Some Experiments Performed with a Reflected-Light Pulsed-Laser Holography System

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A short-exposure, high-energy holography system has been constructed which yields high quality holograms of scenes several cubic meters in volume. The system is constructed around a single mode Q-switched ruby oscillator and a 20-dB gain single-pass ruby amplifier. The output is fully coherent at peak output of 10 J. Front lit holograms of transient events and of live subjects have been made with this system.

Introduction

We describe here a high-performance stop-action holography system. The system is centered around a giant pulse ruby laser oscillator–amplifier combination which produces 40-nsec pulses containing up to 10 J of energy. The development of this system has been motivated by a fundamental consideration: a hologram is a recorded interference pattern. In order to record the interference pattern, the fringes must be fixed in position throughout the exposure time. Instead of taking the usually elaborate precautions necessary to provide the requisite mechanical stability for long exposure holograms, it is considerably easier to make the hologram with such short exposure that all motion is frozen throughout the exposure time. The giant pulse ruby laser is the most effective means for doing this at present. It is interesting that giant pulse holograms, in addition to being unaffected by ordinary vibrations, are made with such brief exposures that systematic motion of the subject in excess of 10 m/sec is tolerable.

Other pulsed ruby laser systems that are applicable to holography have been described in the literature.[1–4] The distinctive feature of the system reported here is the combination of high energy per pulse and high coherence. The output of the laser is essentially fully coherent (both spatially and temporally) at full energy output. Thus, although similar systems have been previously reported, systems with this level of performance have not. To emphasize the high-performance characteristics of this laser we have included, along with the discussion of the holography system, a description of several experiments that we performed to establish the coherence properties of the laser.

System Description

A schematic diagram of the system is shown in Fig. 1. The laser consists of two units: a ruby oscillator and a ruby amplifier. Both units are water cooled from the same reservoir in order to match the gain lines of the two crystals. The oscillator laser head contains a 10 cm long, 0.63-cm diam ruby crystal, corrected to less than one fringe in transmission, and set between two linear xenon flashlamps in a double elliptical pumping cavity. The ruby crystal is water cooled by a closed-cycle refrigeration system. The laser resonator is formed by a two-element resonant reflector and a high-reflectivity, dielectric-coated, flat mirror. The cavity length is approximately 1 m. The laser is Q switched by means of a rotating prism arranged as shown in Fig. 1.

In order to obtain high coherence for the output from the oscillator, intracavity devices are employed to ensure that the laser operates in a single mode. Longitudinal mode control is accomplished by the techniques of McClung and Weiner.[5] The output reflector consists of two flat and parallel (in transmission) fused silica flats, 2 mm and 5 mm thick, separated by a cylindrical, 25 mm thick, flat and parallel, fused silica spacer. Provision is made for varying the pressure of the air in the spacer. This reflector is aligned parallel to the front face of the ruby rod. The longitudinal mode selection is adjusted by temperature tuning the ruby fluorescence line to one of the resonances of the 2-mm flat (approximately −4°C with this laser) and then pressure tuning the resonant reflector to achieve single mode operation. The exact operating conditions for obtaining a single mode are determined by monitoring the longitudinal mode structure with a Fabry-Perot interferometer. Transverse mode control is obtained with the aid of an intracavity aperture located as shown in Fig. 1. The aperture diameter required to obtain reliable single transverse mode operation was found to be 2.5 mm. This was determined by monitoring the beam

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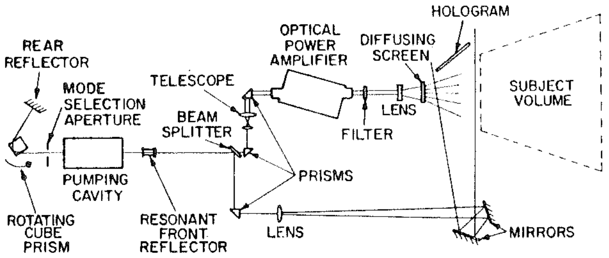

Fig. 1. Experimental setup for pulsed laser reflection holography. The oscillator consists of rear reflector, rotating cube prism Q switch, mode selection aperture, ruby pumping cavity, and resonant front reflector. The amplifier consists of beam expanding telescope, prism, and ruby pumping cavity. The remainder of the optics serve to illuminate the scene and to form the holographic reference beam.

divergence and near-field distribution of the output as a function of aperture diameter. At an aperture setting of 2.5 mm it was found that essentially diffraction-limited beam divergence was obtained, implying that the laser was operating in the TEM_{00} mode only.

The active element in the amplifier is a 35 cm long by 1.6-cm diam Czochralski grown, Brewster angle, ruby rod. It is pumped by four linear flashlamps situated in a close-coupled pumping cavity surrounding the rod. The amplifier is a single-pass device providing up to 20 dB of small signal power gain. The output from the oscillator in single mode operation is 3 MW. The maximum power output of the amplifier is 250–300 MW. The pulse duration is approximately 40 nsec. Therefore, the maximum energy output of the amplifier is approximately 10 J.

As can be seen from Fig. 1, the holography system utilizes the conventional two-beam geometry. A beam splitter provides about 4% of the oscillator output for the reference beam, which passes through a lens and then to the film. The reference beam is not amplified because the relatively poor optical quality of the amplifier crystal would deteriorate the quality of the point source.[4] The subject beam is amplified and diffused to illuminate the scene being recorded. With this arrangement we have approximately 4 mJ in the reference beam and up to 10 J in the object beam, depending on how hard the amplifier is driven.

Experiments

The first experiments performed with this system were intended to determine in a direct way the optical quality of the laser output as it applies to holography. Holographic methods were used to measure the longitudinal and transverse coherence of the laser output. The longitudinal coherence was determined by making holograms of objects which provide a range of path length differences between subject and reference beams. A reconstruction from one of these holograms is shown in Fig. 2. A Scotchlite covered stick 5 m long, with markers placed every 10 cm and pins every 1 m, was used as the subject. The stick was placed with one end at the point where the path lengths between reference and subject beam are matched and was oriented so that the markings on the meter stick were a direct measure of path length difference. As can be seen from the photograph, a bright reconstruction is obtained up to the maximum length of the stick. The arrows on the photograph indicate the position of the pins which mark the 1-m intervals. Thus, the depth of field for this hologram is 5 m, which implies that the coherence length is greater than 10 m.

It should be noted that this measurement did not determine the limit of the coherence length of the laser; it merely set a lower bound. The image of the 5 m long stick is bright all the way to the end of the stick indicating that the limits of the depth of field due to coherence effects were not reached. Nevertheless, the measurement determines some interesting facts about the longitudinal mode structure of the laser. A Fabry-Perot measurement made at the same time as the hologram shown in Fig. 2 indicated that the laser oscillated in a single longitudinal mode. The frequency selectivity of the Fabry-Perot used in this experiment is only 200 MHz, which is not sufficient to determine the exact linewidth of the mode. However, an upper bound on the linewidth can be inferred from the maximum path length difference observed in the hologram:

$$\Delta\nu_l \cong \frac{c}{L_{\text{coh}}} = 3 \times 10^7 \text{ Hz}.$$

This implies that the linewidth of the oscillating mode in this laser is less than 30 MHz. It is interesting that the spectral width of the laser pulse due only to the (short) duration of the pulse is

$$\Delta\nu_p \cong \frac{1}{\Delta t_p} \approx \frac{1}{40 \times 10^{-9}} \text{ Hz}$$
$$\cong 2.5 \times 10^7 \text{ Hz}.$$

These numbers suggest that the coherence length of the laser is limited by the pulse length (approximately 12 m)

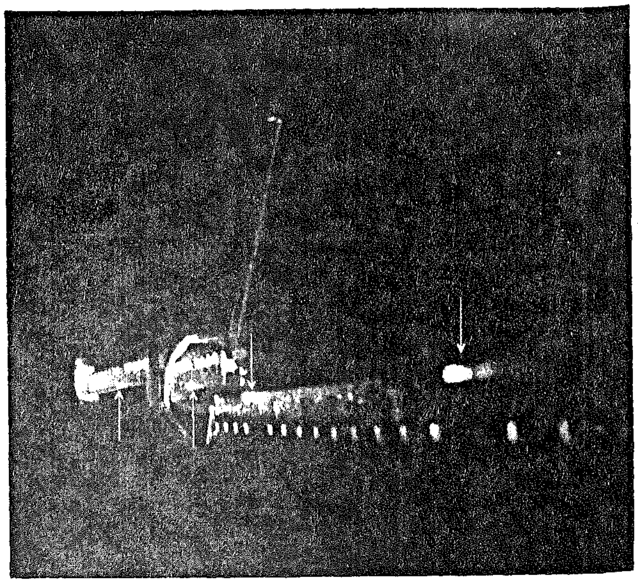

Fig. 2. Reconstructed image from hologram demonstrating 10-m coherence length for laser.

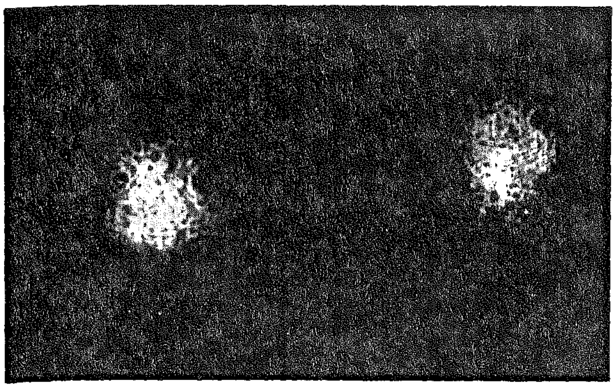

Fig. 3. Elementary hologram reconstructions demonstrating ruby laser transverse coherence. See discussion in text.

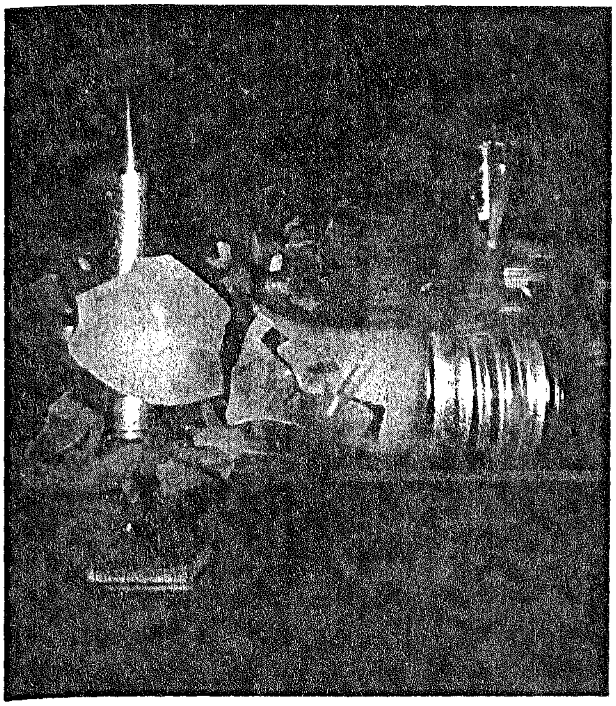

Fig. 4. Light bulb in the process of bursting.

rather than by the frequency stability (linewidth) of the laser longitudinal mode.

To obtain a direct measure of the effectiveness of the transverse mode control for producing high quality holograms, an experiment was performed to determine directly the spatial coherence of the laser output.[6] In this experiment the light from the laser was used to make an elementary hologram (a hologram made in collimated light in which no subject is present). The optics were arranged so that the rays of the subject beam were interchanged across the central ray of that beam when the hologram was made. Thus, the hologram was formed from the interference of pairs of rays which originated at opposite sides of the central ray of the laser beam. As a result, playback from this hologram provides a direct measure of the degree of spatial coherence of the light as a function of radial position across the reconstructed laser beam. These data immediately determine the area of coherence of the beam. Using this holographic method, it was found that for intracavity aperture settings of 2.5 mm or less the laser output is spatially coherent across the entire beam. A typical result from this experiment is shown in Fig. 3. The photograph on the right shows reconstruction from an elementrry hologram of the type described above. That on the left is a reconstruction from a hologram in which the rays of the subject beam are not interchanged but are carefully registered. This latter photograph serves as a datum which defines the size of the laser beam. Comparison of the two photographs shows that the two reconstructed beams are the same size. Since the two reconstructed beams are the same, even though in one case the rays of the subject beam were interchanged across the central ray of that beam, it is apparent that the beam is coherent across its entire cross section.

In addition to these experiments, we have made holograms of a variety of subjects using the Agfa-Gavaert 8E75 emulsion. Figures 4 and 5 show reconstructions made from two such holograms. Figure 4 shows a photograph of the reconstructed image of a hologram of a light bulb in the process of being smashed. Some of the elements of this scene were moving at velocities estimated to be in excess of 10 m/sec. The ability to record holographically such transient events is the result of the short 40-nsec pulse duration of the laser output. Figure 5 shows the reconstruction from a hologram of the authors. Here we demonstrate the large scene capability of this system. To protect the eyes of the subject, a ground glass diffuser was arranged to give a diffuse illumination source, 30 cm in diameter. This provided fairly wide angle illumination for the large subject and decreased the energy density at the retina to more than an order of magnitude less than the level below which eye damage will not occur with certainty.[7] The subjective response to the less than 3 J used for illumination was considerably less than that resulting from an ordinary photographic flashbulb. Essentially no retinal retention was experienced.

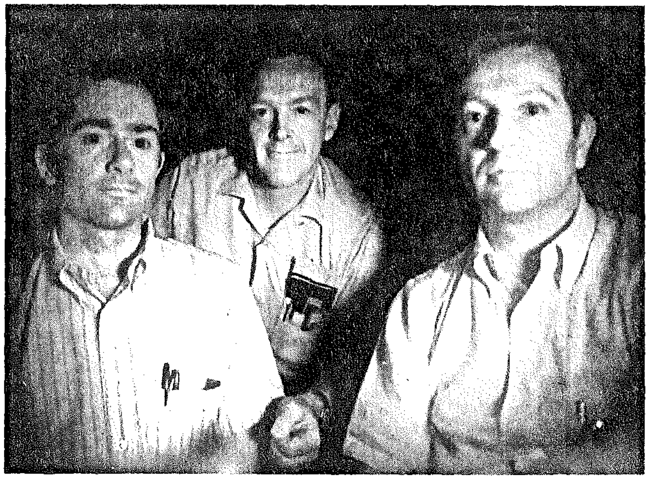

Fig. 5. Hologram group portrait.