Holographic recording of fast phenomena

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We report on a holographic method for recording fast events whose speed is limited by the laser pulse duration if the recording material has sufficient sensitivity to reliably record a frame of the fast event with a single pulse. The method we describe uses the angular selectivity of thick holograms to resolve frames that are recorded with adjacent pulses. Two specially designed cavities are used to generate the signal and reference pulse trains. We experimentally demonstrate the system by recording laser induced shock waves with a temporal resolution of 5.9 ns, limited by the pulse width of the *Q*-switched Nd:yttrium–aluminum–garnet laser used in the experiments. [DOI: 10.1063/1.1446205]

Since the early days when holography was invented, people have been studying high-speed events using holographic techniques. A well-known example is double exposure interferometry.[1] Multiple frames can be stored and reconstructed separately using multiplexing techniques. Previous work has focused on spatial multiplexing[2–4] where holograms are recorded at different locations of the recording medium. Pulsed holograms have also been angularly multiplexed taking advantage of the thickness of the recording medium. In one method, three lasers are used to generate three reference beams with different angles and each laser fires a pulse in a different time.[5] A rotating mirror[6] or electro-optic switches[7] have also been used to generate the reference beams. In these efforts, the speed is limited by electronics or mechanical scanning. In the system we describe the speed is limited by the pulse width of the laser (5.9 ns). With proper modification the method can also be used with subpicosecond pulses. During recording, a sequence of signal and reference pulses are incident on the holographic medium. The signal pulses all travel in the same direction while the reference beam direction changes from pulse to pulse in order to angularly multiplex holograms. After the recording, a cw laser at the same wavelength is used to readout individual frames. Depending on the incidence angle, different frames can be readout separately due to the angular selectivity of the thick hologram.

In the experiments, both the signal and the reference pulse trains are generated by a single pulse from a frequency doubled *Q*-switched Nd:yttrium–aluminum–garnet (YAG) laser (wavelength 532 nm, pulse width 5.9 ns, energy per pulse 300 mJ, and beam diameter 9 mm). The system is shown in Fig. 1(a). In the signal cavity, a polarizing beam splitter is used to couple the vertically polarized (perpendicular to the paper) incident pulse into the cavity. The Pockels cell is timed to behave like a temporary λ/4 wave plate (effectively a λ/2 wave plate since the pulse passes it twice each round trip) to rotate the polarization of the incident pulse to horizontal direction after it first enters the cavity. It is turned off afterwards while the pulse travels back towards the opposite mirror. The pulse is then trapped inside the cavity since the polarizing beam splitter transmits beam with horizontal polarization. A λ/4 wave plate is used to slightly rotate the polarization of the pulse and the induced vertically polarized component is coupled out of the cavity from the polarizing beam splitter. In the reference cavity, the incident pulse enters the cavity via a small coupling mirror. After the coupling mirror, it travels as if it had originated from the center of the lower mirror. The two lenses form an imaging system and the pulse hits the center of the upper mirror. We break the symmetry of the cavity by slanting the upper mirror slightly. The reflected pulse then travels at a smaller angle with respect to the axis, just missing the coupling mirror. The pulse hits the center of each cavity mirror at slightly different angle after every round trip. Pulses are coupled out of the cavity by making the lower mirror partially reflecting. We generate five signal and reference pulses out of a single pulse from the Nd:YAG *Q*-switched laser using the earlier method. The pulse separation is about 12 ns which can be changed by tuning the cavity length. Our current signal cavity is quite lossy due to the reflections from the optical components and the spatial filtering that is used to improve the beam profile and this limits us to only about five signal pulses. We recorded five plane wave pulsed holograms in the Aprilis material.[8] The diffraction efficiency of each frame and the angular selectivity curve are given in Fig. 1(b). The Aprilis material yields a diffraction efficiency of approximately 1% for a 1.6 mJ/cm^2 exposure of cw illumination or a single 5.9 ns pulse. The diffraction efficiency when M holograms are superimposed goes as $\eta=(M\sharp/M)^2$ where $M/\sharp$[9] is a material dynamic range parameter. The measured $M/\sharp$ of the Aprilis material is 6. Since we typically can obtain high fidelity reconstructions with $\eta=10^{-4}$, movies with several hundreds of frames can be recorded with an improved cavity design.

This apparatus is used to record optical breakdown events. We split part of the pulse from the laser and focus it on the sample. This pumping pulse induces optical breakdown.[10–14] Figure 2(a) shows the optical breakdown on a poly(methylmethacrylate) (PMMA) sample. Frame I shows the plasma created by the pumping pulse. The tail is likely due to the discharge in the air in front of the sample. In frame II, a shock wave is clearly seen. The average propagating

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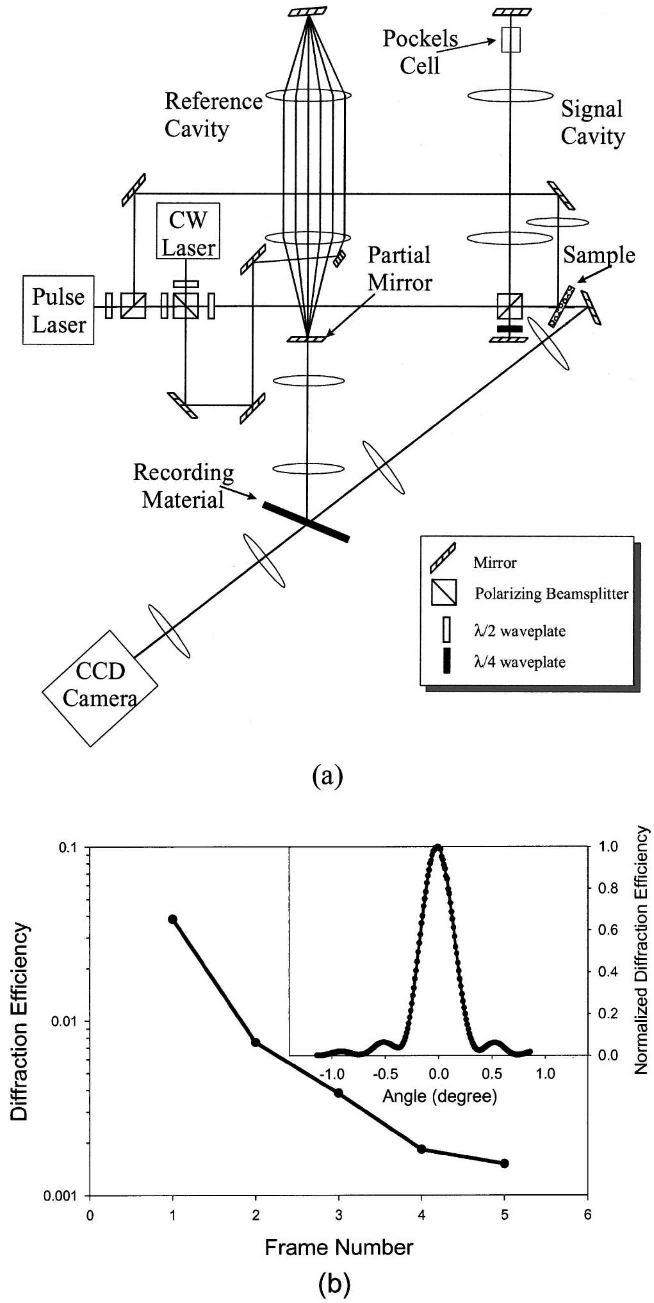

FIG. 1. High speed holographic movie camera. (a) Optical system. (b) Diffraction efficiencies of five pulsed holograms and the selectivity curve of the first frame. Both the reference and signal pulse train have a total energy of about 37 mJ. The pulse energy in the reference and signal pulse train decays and the successively recorded holograms get weaker and weaker. Aprilis material ULSH500-7A-22 is used as the recording medium. The thickness of the material is 200 μm. The pre-exposure energy is about 2 J/cm^2 (white lamp).

speed of the shock wave between frame I and II is about 10 km/s and that between frame IV and V is about 4 km/s. In Fig. 2(b) we show the breakdown in air. Similarly, plasma is created in frame I and soon a shock wave forms. The air discharge happens in a region near the focal point of the lens and the length of that region is about equal to the depth of focus. A line of spark is visible during the experiment. In Fig. 2(c) we focus the pumping pulse near a blade (the dark rectangular shadow). The threshold of optical breakdown is lowered dramatically by the presence of the metal blade. The optical breakdown happens mainly at a small region around the focal point which is close to the metal and produce a more spherical shock wave. We also focus two pumping beams on PMMA and generate two shock waves as shown in Fig. 3. In (a) the lower pumping pulse has higher energy as

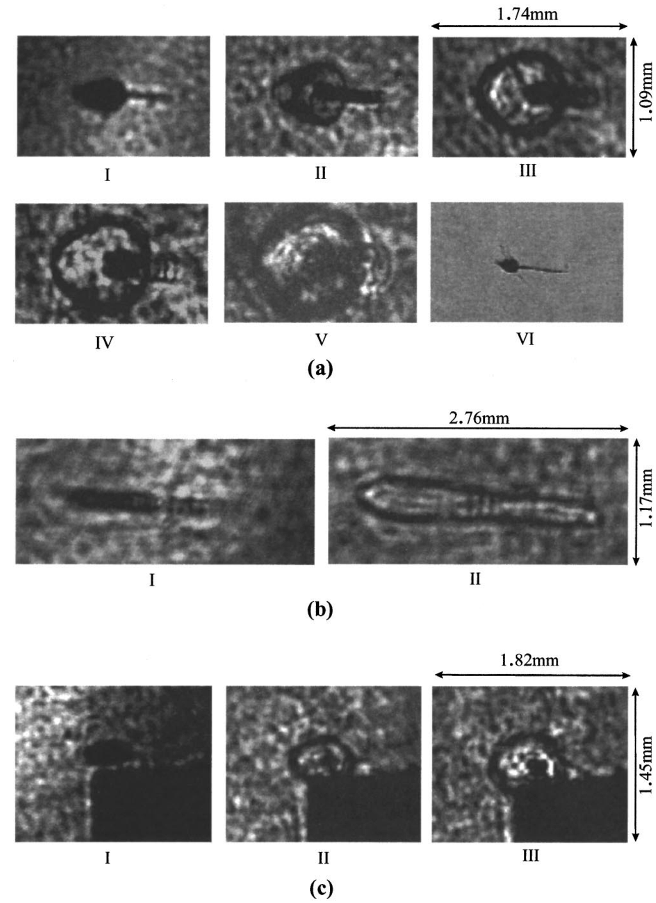

FIG. 2. Optical breakdown. (a) Optical breakdown in a PMMA sample. Frame I is recorded about 1 ns before the pumping pulse vanishes. I, II, III, IV, and V are the recorded frames with frame interval 12 ns. VI is the final direct image of the sample after the optical breakdown. The intensity of the pumping beam is 1.6×10^{12} W/cm^2. (b) Optical breakdown in air. The intensity of the pumping beam is 5.2×10^{12} W/cm^2. (c) Optical breakdown in air with a metal blade near the focal point of the pumping beam. The intensity of the pumping beam is 1.6×10^{12} W/cm^2.

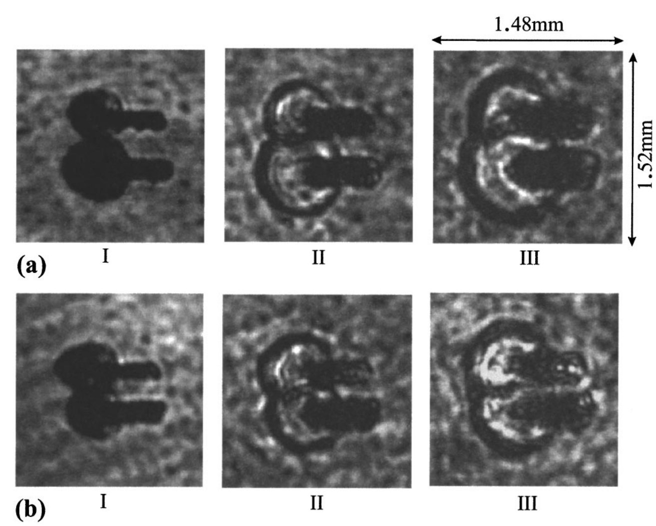

FIG. 3. Interaction of two shock waves. (a) Unbalanced double shock waves. (b) Equal intensity waves.

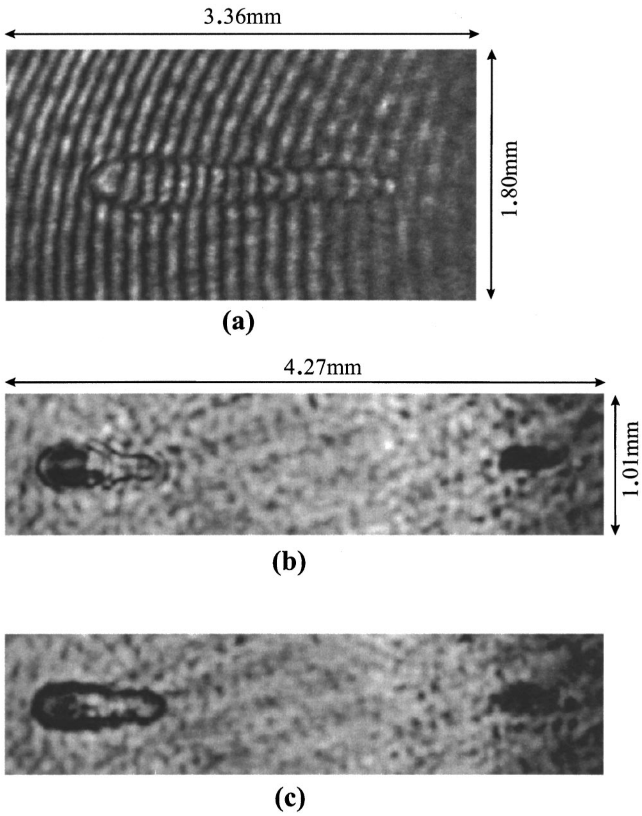

FIG. 4. Holographic reconstruction of the object field. (a) Interference between a reconstructed frame and its reference wave. (b) and (c) focusing at different depths. The angle between the pumping beam and the signal beam is about 20°. The pumping pulse is focused at about 1 cm in front of the PMMA sample which is consistent with the measured image depth position difference between (b) and (c).

we can see from the plasma size in frame I. When the two shock waves meet, the one with higher pressure penetrates as shown in frame III. In (b) the two shock waves roughly have the same pressure, they balance with each other in the middle.

A unique feature of the holographic recording is that it records the field and thus has both the amplitude and phase information. We interfere the second frame of an air discharging event with the reference (a plane wave). The fringes are shown in Fig. 4(a). Apparently, the refractive index inside the region surrounded by the shock front is different from that of the outside and there is an index gradient. In the holographic reconstruction we can focus at different depths since the object field is reconstructed. In Fig. 4(b) the plasma created on the PMMA sample is in focus while in Fig. 4(c) the shock wave due to the discharge in the air (in front of the sample) comes to focus by changing the position of the charge coupled device camera.

In conclusion, we have demonstrated a system which can record fast events in nanosecond scale. The technique can be extended by using shorter pulses and generating the signal beam pulse train through wavefront division or nonlinear optics rather than the electro-optically switched cavity described here.

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