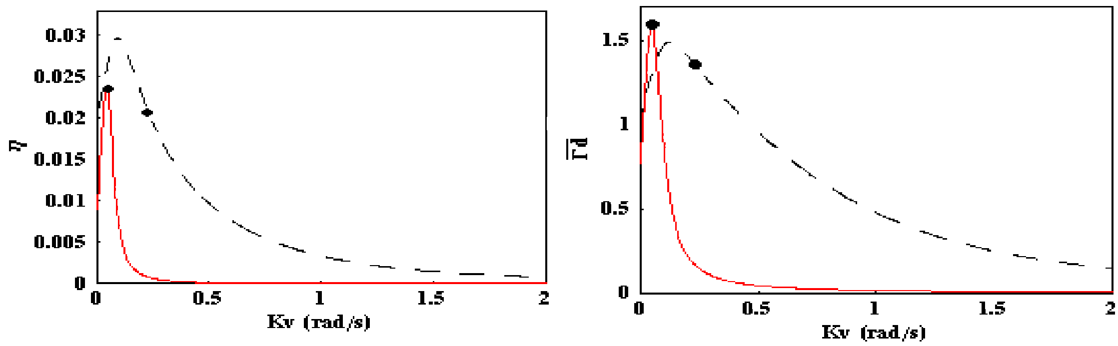

Figure 8: *Simulated data for same parameters as above but for 633nm where $\alpha \approx 90m^{-1}$. Spots are the feedback-controlled data.*

Acknowledgments

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