Optical restoration of photorefractive holograms through self-enhanced diffraction

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For the first time to our knowledge, we demonstrate the use of self-enhanced diffraction to optically restore weak dynamic volume holograms. This restoration process is achieved through the use of a novel beam-toggling scheme that significantly enhances the steady-state diffraction efficiency of volume index gratings stored in photorefractive media. Experiments demonstrating and confirming theory are presented and discussed.

The utility of photorefractive media to store optically induced volume index gratings is well known and has been extensively studied.[1] To overcome the read-beam-induced erasure of these dynamic gratings, researchers have presented schemes wherein the gratings are either fixed in the crystal or otherwise periodically rerecorded.[2–4] It has been shown that holograms stored in appropriate photorefractive media can achieve a transient self-enhanced diffraction (SED) during the readout process as a result of coupling between the read beam and its own diffracted beam.[5–7] Furthermore, if the read beam and the phase conjugate of its diffracted beam periodically interrogate the hologram stored in such a photorefractive medium, then it is possible to achieve steady-state enhancement of the stored hologram.[7] Such a periodic interrogation scheme can be implemented by use of a pulsed laser source and a phase-conjugate mirror, wherein the read pulse enters and diffracts from the storage crystal, and its diffraction is captured by the phase-conjugate mirror and returned to the storage crystal (the round-trip path length between the storage crystal and the phase-conjugate mirror exceeds the pulse length). In this Letter we verify the restoration of dynamic photorefractive holograms by way of this toggled SED process. The need for a more comprehensive theory, i.e., one that includes fanning-assisted two-beam coupling,[8] is also shown to be evident in our experimental results.

The principle of steady-state holographic restoration by means of SED is based on repeated cycles of transient SED processes. Consider the arrangement in Fig. 1, in which beams A and B are used to write a hologram in a photorefractive crystal. Let the initial hologram be a simple dynamic grating, weak but uniform in amplitude from $z = 0$ to $z = L$, and let beam A read the grating after beam B is shut off. Two events occur simultaneously, i.e., erasure of the initial grating by beam A and growth of a new photoinduced grating generated by the interference between beam A and its diffracted beam (the reconstruction of beam B). In diffusion-dominated crystals oriented as in Fig. 1 the new grating written by beam A and its diffracted beam is in phase with the initial grating being read and can therefore enhance the initial grating when the gain–length product for two-beam coupling, ΓL, exceeds 4.[7] As the diffracted beam grows in strength from $z = 0$ to $z = L$, so does the new grating's amplitude. However, because the diffracted beam has zero intensity at the left side of the crystal ($z = 0$), no enhancement can occur there, and the initial grating is only erased (if the gratings have been fixed within the crystal, then no such erasure occurs and transient SED is sufficient[5]). Alternatively, the grating can be read by B*, with the same form of transient results but proceeding from $z = L$ to $z = 0$. To capitalize on this transient SED process, one can instead read for a short while with beam A, then shut off beam A and read for a short while with beam B* (for example, if beam A is a pulse, then beam B* can be generated by phase conjugation of beam A's diffraction). Repeated and continued toggling of the read beams in this manner eventually produces a steady-state (saturated) diffraction efficiency.[7] The duration for which each beam is on per toggle is time t, and the crystal's photorefractive time constant at the intensity of the enhancing beam is τ. The ratios t/τ and I_A/I_{B^*} (the enhancing beams' intensity ratio) are important in determining the achievable saturation SED efficiency.[1,7]

To demonstrate the principles of hologram restoration by means of toggled SED, we utilized a 45°-cut (c axis leaning toward the $z = 0$ face of the crystal) barium titanate crystal with $\Gamma L \sim 5$. When performing experiments with cw beams we used an
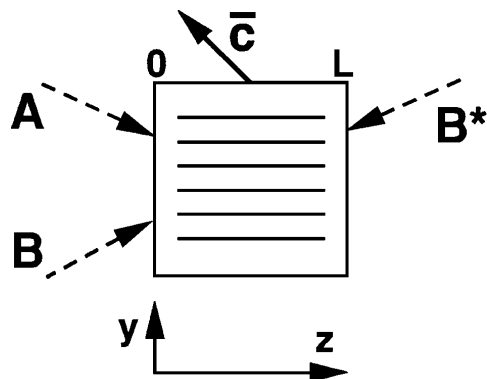
Fig. 1. Schematic of the experimental arrangement. Beams A and B write an initial hologram, and beams A and B* enhance the hologram.
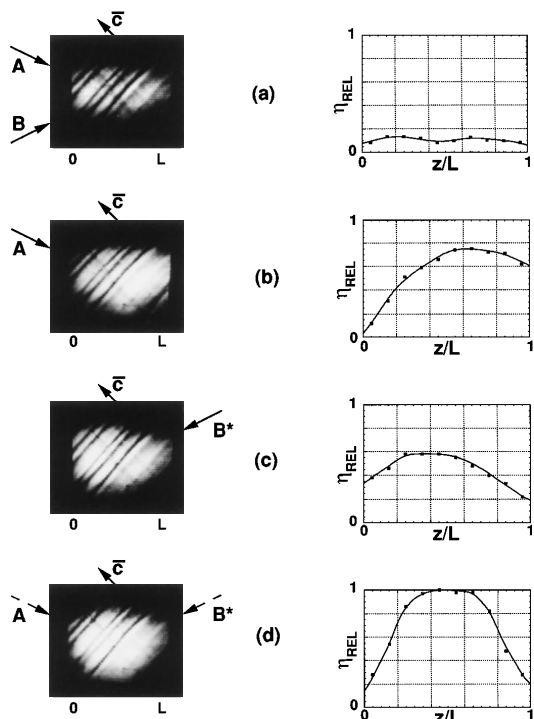

Fig. 2. Diffraction efficiency during the monitoring of spatial grating amplitudes from $z = 0$ to $z = L$ at various points in the SED process. The left column shows photographs of the diffracted read beam, and the right column shows line scans (integrated along y) of the diffraction efficiency: (a) the initial grating, (b) the grating after enhancement by beam A for 10τ, (c) the grating from (b) after enhancement from beam B* for an additional 10τ, (d) the steady-state grating after 100 toggles of beams A and B*, each at $t = \tau/2$.

argon-ion laser source operating at 514 nm, and beams were toggled with mechanical shutters. When performing experiments with pulsed beams we used a Q-switched frequency-doubled (532-nm) Nd:YAG laser source with pulse widths of ~ 8 ns. Beams A and B* in this case were separated by a path difference of 4 m. Experimental results utilizing either laser source were essentially identical. To probe the evolution of simple gratings, we monitored the diffraction efficiency of a weak Bragg-matched He–Ne laser beam at 633 nm.

We begin the presentation of our experimental results with a visual demonstration of the toggled SED process on simple gratings, monitoring grating amplitudes as a function of z/L. Figure 2 displays data received when write and enhance beams at 514 nm entered our photorefractive crystal from its sides (as in Fig. 1) and a Bragg-matched read beam at 633 nm entered the crystal from the top, diffracting out of the bottom of the crystal through a supporting glass slide (this read beam was of uniform intensity along the crystal's z axis). The left column of Fig. 2 shows photographs of the diffracted beam (the diagonal stripes are due to domain boundaries within and common to this type of special-cut crystal), and the right column shows line scans of the diffraction integrated along the y axis. Figure 2(a) displays the initial weak grating written by beams A and B, Fig. 2(b) displays the grating diffraction efficiency after beam A has enhanced it for approximately ten time constants ($t \sim 10\tau$), and Fig. 2(c) displays the grating diffraction efficiency after beam B* has enhanced the grating in Fig. 2(b) for approximately ten more time constants. Finally, Fig. 2(d) displays the saturation SED efficiency after beams A and B* were permitted to toggle 100 times at $t = \tau/2$. From Figs. 2(b) and 2(c) it is evident that beam A produces greater enhancement than does beam B*. This result is perhaps due to fanning-assisted two-beam coupling effects,[8] which give beam A an effectively greater gain than beam B* has because of the crystal's special cut.

We then demonstrated the time evolution of toggled SED as a function of t/τ, utilizing plane waves with our cw laser source. The simple gratings written were read with our (Bragg-matched) 633-nm source entering the crystal in beam B*'s plane of incidence. Figure 3(a) shows results from three such data runs
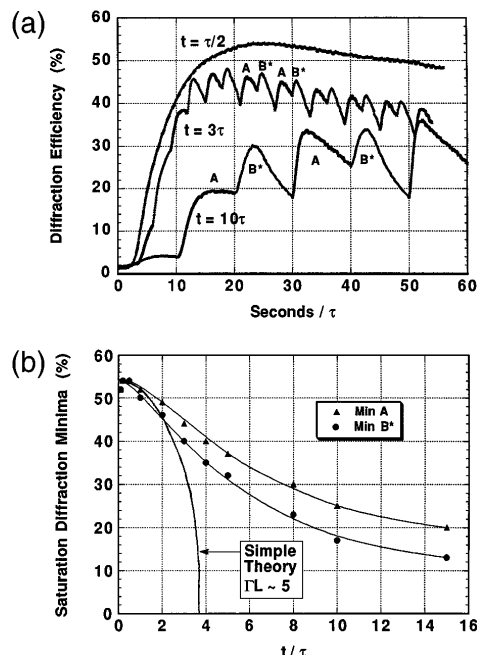

Fig. 3. (a) Toggled SED for $t = \tau/2, 3\tau, 10\tau$. (b) Compilation of data for $t = \tau/10$ to $t = 15\tau$ as well as predictions from simple theory.
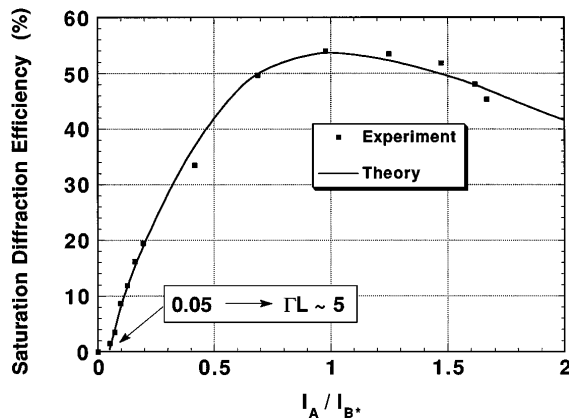
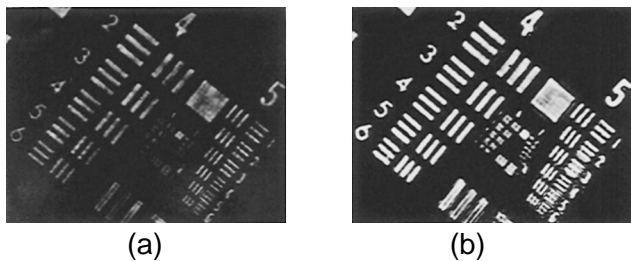Fig. 4. Achieved saturation diffraction efficiency as a function of I_A/I_{B*}.

Fig. 5. Holographic restoration through toggled SED of a (demagnified) U.S. Air Force resolution target: (a) initial hologram, (b) enhanced hologram. Diffraction efficiency gain from (a) to (b) exceeds 60,000%. Effective resolution is ~200 line pairs/mm.

for toggling times $t = \tau/2$, 3τ, 10τ. The asymmetry in gain observed between beams A and B* as a result of fanning-assisted two-beam coupling is evident in these data. The complete family of data obtained in this measurement is then given in Fig. 3(b), in which the saturation diffraction efficiency minima achieved during toggled SED are plotted as a function of t/τ. These data show an improvement over simple theoretical predictions[7] for large values of t/τ. Again, it is believed that fanning-assisted gain plays an important role in this divergence from theory.

Yet another concern is the enhancement-beam intensity ratio I_A/I_{B*}. This ratio influences the achievable saturation diffraction efficiency. Addressing this concern, we utilized our pulsed laser source with $t = \tau/5$ (relative to the fixed energy density in beam B* of ~100 mJ/cm^2) and plane waves to study this relation, the results of which are displayed in Fig. 4. Along with the data is a theoretical curve[7] for this relation for $\Gamma L \sim 5$.

To put holographic restoration by means of toggled SED to the test, we injected images into our system, measured enhancement gains, and observed the fidelity of the holograms throughout the enhancement process. We present our results in Fig. 5, utilizing the pulsed source. The input object was a U.S. Air Force resolution target that was imaged into our crystal in beam A and demagnified by a factor of 3. In Fig. 5(a), beams A and B wrote the initial (low-modulation-depth) hologram, while beam B* read it. Beam B was then disabled, and beams A and B* began the toggled SED process with $t = \tau/5$. Just as the toggled SED process reached saturation, data were again taken and are displayed in Fig. 5(b). The integrated diffraction efficiency in Fig. 5(b) is more than 600 times that in Fig. 5(a). In addition, there is no observable fidelity loss during this enhancement. Considering the demagnification factor, we observed that the limit of resolution in these photographs corresponds to ~200 line pairs/mm. Thus stopping the enhancing process as it achieves saturation preserves the original hologram's resolution quite satisfactorily while permitting a significant enhancement of its amplitudes. Continued toggling after saturation eventually lead to a degradation of image quality, as noise levels owing to internal scattering and reflections grew to match those of the signal. This eventual result was virtually identical to that achieved when the hologram was generated in a double phase-conjugate mirror arrangement, in agreement with theory.

In conclusion, we have experimentally demonstrated what we believe is the first steady-state self-enhancement and restoration of dynamic volume holograms in photorefractive media. We have experimentally validated the theoretical predictions of grating amplitude profile variations during an SED process, studied achievable saturation SED levels as a function of t/τ and I_A/I_{B*}, and shown high-quality results of the enhancement of high-resolution images.

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