EGG-M-90086

EGG-M--90086

CONF-900791--7

DE91 001914

ULTRASOUND GENERATION THROUGH A FIBER OPTIC DELIVERY SYSTEM USING PULSED LASER ENERGY

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Received by OSTI

NOV 05 1990

INTRODUCTION

Short duration laser pulses can generate high frequency, broadband ultrasound in a material without contacting the surface [1-4]. For these noncontacting techniques to be useful on the shop floor, in remote applications, and in harsh environments, a dependable delivery system must be developed. Fiber optic techniques have been used to deliver either moderate laser energy for a large number of pulses or a large laser energy for a few pulses for the purpose of generating acoustic waves [5-7]. However, transmitting high energy pulses continuously through a fiber is required for practical sensing systems.

Fiber optics systems are currently used for long duration pulses (of the order of milliseconds) in laser welding applications; e.g. a welding system developed for manufacture of headlamps uses a fiber optic delivery system [8]. The key to the success of this welding system is the coupling technique used to deliver laser power to the fiber. Because the pulse duration is on the order of several milliseconds, the power density in the fiber is several orders of magnitude below the power densities required for ultrasonic applications.

Burger et al. [4] used pulsed laser light from a ruby laser transmitted through a 2 mm fiber bundle to generate Rayleigh waves on steel. They coupled the laser light through an index matching fluid to reduce the damage to the fiber. Since the work was in the thermoelastic regime, the output energy per pulse must have been less than about 2 to 4 mJ. Work using a single fiber with a 0.2 mm core was less successful - it normally failed after only a few laser pulses [9].

Dewhurst, Nurse and Palmer [5] had better success using a 600 μm diameter fiber. Using light from a Nd:YAG laser with a wavelength of 1.06 μm and pulse width of 25 ns, they were able to generate waves in both the thermoelastic and ablative or plasma regimes with the energy/pulse as high as 10 mJ for many (>500) shots. Using 15 mJ caused immediate fiber damage.

OPTICAL DAMAGE IN FIBERS

Critical parameters in coupling high power pulsed lasers to a fiber optic delivery system are fiber composition, mode, diameter, surface preparation; the fiber optic holding fixture; focal length of the input focusing lens; position of the fiber relative to the focal spot; input laser power; and fiber type and sheathing [10-12]. A study of damage to optical fibers from using a pulsed laser by Allison et al. [10] addresses many of these issues. Their objective was to transmit UV light (392 nm) with a pulse width of 5 ns into an operating gas centrifuge. A maximum energy output of 8 mJ through a 0.6 mm HCS fiber was achieved by polishing the input surface of the fiber "so that no scratches are visible through a 20X microscope objective." Using only cleaving techniques, the damage threshold was a factor of 2 to 10 lower. They observed two damage mechanisms. The first occurred at the input surface and was "easily avoided" by proper surface preparation, described above, and by keeping the surface clean. The second type was an internal failure starting at 5 to 25 mm from the input surface of the fiber. They proposed a model of this damage mechanism in which misalignment of the input beam caused an increase in intensity at the first reflection inside the fiber. This model was consistent with variations in damage with the focal length of the input lens: A short focal length lens produces more rapidly diverging light inside the fiber, less intensity at the site of the first reflection, and thus less chance for damage.

We observed two types of fiber damage in our initial experiments. The first was damage to the input surface due to imperfections in the surface or focusing too close to the surface. The second type, similar to that reported in reference [10] where the laser was misaligned, consisted of extensive pitting on the outer surface of the fiber at 5 to 20 mm from the input face or complete, catastrophic fracture of the fiber in the same region. Damage started at 5 to 20 mm into the fiber and sometimes progressed backwards toward the input surface in just a few spectacular seconds. The fiber usually shattered at the point of damage initiation and broke off. This failure mode is common in smaller diameter fibers because of the difficulty of centering the laser spot on the fiber center and of aligning the fiber in the plane of the beam. The type of sheathing may also affect failure - to prevent the buildup of hot spots along the length of the fiber, one vendor recommends against the use of black sheathing [12].

The peak power at the input surface of the fiber for a typical ultrasonic application can be calculated assuming a Gaussian distribution for the time shape of the laser pulse. The total energy can be calculated by integrating the power:

$$E = \int_{-\infty}^{\infty} P_o \, e^{-t^2/\tau^2} \, dt = \tau \sqrt{\pi} \, P_o$$

The parameter τ is related to the full width at half maximum by

$$\tau = \frac{\Delta t}{2 \sqrt{\ln 2}}$$

Thus the peak power, P_o, can be estimated for a 20 mJ, 20 ns wide pulse to be

$$P_o = \frac{E}{\tau \sqrt{\pi}} = \frac{2E}{\Delta t} \left(\frac{\ln 2}{\pi} \right)^{1/2} = 0.94 \times 10^6 \; W$$

If this power were spread uniformly over the surface of a fiber 600 μm in diameter, the intensity would be 0.33×10^9 W/cm^2, not much below measured values of the damage threshold of silica. (Reference [11] quotes a damage threshold of 50 GW/cm^2. Reference [10] quotes thresholds in terms of pulse energies of 10 to 12 J/cm^2 for a 5 ns pulse, which corresponds to a threshold peak power of about 2 GW/cm^2. Literature obtained from a fiber optics vendor [12] lists "voltage breakdown in fused silica of 10^{10} W/cm^2 maximum.") Of course, the intensity usually cannot be spread uniformly over the fiber surface since the incident laser beam has some distribution of intensity in its cross section and often has some hot spots due to misalignment in the laser cavity or in the transmitting optical train. In addition, the quoted damage thresholds are for very pure materials with extremely carefully prepared surfaces. Damage usually occurs at sites on the surface which are more susceptible due to defects in the surface or local contamination.

Thus careful preparation is key to preventing damage at the input and output surfaces [11]. Internal damage can be prevented by moderately careful alignment of the laser beam. The methods used in our research are described in the next section.

FIBER PREPARATION AND ALIGNMENT

The size of the fiber is important in avoiding fiber damage. As noted in the calculations above, a 600 μm diameter fiber is barely adequate, under ideal conditions, for the power required in some ultrasonic applications. Furthermore, visual alignment of the laser beam on the fiber is very difficult since the eye response is logarithmic. The apparent beam size is somewhat larger than the full width at half maximum; thus it is very easy to concentrate the intensity on an area much smaller than the visually observed area. As a result, a silica-silica fiber with a 1 mm diameter core, which provides almost three times more surface area, was selected. The additional area provides a margin of error for the visual alignment problem as well as allowing for possible hot spots in the beam, cross-sectional intensity distribution in the beam, and imperfections in the surface.

Fiber surface preparation was of great importance for successfully coupling light into the fiber. Approximately 25 mm of the sheath material on multimode fibers was mechanically removed prior to preparing the end of the fiber. (As the fiber warms, the sheath can melt and flow over the face of the fiber.) Although the fiber end can be prepared by cleaving or by cutting on a diamond saw, the results obtained by cleaving a large diameter core are not adequate and are somewhat variable. Therefore, a polishing technique was developed to reduce the chance of damage to the input surface. A thin-sectioning, low-speed diamond blade saw is used for the initial fiber cut. The fiber ends are then polished on a fiber polishing machine using a 3, 1.5, and 0.3 μm grit. The fiber is held normal to its axis and parallel to the polishing platen by a holding fixture. As the final step, freon was used to remove residue and dirt prior to introducing laser light. The finish quality was visually confirmed using a 50X hand-held viewer.

In reference [5], a discussion of the input focusing lens indicated that it should have the shortest possible focal length that would fill the fiber. The focal point should be outside the fiber and the beam diverging toward the input surface. This configuration prevents the beam from being focused inside the fiber. Ideally, the sine angle of divergence should be equal to the numerical aperture of the fiber, which is typically 0.3 to 0.4, corresponding to angles of 17 to 23°. However, the studies in [5] indicate that a focal length producing this angle is not feasible since the fiber is not ideal and significant energy would be lost into the cladding. In addition, the size of the beam at the focal point of the lens could be so small that the air would break down, reducing the energy in the beam and possibly contaminating the lens. Dewhurst et al. [5] found that for their beam profile, a lens of 33 mm focal length provided the optimum energy transfer, even though the angle of divergence was only 4°. In our work, lenses with focal lengths from 19 to 75 mm were used. Reference [12] recommends that a low quality lens be used to enhance the probability of exciting a large number of modes in the fiber.

The fixture for holding the input end of the fiber should be adjustable in three dimensions as well as in fiber tilt to assure that the laser spot is centered on the fiber and input parallel to the axial direction of the fiber. The fiber should be positioned in the fixture such that the pin vise clamps onto the sheath rather than on the bare fiber to avoid unnecessary stress on the fiber. Such stress could create a potential failure point in the fiber. Our fiber was tilted by skewing it in the pin vise clamping fixture.

The initial alignment was performed at low laser pulse energy. Neutral density filters were used to lower the energy to less than 0.1 μJ/pulse so that the beam could be directly observed on the face of the fiber with no eye hazard [13]. The focal point of the lens was determined experimentally by observing the size of the beam on a piece of paper. The fiber was then positioned beyond this focal point until the apparent size of the beam was about the size of the fiber. The major portion of the energy was then in an area somewhat smaller than this due to the logarithmic response of the eye, discussed above. Once the laser spot was aligned with the fiber, the filters were adjusted to provide the required laser energy.

TESTS OF FIBER CAPABILITIES

Initial experiments were performed with a polished 1 mm fiber 200 mm long using a 38 mm focal length lens for input coupling. The input energy was measured by placing a power meter temporarily between the laser and the focusing lens. The input energy to the fiber was increased by removing neutral density filters. In one test the measured input energy to the fiber was 16.3 mJ/pulse and the fiber output energy was 14.3 mJ/pulse, enough energy to ablate steel if the beam were focused. A timed test of output energy was also conducted at this energy level. The test was terminated after forty minutes with the laser operating at a 30 Hz pulse frequency, which corresponds to about 72,000 shots. The output energy decreased to 12.3 mJ/pulse during the forty minutes; the input energy was still 16.3 mJ/pulse. No change in the input surface or along the 25 mm of exposed fiber was observed with a binocular microscope with a maximum power of 50X.

A test series was conducted using 1 mm fiber with various focal length lenses to determine the maximum input energy that can be coupled into the fiber. The results are summarized in Table 1. The 19 mm focal length lens generated plasma at 15 mJ/pulse. When the plasma formed, input coupling efficiency dropped dramatically and the test was terminated. The output power of 26 mJ was obtained for several hours using a 38 mm focal length with no drop in output power or visible fiber damage. Two additional focal lengths were used. The 50.2 mm lens provided an output power of 35 mJ/pulse, and the 75.6 mm provided 37 mJ/pulse. The damage mechanisms observed in these tests confirmed that the polishing technique is quite successful as no fibers failed at the front face. The

Table 1. 1 mm Fiber Study

Lens Focal Length (mm)	Maximum Input (mJ/pulse)	Intensity W/cm²	Maximum Output (mJ/Pulse)	Damage
19	*	*	*	No coupling above 15 mJ/pulse
38	18–33	2.0×10^8	15–26	No failure – ran for hours
50.2	41–44*	2.7×10^8	33–35	Internal fracture 10 mm from input end
75.6	32–42	2.5×10^8	30–37	Internal fracture

* Plasma caused problems on input coupling.

failure mechanism was internal fracturing due to either internal focusing or flaws in the fiber.

FIBER OUTPUT FOCUSING

The output of the fiber is a diverging beam from a broad source at the fiber tip. The source was characterized by measuring the radius of the beam as a function of the distance from the end of the fiber. The beam diverged from a point about 3 mm inside the fiber with a half angle of divergence of 5°. The numerical aperture for this fiber is 0.24, which corresponds to a half angle of about 14° for the exit beam of a completely filled fiber. The observed angle of divergence of the exit beam is smaller due to the relatively small angle of the beam entering the fiber. This can be calculated (from the 6 mm laser beam diameter and the 38 mm focal length input lens) to be 4.5°. A shorter focal length lens at the input to the fiber would fill the fiber more completely.

Although the source is not a diffraction limited spot [12], the output optics were designed as though it were. To obtain a minimum spot size on the metal, a large aperture of 50 mm was chosen for the focusing optics. The initial lens had a focal length of 200 mm, so that the diverging beam almost filled the aperture and the output was parallel. Then the final lens was chosen to have a focal length that was as short as possible, but still convenient for the experimental set up.

GENERATION OF ULTRASOUND

A 2 m length of 1 mm fiber was prepared as described above to test the capability of the fiber optic delivery system to generate ultrasonic waves. The experiment duplicated a previous experiment [2] that used a direct laser beam focused to the diffraction limited size. In this experiment, the beam is focused on a 25.4 mm thick carbon steel plate and the sound is received on the same surface 50.8 mm away. The receiver is an electromagnetic acoustic transducer (EMAT) with a normal magnetic field and a pancake shaped receiving coil that is sensitive mainly to motion in the plane of the steel part.

A 100 mm focal length lens was used to focus the parallel light from the first lens at the output of the fiber. A diffraction limited spot diameter would be 7 μm. The observed diameter of the spot on the steel part was approximately 1 mm, judging from the ablation spot on the metal.

Figure 1 shows some of the various rays that travel from the source to the EMAT receiver; Figure 2 shows the received EMAT signals for ultrasound generated using fiber optics and using a direct focused beam. The signals are very similar in both time and shape. The major differences in the shapes of the waveforms are due to the complicated interference among the various waves that arrive at almost the same time. Small changes in the position of the EMAT affect these shapes significantly. For example, the surface shear wave, the shear wave due to a mode converted longitudinal wave off the bottom of the part, and the Rayleigh wave all arrive at around 16 μs, close to the headwave and the wave consisting of three longitudinal half vees and a final shear half vee, around 22 μs. (Note: a shear wave also arrives at 45° around 22 μs, but the EMAT is not sensitive to this wave at this angle.) The arrival time of the headwave is about 0.4 μs earlier in the direct beam excitation, indicating that the transducer was misplaced slightly.

In the development of a noncontacting inspection system to determine weld quality on a pass-by-pass basis [14], the fiber optic delivery system was used to generate ultrasound in welds produced by the gas metal arc welding process [17]. The ultrasound was detected using an electro magnetic acoustic transducer (EMAT). Other potential uses of this technique are measuring the depth of liquid metals in hearth melting processes [1] and generation of ultrasound in ceramics during processing [15] and inspection [16].

SUMMARY

Silica-silica, multimode fiber optic cable 1 mm in diameter was used to deliver laser pulses from a Nd:YAG laser operating at 30 Hz with a pulse duration of 10 ns. Careful attention was paid to the preparation of the input and output ends of the fiber to optimize input coupling and

Fig. 1. Diagram of some of the rays traveling from the source to the EMAT receiver. (L - Longitudinal, T - Transverse or Shear)

Fig. 2. Received EMAT signal from ultrasound generated by laser light through a fiber (upper A scan) and direct laser light (lower A scan). (L - Longitudinal, T - Transverse or Shear).

transmission. The mounting fixture at the input end of the fiber had adequate degrees of motion and skew to inject the laser light into the fiber parallel to its axis. The fiber was placed beyond the focal point of a short focal length lens capable of exciting a large number of modes in the fiber. The output energy from the fiber was sufficient for sound generation in both the thermoelastic and ablation regimes. Experiments performed with the fiber optic delivery system correlated well with the results obtained using the focused laser beam. This was a critical initial step in establishing a convenient system to deliver laser light for noncontacting ultrasound generation in solids and liquids, which will find numerous applications in the evaluation of material characteristics and in the real-time control of processes in harsh environments.

ACKNOWLEDGMENTS

We acknowledge the generous contributions of the following persons: Marshall Jones of General Electric, Gregory Burke of General Fiber Optics, and Vonda Smith-Wackerli, Gary Fletcher, and Colleen Stander of the Idaho National Engineering Laboratory. This work is supported by the U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences under DOE Contract No. DE-AC07-76ID01570.

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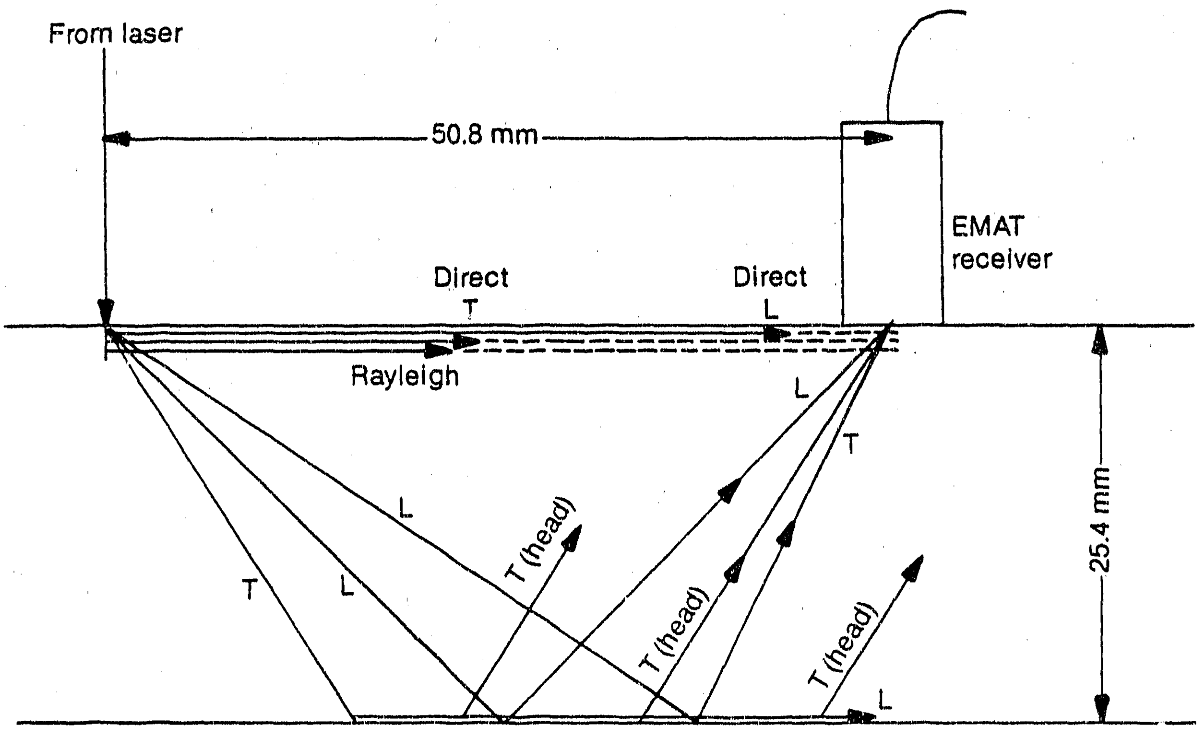
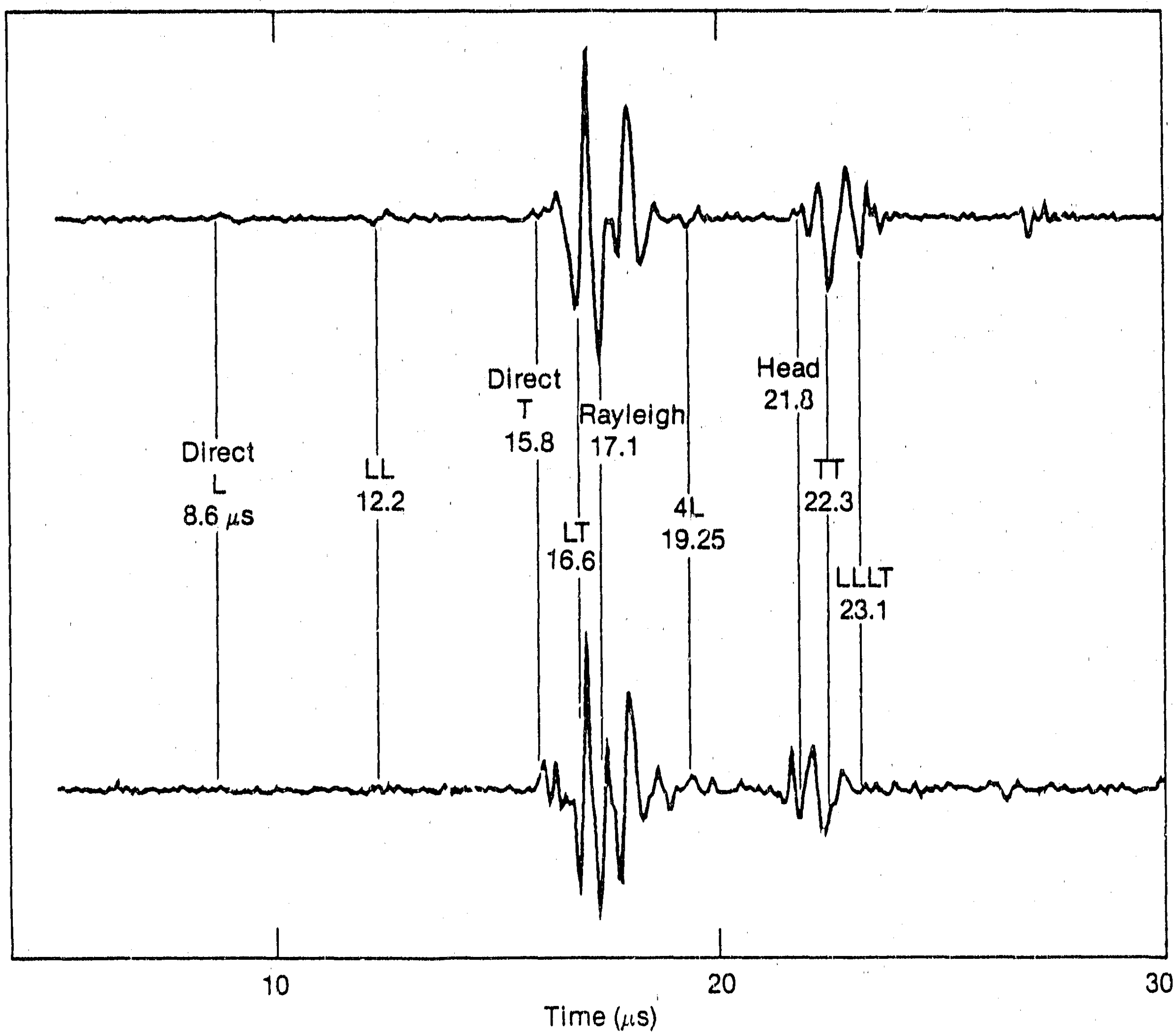


Carlson Fig 1

Fig 1



Carlson Fig 2

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