Nanosecond photography of fast processes in invisible (UV) light with a nitrogen laser and new study of a train of shock waves

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A simple and effective method for nanosecond photography of fast processes is described. It uses self-shortened UV pulses from a nitrogen laser. This method has been used to detect new processes in shock-wave physics: a generation of a train of shock waves in air and water during fluctuations of energy release (oscillations of the current in a discharge circuit). It thus becomes possible to study the interior of the shock wave and a directed propagation of shock waves in the flow of a heated or light gas. A train of shock waves can be used for effective reflection of rf and visible radiation.

Many processes in the physics of shock waves and high energy densities could not be studied or even formulated in the absence of a fast, efficient, high-resolution recording instrument.

1. Short light pulses from lasers with controlled Q switching are often used to photograph fast processes in experimental and applied physics.[1] We have used a simpler method to generate short and ultrashort pulses: lasers operating on self-terminating transitions, which generate pulses only at the leading edge of the discharge current,[2–4] because of self-terminating transitions, since the generation conditions are disrupted.[2–4] The most interesting laser is the nitrogen laser,[2–4] which generates a UV pulse 1–10 ns long (in some cases, the pulse lengths are as short as several microseconds[2]) with a wavelength $\lambda = 337$ nm. This wavelength has a strong photographic effect on a photographic emulsion, but it is only weakly absorbed in water, air, plasmas, and quartz. The short wavelength means that diffractive distortions are small. We have used one of the lowest-power nitrogen lasers, the LGI–21 (Ref. 4), which generates pulses $\lesssim 10$ ns long with an energy $\simeq 1$ μJ, a divergence of 3×10^{-3} rad, and a pulsed power $\simeq 1$ kW. This laser can operate at repetition frequencies of 10–100 Hz and also in a single-pulse regime with external triggering. In longitudinally pumped lasers of this sort, at low repetition frequencies, the light distribution has an annular profile. This profile does not interfere with the use of optical waveguides of various lengths to record a series of photographs at intervals of $1–10^3$ ns (in this case, the fast process which is to be recorded can be triggered directly by the laser pulse), but a continuous beam profile is desirable for photography directly in the single-pulse regime. A smooth profile can be obtained from a tubular profile by means of condenser lenses made of axicons or of an axicon and a simple lens (depending on the degree of divergence of the annular distribution). One cuts out part of the light from the ring or uses a shutter to select one or two pulses from a regular train of laser pulses with a good distribution. In this case it is possible to trigger the process of interest by means

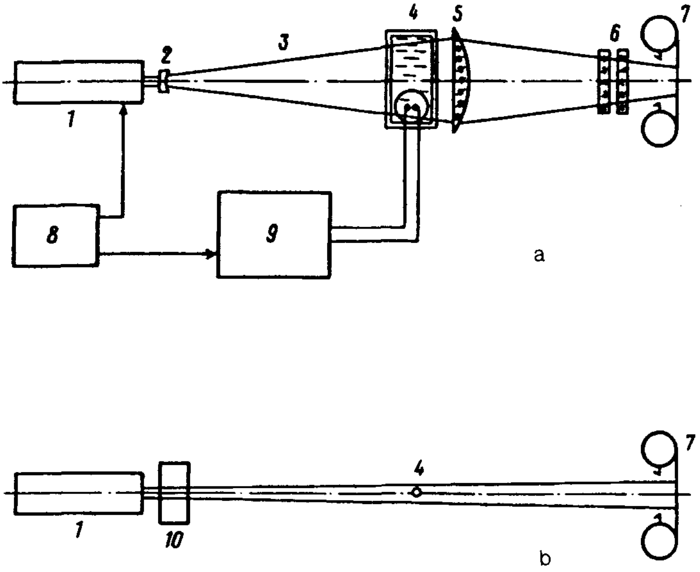

FIG. 1. Layout for detecting shock waves with the help of a nitrogen laser. a: 1) LGI-21 laser; 2) lens with a focal length $F = 10$ cm; 3) laser beam; 4) object under study (a cell holding a liquid with a spark discharge or a gas layer above a spark gap and above a burner); 5) lens with a focal length $F = 25$ cm; 6) filters for shielding the exposed film from light from the spark and from daylight and for attenuating the light from the laser; 7) camera back; 8) delay circuit to trigger the laser; 9) trigger unit for the delay and ignition circuit and for supplying power to the spark. b: Layout for cutting pulses out of a train of laser spikes with a uniform distribution; 10) shutter for cutting out a laser pulse.

of the pump pulse, by means of the laser pulse (and, later on, in the regime of a partitioning of the beam for framing photography), or by means of an earlier light pulse with the appropriate delay. For transverse-pumped lasers, the intensity distribution is continuous.

For recording the events of interest we selected a simpler method. Having observed that an annular beam has not yet formed near the laser, and that the intensity distribution is approximately flat, we placed a lens near the laser. The purpose of this lens was not exclusively to make the beam more uniform but also to increase the area which could be illuminated by the beam.

Incidentally, it is possible to visualize or photograph a process which repeats itself many times in the light of the luminescence of a screen (paper, for example, is highly luminescent) for a process which repeats itself many times at the frequencies of pulses which give a uniform distribution (e.g., 100 Hz), arriving with the appropriate delay.

2. A spark between electrodes was used to study shock waves in air and water. The parameters of the discharge circuit were chosen with the goal of achieving a fast, repeated release of energy.

Figure 1 shows the layout of the apparatus. Laser *1* and lens *2*, with a focal length

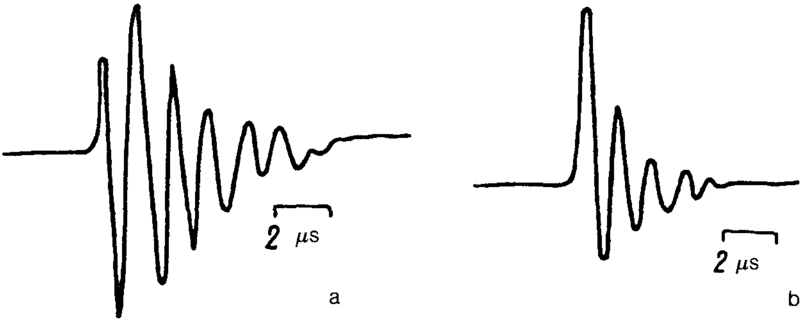

FIG. 2. Oscilloscope trace of a discharge from a Rogowski loop. a—Discharge in air; b—in water.

of 10 cm, produce a beam *3*, which "illuminates" (visibility is achieved by means of luminescence) the zone of a spark gap 6×6 cm in area at a distance of 1.5 m. The beam is then focused by lens *5*, with a focal length of 25 cm, directly on photographic film *7*, positioned 50 cm away from the field of the shock waves. (An objective is undesirable here because of the UV absorption by glass lenses and cements.) Filters (UF glass) are placed in front of the camera in order to cut out the visible light, to attenuate the emission from the spark, and to attenuate the laser beam. The signal from control unit *8* triggers discharge unit *9* and also delay circuit *8*, which turns on the laser after the appropriate time.

The spark discharge current is measured with a Rogowski loop with a self-inductance of a few microhenries and a capacitance on the order of 100 pF (the capacitance is that of the conducting cable and the oscilloscope input). The capacitance of the discharge capacitor is 0.05 μF, the voltage is 10 kV, and the stored energy is 2.5 J. Figure 2 shows oscilloscope traces of the current as found from the readings of the Rogowski loop; part a corresponds to a discharge in air, and b to a discharge in water.

The first photographs showing that a shock wave which enters a tube is outpaced by a shock wave which propagates outside the tube revealed high resolution and clarity. (See Fig. 3a, where the spark is 0.5 cm away from the entrance to a tube 2 cm long and 6 mm in diameter.) The resolution and clarity are achieved not only because of the quality of the light but also because there is no luminescence from the photographic film. These aspects of the procedure made it possible to detect the following new effects and new directions for advanced fluid dynamics.

Observation of internal structure of shock waves. This structure arises from fluctuations in the release of energy (Fig. 3, b–d). This phenomenon extends the range of applicability of such simple solutions as a one-shot point explosion. It also allows one to study the propagation of shock waves within shock waves and to thereby obtain new information about internal processes within shock waves. This probing of the interior is extremely valuable, since simple solutions have been found under the assumption that the adiabat remains constant. This assumption is obviously wrong in intense shock waves which contain heterophase regions. (Examples are the zone of a fireball

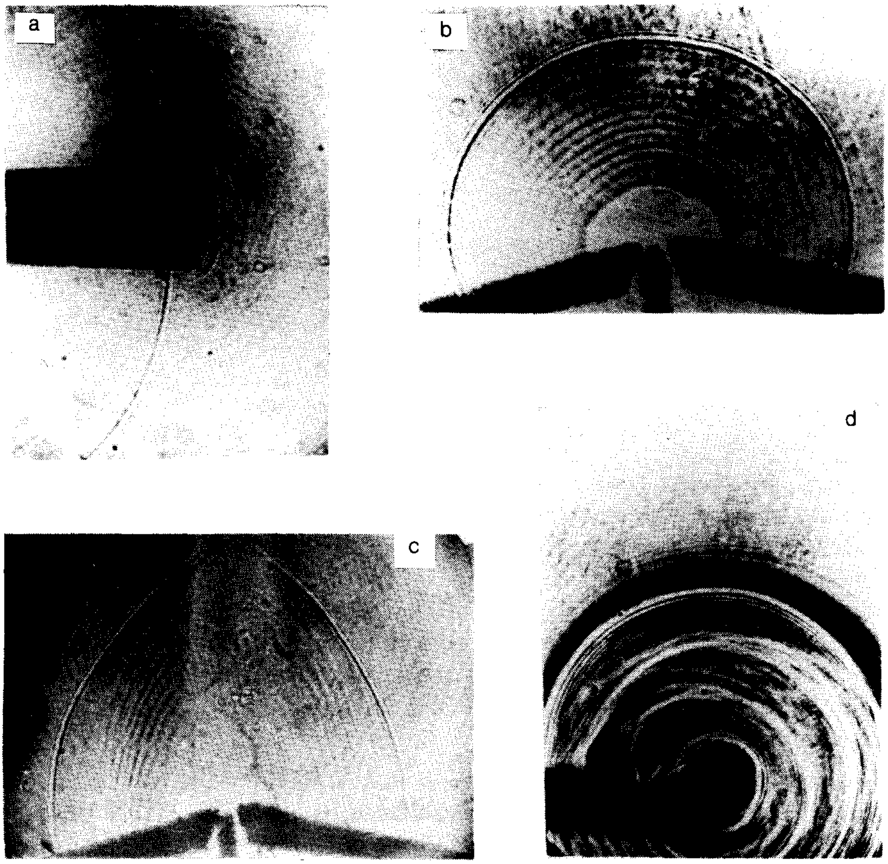

FIG. 3. Snapshots of shock waves. a: The shock wave incident on the tube leaves it before the shock wave propagating above the tube. The delay of the photograph is 30 μs. b: Train of shock waves from a pulsating explosion from current oscillations in the discharge circuit of a spark in water. The electrodes are 2 mm thick. The delay is 30 μs. c: Shock wave in a candle flame. The directionality of the propagation of the shock wave through the flame is evident. The delay is 10 μs. d: Shock wave from a spark in water. The generation of a train of waves can be seen. The delay is 3 μs.

and zones of intense vibrational excitation; these zones behave anomalously when a new shock wave or an intense sound wave passes through them. This new wave may not only be replenishing a stronger main wave but also probing its internal parameters.) Experiments have shown that, contrary to expectations, secondary waves do not overtake the primary wave; the waves move in a nearly equidistant fashion, at any rate over the distances studied here.

Observation of the direction in which shock waves are propagating. This direction can be observed by making use of a rising jet of hot gas from a flame (or of a lighter gas) (Fig. 3c). This capability opens up some broad opportunities for studying this phenomenon for various flows and for studying the velocities of motion during the injection of submerged or convection jets of a heated or lighter gas. Studies were carried out in a candle flame, and a clear elongation of the shock fronts over the flame was observed.

Train of shock pulses in water. This case, also studied, is illustrated by Fig. 3d. The distance between the shock waves is extremely close to the distance traversed by intense sound over an oscillation half-period.

Train of shock waves. This case is of interest because such a train can cause intense scattering of radio or light waves. The reasons are the high intensity of the reflection and scattering by jumps of high density and the sharpness of the boundaries. (We recall that in strong shock waves the density in the compression layer increases to a value $[(\gamma+1)/(\gamma-1)]\ \rho 0$, where γ is the ratio of specific heats, and ρ_0 is the initial density of the gas. This value is many times the compression in sound waves, in which case we would have $\Delta\rho \ll \rho_0$.) This capability might be utilized to detect and analyze a train or to retranslate radio waves by an array of compressional waves from pulsating microwave discharges produced at altitude. There is the possibility of a multiple (including resonant) amplification of reflection when reflection phases are matched.

Particularly noteworthy are possibilities for amplifying the effect of a train of shock waves, because of the ability to select a resonance of the excitation of oscillations and the crumbling of media being destroyed. This possibility is important for lithotrity, processing, etc.

The research on and use of trains of shock pulses are just beginning. The generation method which we have selected—a pulsating spark discharge in air and water—and the recording procedure may prove extremely useful.

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[1] A. S. Dubovik, *Photographic Recording of Fast Processes*, 3rd edit. (Nauka, Moscow, 1984), Part 4, Chap. 20.

[2] O. Svelto, *Principles of Lasers* (Plenum, New York, 1989).

[3] K. I. Krylov, V. T. Prokopenko, and V. A. Tarlykov, *Basic Laser Technology* (Mashinostroenie, Leningrad, 1990).

[4] V. V. Kyun, V. G. Samorodov, and Yu. M. Tolkunov, Impul'sno-periodicheskie azotnye lasery. Obzory po elektronnoĭ tekhnike, Ser. II, No. 2, 1437 (1989).

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