LASER GENERATION OF NARROW BAND ULTRASOUND

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INTRODUCTION

Laser based sensor systems to replace conventional piezoelectric contact transducers for ultrasonic testing continue under development for applications where contact with the specimen surface is undesirable or impossible. To date, such systems are considerably less sensitive than their piezoelectric counterparts. As a result, a great deal of effort has contributed to the development of a number of interferometric transducer systems to detect ultrasound. Increasingly, however, researchers have begun looking at laser ultrasonic sources to see what improvements might be made to enhance overall system sensitivity for laser generation and detection of ultrasound.

Most systems using lasers to generate ultrasound incorporate pulsed lasers focused to a single point on the specimen's surface. Considerable enhancement to sensitivity for laser generation and detection systems may be obtained, however, using a laser source which provides a burst of several pulses instead of a single pulse. Improvements in system signal-to-noise ratio may be obtained through two mechanisms. With the proper application of the laser source, it may be possible to direct ultrasonic energy in the specimen, thus increasing the amount of signal directed toward the receiving transducer. Secondly, owing to the repetitive nature of the pulse burst wave form, it is possible to reduce the overall system frequency bandwidth.

By controlling the shape of the laser spot illuminating an object surface, directionality, particularly of surface acoustic waves, has been demonstrated [1]. Projected arrays of laser spots have been proposed for the purpose of "steering" laser generated acoustic waves within bulk materials [2]. Periodic temporally phased arrays have been shown to produce a remarkable degree of beam directivity [3].

Experiments in volume absorbing materials, and in water in particular, have shown that the shape of the absorbing volume and the repetition frequency of the laser source may be used to direct the acoustic energy in the specimen [4]. More recent work has shown that through the proper selection of these same parameters, it should be possible to generate directed ultrasound with extremely narrow frequency bandwidth. While these studies have been performed using water as the specimen medium, it should be possible to extend these concepts to ceramic or polymer material.

THEORY

The potential for generating narrow frequency bandwidth signals, directed or undirected, can be put to great advantage in reducing the overall noise in the laser generation and detection system. Consider the equation below defining the signal-to-noise ratio for heterodyne interferometer system.

$$SNR_{het.int.} = \left[\frac{P_0 \eta}{h \nu B}\right]^{1/2} \cdot \frac{2 \pi K}{\lambda_0 \left[1 + K^2\right]^{1/2}} \delta$$

Note that with increasing bandwidth, B, the signal-to-noise ratio decreases. Since the detection bandwidth for acoustic signals generated by a single laser pulse must be very large, the sensitivity of the detecting system is reduced. Conversely, if it were possible to generate a narrow band ultrasonic signal, then the bandwidth of the detection system could be correspondingly reduced, thus improving the detection signal-to-noise ratio and the overall system sensitivity.

The physical characteristics of the specimen determine to a great extent the shape of the acoustic pulse to be generated upon interaction with a laser source. Assuming, however, that a configuration can be obtained which results in the production of a single acoustic spike corresponding to each laser spike in a pulsed train, an understanding of the bandwidth narrowing provided by such a signal is more easily understood. Figure 1 shows graphically two Fourier transform pairs, the first consisting of a single pulse in the time domain. Note that in the frequency spectrum of this pulse, the acoustic energy exists continuously over a broad range of frequencies. In the lower part of the figure, a packet of 10 identical pulses is shown. The corresponding spectrum shows that in this case, while the energy follows the envelope of the single pulse case, it is not distributed continuously throughout the spectrum, but is instead concentrated about those frequencies which are multiples of the pulse repetition frequency. It should be possible, therefore, to process this signal with a comb-shaped filter, passing only those frequencies where the signal energy is concentrated and rejecting signal and, more importantly, noise in those regions of the spectrum where the signal energy is small.

Ignoring, for the moment, specimen geometry, the production of packets of pulsed ultrasonic energy requires appropriate laser systems capable of providing pulsed energy as well. For this purpose, three modes of intracavity laser modulation have been considered: mode-locking, cavity dumping and multiple Q-switching. Intracavity modulation is, in general, more efficient than extracavity chopping in that higher peak powers may be obtained. Depending on the type of modulation, the pulse powers may be from 10 to 10,000 times higher than

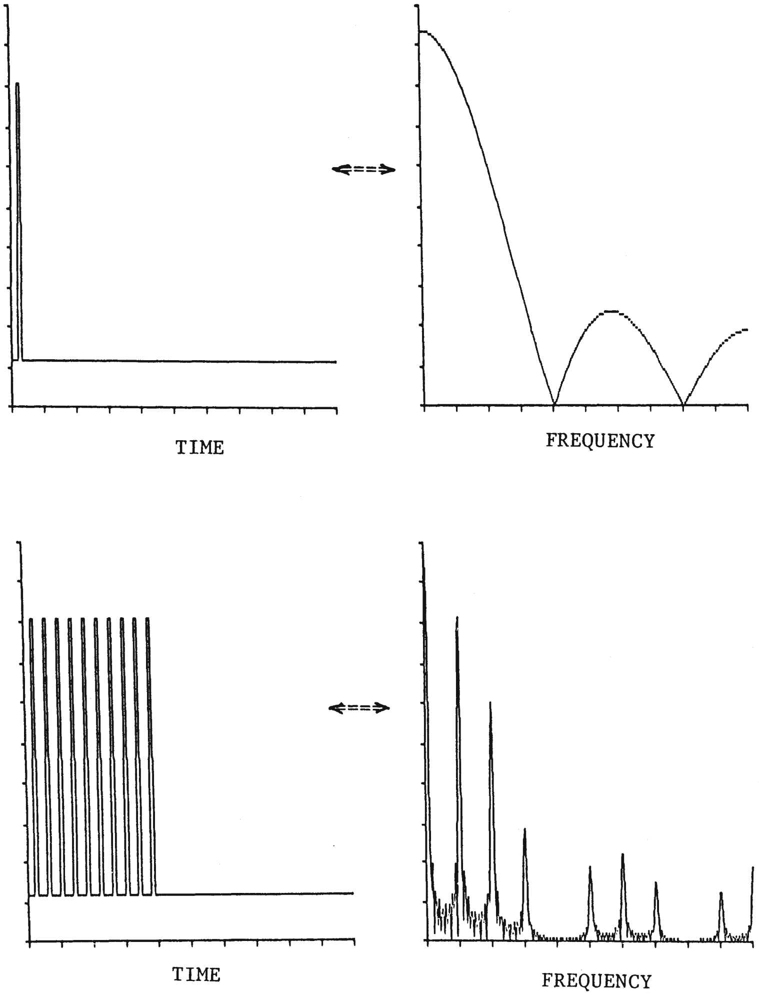

Fig. 1. Fourier transform pairs for ideal single (top) and ten (bottom) pulse acoustic signals. In these models, the time and frequency units are arbitrary. The spacing of the frequency spikes for the multiple pulse signal corresponds to the pulse repetition rate.

the corresponding CW power. Mode-locking methods have been used in the past to generate high-frequency ultrasound in thin films [5, 6]. Mode-locking typically generates pulses with the widths of tens of picoseconds at a repetition rate from 50 to 200 MHz. Cavity dumping produces pulse widths of tens of nanoseconds and repetition rates up to several MHz. Finally, multiple Q-switching also produces pulses of tens of nanoseconds duration but with a repetition frequency only up to about 50 KHz.

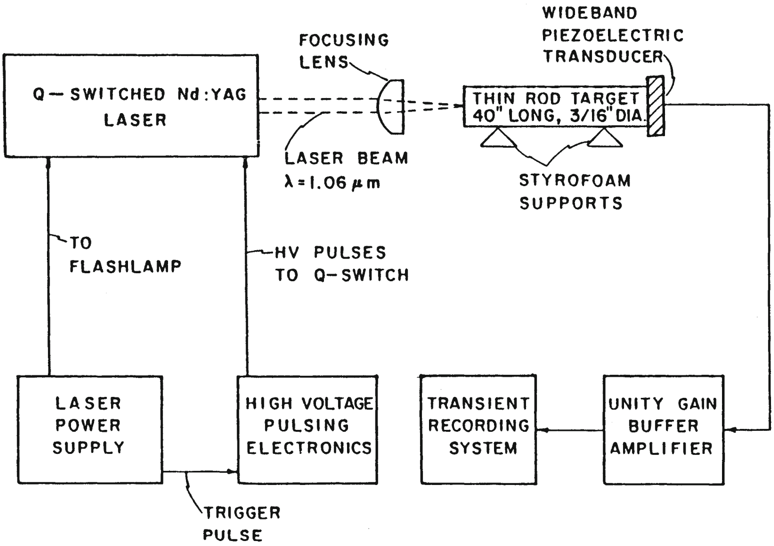

Fig. 2. Experimental arrangement for repetitively Q-switching the Nd:YAG laser several times during a single flashlamp cycle.

EXPERIMENTAL RESULTS

Multiple Q-switching of a Nd:YAG pulsed laser has been used to demonstrate the reduction in bandwidth of the generated ultrasonic signals. The experimental system is shown in Figure 2 where it can be seen that a long, thin rod was used as the specimen in this case. Bar modes in the thin rod produce single monophasic spikes with each incident laser pulse. Typical displacements in a long thin rod are shown in Figure 3 where a four nanosecond Nd:YAG laser pulse was used to thermoelastically excite acoustic displacements detected by an optical heterodyne interferometer. Note that a small displacement is observed at a time corresponding to the longitudinal wave speed, but that a large and broad pulse is observed several microseconds later.

In the experimental setup, the drive circuit for the electro-optic Q-switch in the Nd:YAG pulsed laser was modified to provide up to ten pulses per flash lamp cycle. The beam was directed onto the end of a steel rod (3/16" diameter), and thermoelastically generated laser pulses were detected at the far end of the rod using a broadband acoustic emission piezoelectric transducer. The waveform and corresponding spectrum of the detected pulses are shown in Figure 4. Note the similarity between the spectrum of the pulsed acoustic signal and the computed spectrum for a pulsed train shown in Figure 1. A comb-filtering process was computationally applied to this signal resulting in the signal waveform shown in Figure 5. A bandwidth reduction of about 1 order of magnitude resulted from this filtering process, thus producing an improvement in signal-to-noise of about 3 to 1. Experiments are continuing using a newly implemented cavity-dumped CW Nd:YAG laser system shown schematically in Figure 6.

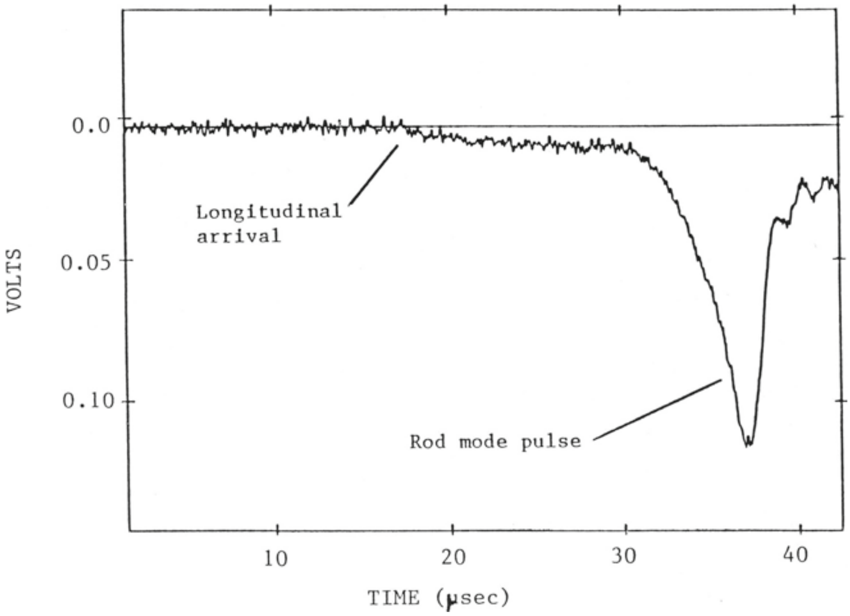

Fig. 3. Typical acoustic signal generated in a thin rod by a single 4 nsec Q-switched Nd:YAG laser pulse.

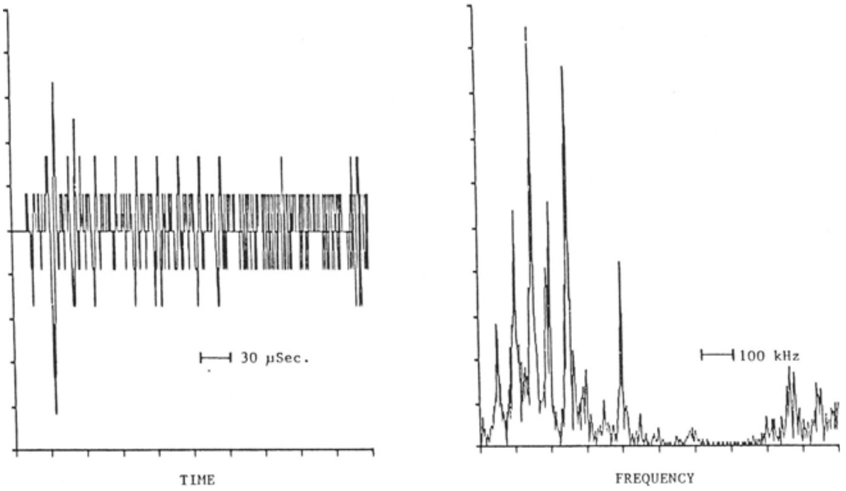

Fig. 4. Fourier transform pair for a typical 10 pulse acoustic signal generated in a thin steel rod (3/16" dia.) by Q-switching the Nd:YAG laser ten times during a single flashlamp cycle. The pulse repetition rate of 52 KHz is at the upper limit for this technique.

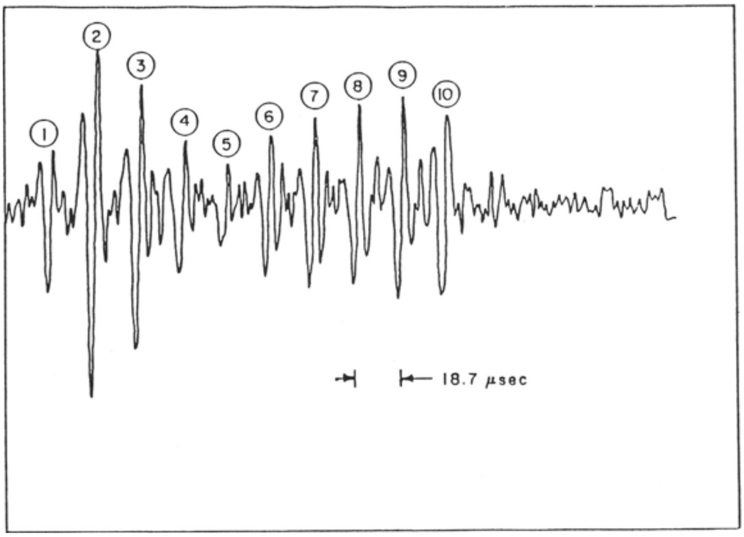

Fig. 5. A digitally filtered version of the acoustic signal shown in Fig. 4, containing only those frequency components lying within the spikes in the Fourier transform.

DISCUSSION

Although bandwidth narrowing of acoustic signals resulting from trains of optical pulses has been demonstrated clearly in the Q-switching experiment discussed above, there are several significant issues which must be considered before these results can be generalized for all cases of laser generation and detection. Many of these issues are related to the interaction of the laser beam with the specimen surface. For example, in the case of thermoelastic generation, it is not clear whether repeated high-frequency excitation of a single point will in fact result in a superposition of the acoustic signals which would have been generated by a single pulse. Changes in material reflectivity and thermal conductivity with increasing temperature have yet to be incorporated into current models for thermoelastic generation of acoustic waves. Other issues arise if one wishes to operate in an ablative or near-ablative regime where a plasma forms as a result of laser interaction with the surface. Issues of plasma decay time, plasma shielding and changes in surface morphology must be addressed. Surface roughness, especially in cases where thermoacoustic arrays are to be generated using patterned illumination, clearly plays a key role in the efficiency with which directed acoustic energy can be generated.

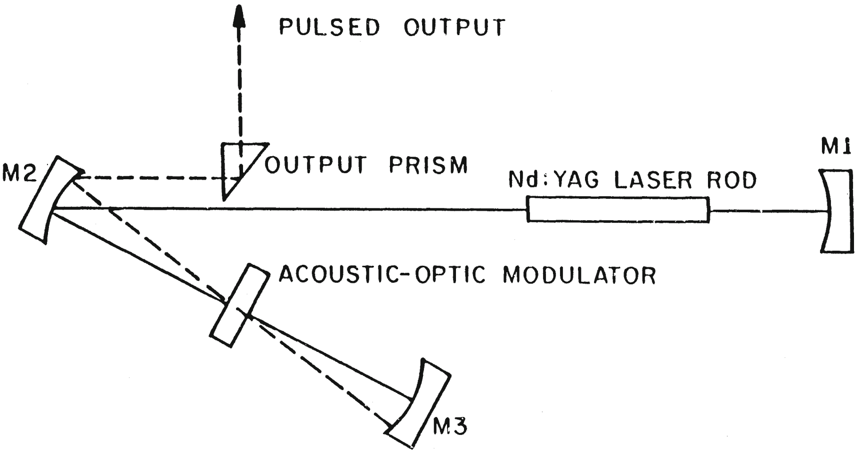

Fig. 6. Schematic arrangement of the cavity dumped Nd:YAG laser. All mirrors are coated for maximum reflectivity. Light pulses are coupled out via the prism each time a drive pulse activates the acousto-optic modulator.

CONCLUSIONS

The use of pulse packets rather than single pulses from lasers to generate ultrasonic signals offers the potential of improving signal-to-noise ratio and thus the sensitivity of laser ultrasonic systems. While some enhancements in signal may be obtained by generating directed ultrasound, experimental results have shown it is possible to reduce noise by frequency bandwidth narrowing. Work is continuing using higher frequency laser modulation schemes to produce both narrow band and directed laser generated acoustic signals.

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