DESIGN AND APPLICATION OF A PHOTOACOUSTIC SENSOR FOR MONITORING THE LASER GENERATED STRESS WAVES IN OPTICAL FIBER

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Abstract Measurement of stress transients generated by a 400ns pulsed HF laser in an infrared fluoride glass fiber has been made using fast time – response piezoelectric film transducer. Acoustic signals up to 12 mV with frequencies ranging in megahertz generated by 21 mJ laser pulse when passed through the fiber axis in the linear region. It is shown that useful information such as onset of non - linear behavior of the fiber can be gained from such measurements, which in turn can be used as a means of monitoring the quality of fiber surface during an operation.

Key Words Photo Acoustic Sensor, Laser, Optical Fiber

1. INTRODUCTION

The interaction between laser light and the material in general is of great interest. The efficient generation of ultrasonic waves promises to have a variety of practical applications [1-6]. The physical principle of the photoacoustic effect consists in the fact that, for a time-varying light beam propagating through a medium, the radiation less absorption causes differential heating and thermal expansion generation of both stress and thermal waves. It should be noted that radiation is not transformed into heat such as scattering is not detected photoacoustically [7]. A very high signal to- noise ratio is achieved with this method because the measured signal depends directly on the absorbed beam energy.

Photoacoustic generation can be classified as either direct or indirect. In the direct generation the acoustic wave is produced in a coupling medium adjacent to a sample, usually due to heat leakage and to acoustic transmission from the sample [8]. Photoacoustic generation can also be classified according to the two-excitation modes: the continuous-wave (cw) modulation mode, and the pulsed mode. The effect of photoacoustic in an optical fiber has already been studied using barium titanate discs [7]. There is currently much interest in the development of fiber delivering system for tissue ablation [9-11], imaging [12,13], spectroscopy [14,15], thermometry [16,17] and similar fields using ir and uv lasers.

In this paper the potential of a fluoride glass fiber for delivering multiline HF laser pulses is evaluated. Also, a diagnostic technique based on the use of a wide – band width PVDF thin film piezoelectric transducer is developed to measure the stress waves generated in optical fiber as a means of monitoring the integrity of fiber surface during the operation.

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2. THEORETICAL BACKGROUND

Stress waves are generated in laser irradiated media through a variety of mechanisms, which depend on the local condition [18]. Whenever photons are absorbed or reflected there is an associated radiation pressure, which is directly proportional to the irradiance. In transparent media electro restrictive forces are developed and, if the irradiance is high enough, dielectric breakdown can occur leading to the formation of a high pressure plasma and the production of large amplitude stress waves in the irradiated sample. In absorbing samples two additional mechanisms are encountered: thermoelastic effect and ablative recoil stress.

3. THERMOELASTIC EFFECT

It is well known that most materials expand upon heating as an increase in temperature leads, on average, to a larger equilibrium atomic spacing. The expansion is driven by internal forces and if this is hindered, as in the case of a constrained body or by the material inertia under conditions of rapid heating, large stresses develop. This is known as the thermoelastic effect. The generation of stress waves by the thermoelastic effect in liquids and solids irradiated by pulsed lasers has been studied extensively since the early days of the lasers [19,20]. The effect of rapid heating is to produce stress waves propagating away from the energy deposition site as shown schematically in Figure 1.

Neglecting heat conduction, the temperature profile is rectangular and prior to the material adjusting to its new mechanical equilibrium position there will be a pressure rise associated with this higher temperature region. Here for a free surface (unconstrained) a rarefaction wave \( R_0 \) propagates in to the material from the surface and a rarefaction \( (R_1) \) and compression \( (C_1) \) wave move away from the other pressure step. The leftward propagating rarefaction is inverted as it is reflected at the free surface and after a time \( \tau = \frac{2d}{v_a} \), where \( v_a \) is the acoustic velocity, the surface has adjusted to its new mechanical equilibrium position. The resulting stress wave propagating in to the material consists of a symmetric bipolar signal \( \sigma \) (compression followed by rarefaction) propagating at the sound speed (Figure 1a). A stress wave detector located to the right of the surface thus registers a bipolar temporal signal. When laser absorption is replaced by the more realistic case of an exponential fall-off of absorbed energy with distance in to the material, similar arguments apply but the acoustic transient now mirrors the assumed exponential drop as shown in Figure 1b. These qualitative arguments are substantiated by mathematical modeling based on the thermoelastic wave equation [19-21]. An important and valuable finding is that for exponential attenuation one-dimensional wave propagation, the early portion of the stress waveform, \( \sigma \), is exponential in time and of the form:

\[
\sigma = Ae^{\alpha t'}
\]

Here \( A \) is a constant, \( \alpha = \alpha v_a \) where \( \alpha \) is the attenuation coefficient for radiation in the absorbing medium at \( t' = t - l/v_a \) where \( l \) is the distance from the surface to photoacoustic transducer. Thus as first shown by Carome et al. [19], the measured stress transient can provide information on the attenuation coefficient provided \( v_a \) is known. This is particularly valuable under conditions where both absorption and scattering contribute to attenuation, as is often the case with tissue samples. Relatively simple forms for the thermoelastic transients can be derived for a laser pulse shape of the form:

\[
I = I_o (1 - \exp - kt) \exp - mt
\]

Where \( I \) is the irradiance and \( k \) and \( m \) define the rates of rise and fall of the pulse respectively. \( I_o \) is defined as:

\[
I_o = m(m + k)F / k
\]

Where \( F \) is the fluence. With an irradiance of the form described by Equation 2 and assuming the instantaneous relaxation of absorbed energy to heating, no heat conduction and one-dimensional
wave propagation, the stress becomes [22,23]:

\[
\sigma = \frac{\alpha I_0}{2} \frac{k}{(m+a)(k+m+a)} \quad t' \leq 0
\]

\[
\sigma = \frac{\Gamma}{2} \left[ \frac{2m e^{-m't'}}{(m^2-a^2)} - \frac{2(m+k) e^{-(m+k)t'}}{(m+k)^2-a^2} \right] \quad t' > 0
\]

With \( t' = t - \frac{1}{v} \) and \( \alpha = \alpha v_\alpha \), \( \Gamma \) is the Gruneisen constant

\[
\Gamma = \gamma \frac{v^2}{C_v}
\]

Where \( \gamma \) is the volume expansion coefficient, and \( c_v \) the specific heat capacity at constant volume.

4. EXPERIMENTAL SET UP

The home-built laser used in these experiments operated on an SF6-C3H8 gas mixture at low pressure (≈60 torr) and was excited by a fast, transverse, and high-voltage discharge between a pair of change profile electrodes. Multiline output energies up to 380 mJ in a 400ns full width half maximum (FWHM) pulse could be obtained at a pulse repetition rate of ~ 0.2 Hz. Spectral measurements revealed that 20 transitions spanning the wavelength range 2.67-2.96 μm appeared in the output with dominant emission at 2.76, 2.78, 2.82 and 2.92 μm.

The output beam from the laser was passed through a circular aperture of 10mm diameter to select a region of uniform fluence and this aperture was then suitably imaged on to the target zone using a NaCl lens of 50mm focal length. A set of glass attenuators was used to vary the fluence and energy measurements being made using a Gentec pyroelectric joule meter. An IR grade quartz beam splitter following the aperture directed a small fraction of the output beam on to an InAs photodiode (Judson J12) allowing the relative laser output to be monitored on a shot-by-shot basis. The laser beam divergence was measured in two different methods: (i) by scanning the beam with a Gentec joule meter covered by a 0.5mm pinhole, and (ii) by focusing the beam on to Polaroid film using a gold concave mirror (R = 50cm). In both case, a value of about 3 mrad was obtained for beam divergence.

A fluoride glass optical fiber supplied by Infrared Fiber Systems was used in experiments. The diameters of the core and core-cladding are 500 and 600μm respectively and the overall fiber diameter 800 μm. The fiber ends were cleaved, polished using aerosol cutting polish (RS556-34) and then inspected under visible light illumination using an optical microscope (Figure 2). For this experiment a short length of the fiber (~30mm) was fitted with a simple photoacoustic sensor based on a polyvinylidene fluoride (PVDF) piezoelectric film (Metal Box Co). This sensor as shown in Figure 3, consists of a single layer of 9μm thick PVDF film (10x20mm²) wrapped around a perspex cylinder through which the fiber passed. The 5mm radius cylinder acted as impedance matching stub which minimized acoustic reflection at the interface giving a rise time limited by the transit time of the longitudinal wave in the transducer, 4ns in the present case.

Intimate contact was maintained between the fiber and cylinder by means of silicone grease. A second cylinder of perspex was used to clamp the film in place. Electrical contacts were made to the aluminized PVDF film using silver epoxy and the output leads taken to a 100MHz storage oscilloscope (7834 model) with a 7A19 plug-in amplifier and 1MΩ high input impedance. The output voltage can be shown to be:

\[
v(t) = \frac{d_r}{c_D + c_L} \int F(t) dt
\]

Here \( F(t) \) is the time-varying normal force at the transducer (\( C_D \approx 2.7 \) nF) and \( C_L \) are the transducer and load capacitance respectively, and \( d_r \approx 20 \) pC N^{-1} is the thickness mode strain constant for PVDF. The overall transducer display system
has a rise time estimated to be \( \leq 5 \text{ns} \). In this way thermelastic stress waves generated by heating as a result of laser absorption at the fiber face could be detected following their propagation through the fiber and inner cylinder of the photo acoustic sensor. In addition, for some experiment a sensitive InAs detector (Judson J12) was employed to detect laser radiation scattered from the fiber at different position along its length.

5. EXPERIMENTAL RESULTS

The presence of non-linear absorption at the entrance surface to the fiber was obtained from measurements using the photoacoustic sensor described in section 3. With fiber input surface located 1mm from front face of the transducer as indicated in Figure 3, measurements of the voltage response were made as a function of the input fluence. The transient voltage response shown in Figure 4 (see inset) consisted of an initial step delayed by \(-2 \mu s\) with respect to the HF laser pulse, and rising to produce a relatively large amplitude pulse peaking at \(-4 \mu s\). The initial delay is consistent with the propagation time for an acoustic wave to travel through the fiber and the Perspex cylinder having originated at or near the fiber surface. In an experiment Gutfeld et al. [24] used repetitive pulses of N2 and Dye lasers with (10-25ns) width, which produced signals of 20MHz when the surface of aluminum was irradiated. Dyer et al. [25] detected a high frequency of about 160MHz large-amplitude acoustic waves when they irradiated a thin absorbing polyethylene terephthalate (PET) polymer. Burt et al. [7] detected signals in order of 2MHz corresponding to 2mV in amplitude in an optical fiber using 1J ruby laser. The maximum signal amplitude, shown in Figure 4 as a function of the input fluence exhibited a linear increase up to 15 Jcm\(^{-2}\) but beyond this increased loss is non-linearly related to the fluence.

At high fluence where physical damage resulted at the fiber input face, the response of the sensor exhibited a relatively complicated behavior. The first laser pulse at 37 Jcm\(^{-2}\) caused a plasma formation as evidenced by a bright spark and audible noise and recorded photo acoustic signal was essentially unipolar as shown in Figure 5. The second pulse produced an even brighter and louder plasma response and again a unipolar, compressive photoacoustic signal but with continued exposure the plasma became progressively weaker and the signal decreased correspondingly. The steady drop in peak signal illustrates this after the second pulse shown in Figure 5. At this stage it was decided to investigate more on the origin of the non-linear behavior beginning at fluences \(\geq 15\text{Jm}^{-2}\) observed in Figure 4. Measurements using the side-viewing IR photodiode appeared to rule out physical damage as a contributory factor to this loss.

This is evidenced by the constancy of the scattered signal (Figure 6) with number of laser pulses, even at fluences considerably above the value at which the photo acoustic response became non-linear (Figure 4). In contrast at higher fluences (\(\geq 32\text{Jcm}^{-2}\)) where catastrophic laser damage to the input of the fiber occurred (Figure 2b), the scattered signal increased abruptly as shown in Figure 6. In this case input radiation is scattered out of the core because of the damaged end face.

The fiber transmission can be conveniently summarized by plotting the output versus the input fluence as shown in Figure 7 for a fiber length of \(L = 15\text{cm}\). Here the output fluence from the fiber was calculated using the core area and the results are based on the transmission after exposure to 100 pulses at each fluence. For input above \(\sim 15 \text{Jcm}^{-2}\) the transmission begins to fall due to increasing end losses and beyond \(\sim 32 \text{Jcm}^{-2}\) catastrophic damage produced by the 400ns duration HF laser pulse and the output fluence drops sharply. Tests of the fiber lifetime could only be carried out over a relatively small number of pulses because of the low pulse-rate of the laser. However, the limited results obtained indicated that for input fluences \(\leq 15 \text{Jcm}^{-2}\) the fiber transmission remained constant for at least 700 pulses as shown in Figure 8. At higher fluences not only was the initial transmission lower but this also continued to decrease with continued exposure as indicated, for example, by the results for a fluence of 24 Jcm\(^{-2}\).
6. DISCUSSION

It has been demonstrated that a relatively large diameter infrared fluoride glass fiber (~ 500/μm core) can be used to deliver the multiline HF laser at suitably high output fluence (≤7 J/cm²) for industrial and medical purposes. Fast time responses photoacoustic technique have been found to provide useful information on the interaction of short pulse laser with materials. A variety of relevant parameters can be measured from the detected stress waves: laser attenuation coefficients from the thermo elastic response in the subablation regime, ablation thresholds and timescales, and the magnitude and nature of potentially disruptive stress transients. The observation of thermo elastic signals also provides evidence for fast thermalization of photo-excited states. The origin of the stress wave signal observed in these experiments assumed to be the thermo elastic effect produced by the local temperature rise associated with the absorption of laser radiation at fiber input surface and its subsequent decay to heat. The precise mechanism is not known but it most likely relates to absorption at surface states at the fiber input (and possibly exit) faces. Optical signal measurements using the side-viewing IR photodiode appeared to rule out physical damage as a contributory factor to loss at 15 J/cm² where non-linearity began (Figure 4). This is evidenced by the constancy of the signal (Figure 8) with number of laser pulses, even at fluences considerably above the value at which the photoacoustic response became non-linear. In contrast, at higher fluences where catastrophic laser damage to the input face of the fiber occurred (Figure 2b), the scattered signal increased abruptly. In this case input radiation is scattered out of the core because of the damage end face.

7. CONCLUSIONS

The results obtained indicate that megahertz laser induced thermoelastic or ablative stress transients can be a practical and convenient method to monitor the optical fiber characteristics such as surface integrity during an operation. For this purpose a simple photoacoustic sensor can be used to study the fiber nonlinear behavior and the change in signature of photoacoustic signal produced in the fiber.

8. REFERENCES


Figure 1. (a) Surface adjusted to new mechanical equilibrium position with bipolar stress wave propagating into sample, (b) stress wave form for exponential absorption, T and G are step temperature and stress respectively.

Figure 2. Optical micrograph of polished fluoride glass fiber under white light transmission (a) and scanning electron micrograph of damaged input face of fiber by 1 pulse at 35 J/cm² (b).

Figure 3. Schematic diagram of photoacoustic transducer used to investigate loss at the input surface of fiber. The 9 μm thick PVDF film has dimensions of 10×20mm² and forms a partial wrap around the inner Perspex cylinder.

Figure 4. Peak amplitude of the photoacoustic transducer response as a function of fluence to fluoride glass fiber.

Figure 5. Peak amplitude of the photoacoustic transducer as a function of laser pulse number at 37 J/cm².