

Thermal Acousto-Optic Excitation for Non-Contacting NDE

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ABSTRACT

This paper[†] describes experiments designed to generate acoustic waves by using a laser pulse, transmitted through fiber optics, to thermally shock the surface of a steel specimen. The purpose of this effort was to explore the non-contacting generation of Rayleigh surface waves appropriate to the interrogation of structures for the detection of subcritical defects.

INTRODUCTION

The goal of the engineering research program on Thermal Acousto-Optic (TAO) nondestructive evaluation is to explore the synthesis of fiber optics/high power laser excitation systems with sophisticated coherent optical and thermal imaging techniques to inspect, detect, and characterize internal structural defects in normally inaccessible components. This technique will generate thermal acoustic (mechanical) waves by guiding high energy laser pulses through a remotely controlled fiber optic probe to an appropriate (possibly interior) location on the test structure where the output is focused onto a surface. The resulting thermal shocks generate both acoustic (mechanical) and thermal (temperature) waves which interrogate the structure. After interacting with a defect the modified responses can be monitored by standard acoustic wave or thermal transient detection techniques.

It is intended that TAO-NDE be a flaw-detection technique with the capacity, through the use of flexible fiber optics, of reaching and interrogating otherwise inaccessible regions of a structure. In addition, it will utilize one means of excitation, focused high energy laser pulses, to generate two types of signals with different propagation characteristics, one of them acoustic and the other thermal, which can be detected and evaluated separately. Finally, since TAO-NDE will not require the mechanical coupling of an excitation transducer to the surface of the test structure, it will have a significant advantage over traditional piezoelectric transducer based ultra-sonic excitation techniques which can be very difficult to apply to structures with complex surface geometries. Consequently, it is anticipated that the TAO-NDE technique, if successful, would be of great value in the inspection of many structures where conventional methods of excitation are not appropriate, such as aircraft engines, nuclear reactor pressure vessels, pipelines and similar enclosed assemblies with limited access.

OBJECTIVES

The primary objective of this research program was to demonstrate the feasibility of generating acoustic (mechanical, ultrasonic) waves in a metal specimen by impacting its surface with a laser pulse delivered through a flexible optical fiber element and recording the resulting Rayleigh surface wave with a standard piezoelectric Rayleigh wave transducer and wedge. The second objective was to demonstrate the detection of a "flaw" in the metal bar through the use of the above system and a standard ultrasonic piezoelectric transducer detector.

Task 1 - Generating an Acoustic Wave with a Laser Pulse

In order to establish a reference system a pitch-catch arrangement for both input and output through piezoelectric type Rayleigh wave transducers was set up as shown in Figure 1(a). Figure 1(b) shows the equivalent set-up with a direct laser-pulse input and a piezoelectric output while Figure 1(c) shows the same set up with the laser pulse input through a flexible fiber optic component. The paired piezoelectric transducer arrangement of Figure 1(a) was used extensively to characterize different trigger and recording set-ups. When the distance between the transducer faces in this setup was reduced to zero, the initial delay "between the input pulse to the sending transducer and the output pulse from the receiving transducer" was found to be 20 μ s. Consequently, for all time-of-flight measurements from the laser input to the measured pulse in the set-up of Figures 1(b) a delay of half this amount, that is 10 μ s, was subtracted from the time base on the oscilloscope screen to provide the appropriate correction to the signal. Because the delays in the optical fiber elements used in the subsequent Figure 1(c) type tests were relatively insignificant, the same 10 μ s time base correction was used there also.

[†] This paper was prepared for presentation at the 1986 Spring Conference on Experimental Mechanics to be held in New Orleans, Louisiana on June 8-13, 1986.

All specimens were AISI 1020 steel bars (1"x1"x8") with normal "as machined" surfaces and no special surface treatments except where otherwise described. The Rayleigh wave velocity, C_R , in the steel was measured at 2.96 mm/ μ s which is reasonably approximated as $C_R = 3$ mm/ μ s for convenience.

Task 1.1 - Excitation with a Direct Laser Pulse

The first series of tests were conducted using the configuration of Figure 1(b) to explore the use of 20 ns laser pulses to generate detectable elastic waves in the steel test bar. The effects of varying the "illuminated" spot size and intensity (power) were determined by placing a beam limiting aperture and a long focal length lens in the path of the laser pulses (to converge the "beam" as shown in Figure 2). By appropriately varying the distance of the specimen and the size of the aperture it was possible to achieve a variety of input conditions and observe the corresponding responses of the piezoelectric transducer detector. Apertures of 20 mm, 5 mm and 1 mm diameter were used to vary the input power. Figure 3 shows typical signals from a selection of aperture and spot size combinations. From these results it can be seen that, within the range of power densities employed here, the wave shape depends strongly on the input spot size and rather less so on the power, with the cleanest Rayleigh wave shape appearing when the illuminated spot was around 1 mm in diameter.

In all cases the input conditions were in the thermoelastic range, i.e. all effects were caused by thermoelastic phenomena rather than so-called plasma phenomenon where ablations, melting and so forth occur at the point of "laser impact."

Task 1.2 - Excitation through a Flexible Optical Fiber Element

With the conditions for generating clean Rayleigh waves established, a second series of tests were conducted to explore the use of fiber optic components to deliver laser pulses appropriate to the generation of comparable quality waves. Using the configuration shown in Figure 4, both single optical fibers and flexible optical fiber bundles were evaluated. Again, the target surface was the shiny, "as machined" surface on the same steel bar specimen used in all the previous tests.

Coupling the laser pulse into the fibers was accomplished through a specially built device as shown in Figure 5. This device consisted of a plano-concave collimating lens (or a plane quartz window) at the input end which directed the incoming pulse onto the end of the fiber optic bundle (or single optical fiber) through a cell which could be filled with an index matching fluid. Both Cargille Laboratories Code 50350 immersion liquid and pure olive oil were used successfully. This fluid cell was made large enough that the absorbed energy from the laser pulses did not heat the fluid excessively.

Figure 6(a) shows the results recorded with the set-up of Figure 4. Here the laser pulse was launched into and guided through a 2 mm diameter fiber optic bundle with its output focused through an output lens onto a 1 mm diameter spot on the surface of the specimen. It can be seen in this trace that the quality of the resulting wave was quite good. When the surface of the specimen was artificially blackened in an effort to enhance coupling energy into the metal and increase amplitude, the wave-shape changed to that shown in Figure 6(b). In this case the phenomena that generate the elastic wave were no longer purely thermo-elastic but included impact from the ablation of the surface coating, with an obviously less satisfactory result.

Finally, the fundamental transmission efficiency of a fiber optic bundle is lower than that of a single low-loss optical fiber. Coupling into a fiber optic bundle with 2 mm diameter is, however, easier than coupling into the core of a single optical fiber. Consequently, only if the laser pulse is very accurately focused onto the core of the single optical fiber will the greater overall efficiency of a single optical fiber be realized. In such a situation longer lengths of a smaller diameter, more flexible single optical fiber can be used, which is highly desirable in applications to remote inspection. In order to test the feasibility of using a single moderately low-loss multimode optical fiber to transmit the laser pulses the set-up of Figure 4 and coupler of Figure 5 were modified for coupling to a 0.5 mm diameter optical fiber with a single 200 μ m core. Since the numerical aperture of the optical fiber was around 0.25 at the operating wavelength, no output lens was used focus the illumination from the optical fiber onto the metal specimen. A spot size of 1 mm was easily achieved at a reasonable (~ 2 mm) stand-off distance between an approximately symbol the optical fiber tip and specimen surface.

While it worked well with a CW laser beam, this system could not provide consistently accurate coupling of the pulsed ruby laser output even into the optical fiber with the much larger 200 μ m diameter core. Consequently, the system was significantly less efficient than it might have been. As a result, it generated Rayleigh waves of much smaller amplitude than those seen in the previous tests with the fiber optic bundle. Interestingly, at the high gains used in the process of measuring the shapes of these much weaker waves it was found that the Lucite wedge of the ultrasonic transducer passed light scattered from the vicinity of the impact point to the piezoelectric transducer. This light somehow excited the crystal itself, thereby creating "noise" in the oscilloscope trace during the initial few microseconds after the laser was triggered. Figure 7(a) shows this noise and also suggests that, under certain circumstances, this effect can distort the Rayleigh wave signal. When the transducer was optically screened from the light both the initial noise and the apparent distortions disappeared and a clean signal was obtained as shown in Figure 7(b). Note that the vertical scale on these figures is 100 times more sensitive than in Figure 6. The low level noise still present in the first 6 μ s of Figure 7(b) is from electromagnetic interference caused by the discharge processes of the pulse laser itself. For Figure 7(c) the experimental set-up was exactly the same as for Figures 7(a) & (b) except that the light pulse from the laser was interrupted before striking the specimen. There is no sign of an elastic wave but the electromagnetic interference is still present. This interference was not found to be bothersome in subsequent work and no effort was made to screen the detector system from electromagnetic interference emanating from the laser and its associated electronics.

At full power the focused laser pulse could easily damage the input end of the optical fiber. To prevent such an occurrence, attenuation plates of clear glass were inserted between the laser and the focusing lens. In this way the effective power launched into the optical fiber and eventually reaching the specimen was easily controlled by adding or subtracting plates. Finally, while the present tests demonstrate that both optical fiber bundles and single optical fibers can be used, the problem of achieving an efficient coupling into the core of the single optical fiber must be solved if the advantages of such single optical fiber systems are to be realized. In the absence of such an optimized coupling technique the flexible fiber optic bundle with an appropriately focussed output clearly provides the most practical means of delivering high intensity pulses of laser light to the impact point.

Task 1.3 - Evaluating the Interaction Between an Optically Generated Rayleigh Wave and a Defect

In order to test the capacity of waves generated by a laser pulse transmitted through a flexible optical fiber bundle to interrogate metal components for defects, 1"x1"x8" steel bar specimens with artificially produced surface "flaws" were tested. These specimens are shown in Figure 8 and the results are shown in the sequence of photographs of Figure 9.

Figure 9(a) shows the reference signal for the test depicted in Figure 8(a) but with the specimen positioned so that there is no "flaw" between the input and readout points. In contrast, the result when there is a "flaw" between the impact point and the transducer is shown in Figure 9(b). This trace displays the classical double wave response associated with the interaction between a Rayleigh wave and a shallow notch.

Finally, the ability of a wave generated from a much lower intensity laser pulse output from a single fiber to interrogate a test bar with a shallow surface slit, Figure 8(c), is demonstrated as the trace shown in Figure 9(c). Once again, the trace is as expected for the transmitted Rayleigh wave after interacting with a slanting surface "crack."

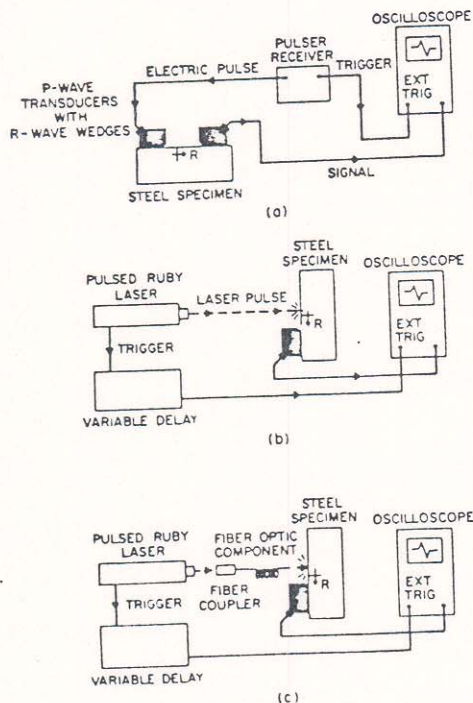


Figure 1. Diagram of Piezoelectric Transducer and Rayleigh wedge Calibration for Ultrasonic Wave Detection System: (a) with a Piezoelectric Transducer and R-wedge Input (Ultrasonic Pitch - Catch Set-up) or (b) with a Direct Laser Pulse Input, or (c) with a Laser Pulse Input through an Optical Fiber Component

SUMMARY AND CONCLUSIONS

The present study has demonstrated the feasibility of using 20 ns laser pulses transmitted through flexible optical fiber elements to excite acoustic waves in a metal specimen, and that such waves may be used to detect flaws in much the same way such waves are used to detect flaws in the standard ultra sound technique. Further work will address the use of real-time IR imaging techniques to sense the accompanying thermal transient, with the ultimate objective being the realization of a flexible fiber optic system for exciting metal structures for interrogation by complementary acoustic and thermal wave techniques.

ACKNOWLEDGEMENTS

The authors wish to thank Iowa State University, AT&T Bell Laboratories, The University of Alabama at Huntsville and the U.S. Army Research Office under grants DAAG 29-85-K-0178 and DAAG 29-84-K-0183 for their support of this effort.

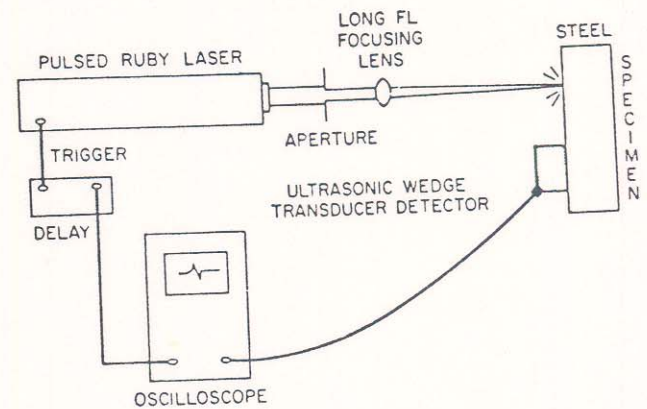


Figure 2. Diagram of the System used to Vary the Illumination Spot Size and the Power of the Laser Pulse.

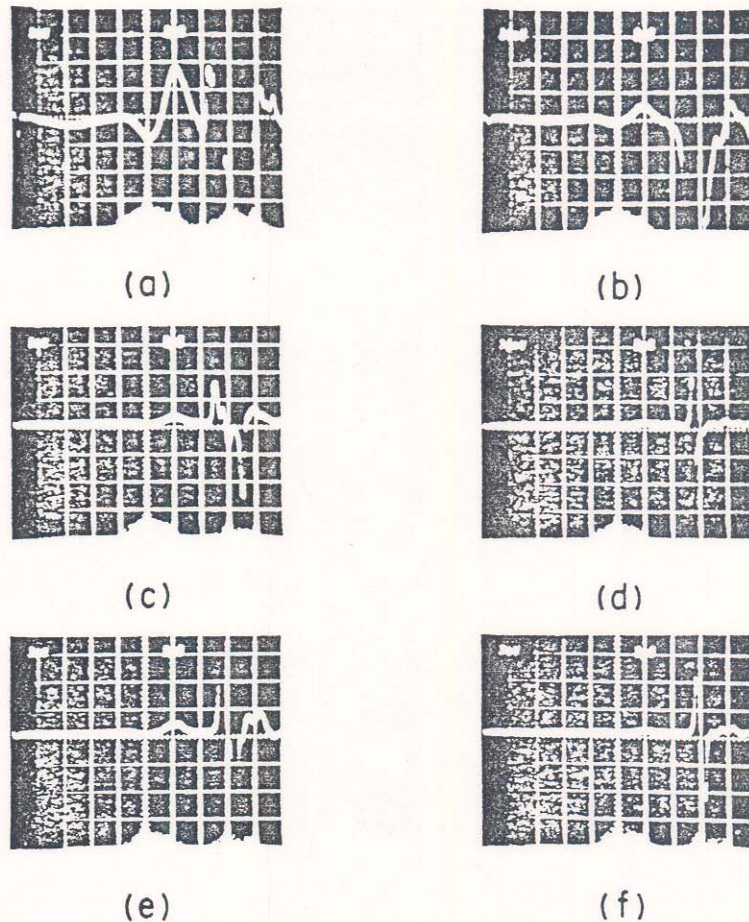


Figure 3. Oscilloscope Traces Showing the Rayleigh wave Response at $2 \mu\text{s/div.}$ from the Piezoelectric Transducer/Detector for a Laser Pulse Transmitted through a: (a) 20 mm aperture to a 5 mm diameter spot (with a Sensitivity of 5 mV/div.), or a (b) 20 mm aperture to a 1 mm diameter spot (with a Sensitivity of 20 mV/div.), or a (c) 5 mm aperture to a 5 mm diameter spot (with a Sensitivity of 5 mV/div.), or a (d) 5 mm aperture to a 1 mm diameter spot (with a Sensitivity of 20 mV/div.), or a (e) 5 mm aperture to a 2.5 mm diameter spot (with a Sensitivity of 2 mV/div.), or a (f) 1 mm aperture to a 1 mm diameter spot (with a Sensitivity of 2 mV/div.).

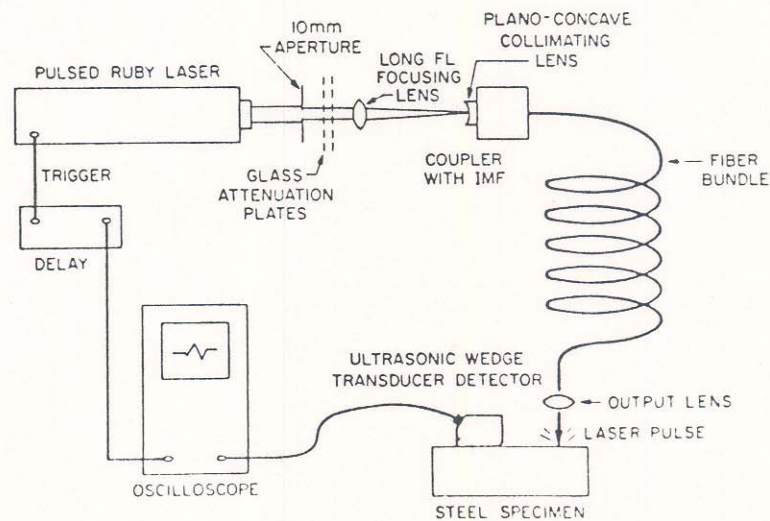


Figure 4. Schematic Diagram of the System Used to Transmit a 20 ns Laser Pulse through an Optical Fiber Bundle to the Steel Bar Specimen and to Detect the Resulting Acoustic Wave in the Specimen.

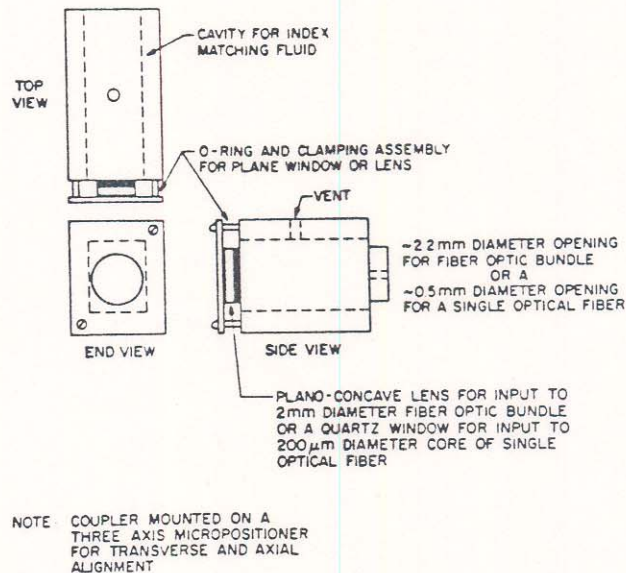


Figure 5. Detail of the Coupler Used in Figure 4.

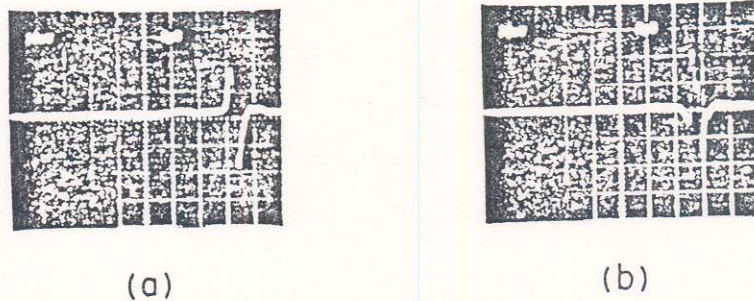
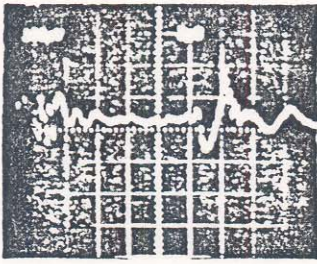
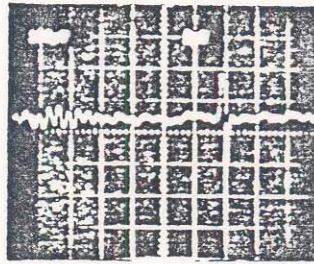


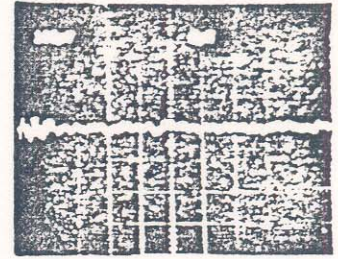
Figure 6. Oscilloscope Traces Showing the Response at 2μ S/div. from the Piezoelectric Transducer/Detector with the Specimen Excited by Laser Pulses Transmitted Through a Fiber Optic Bundle and Focused to a 1 mm Diameter Spot. (a) on a Shiny, As-machined Surface (with a Sensitivity of 10 mV/div.) and (b) on the Same Surface Painted Black (with a Sensitivity of 20 mV/div.).



(a)

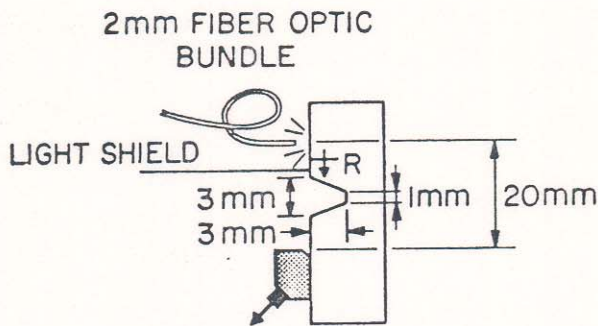


(b)

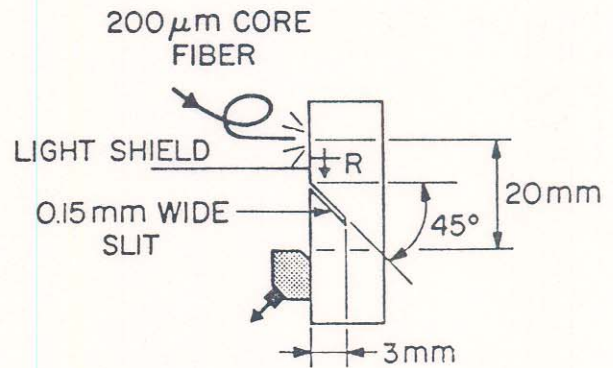


(c)

Figure 7. Oscilloscope Traces Showing the Response (with a Sensitivity of 100 mV/div. at $2 \mu\text{S}/\text{div.}$) from the Detector Circuit with Noise Preceding the Arrival of the Rayleigh wave at the Piezoelectric Transducer Recorded Using the Set-up Shown in Figure 4 with a Single Optical Fiber in place of the Optical Fiber Bundle and No Output Lens: (a) without the Light Screens, (b) with the Light Screens, and (c) with the Light Screens and Blocked Output from Fiber (No Acoustic Wave is Generated).



(a)

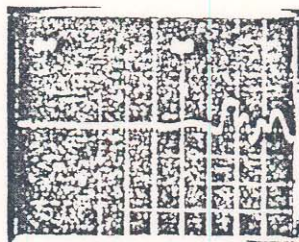


(b)

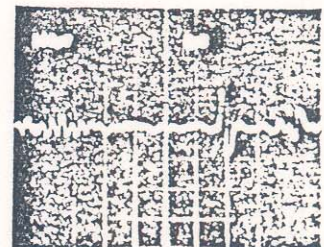
Figure 8. Diagram Showing Steel Bar Specimens with Simulated "Flaws" for Tests with the Laser Pulses Transmitted through: (a) a 2 mm Diameter Fiber Optic Bundle and (b) a Single Fiber with a 200 μm Core Diameter.



(a)



(b)



(c)

Figure 9. Oscilloscope Traces (at $2 \mu\text{S}/\text{div.}$) Showing the Effects of the Interactions Between the Rayleigh wave and Steel Bar Specimens with: (a) the Fiber Optic Bundle and No "Flaw" (with a Sensitivity of 2 mV/div.), or (b) the Fiber Optic Bundle and a V-Notch "Flaw" (with a Sensitivity of 2 mV/div.), or (c) the Single Optical Fiber and a Slanting Slit "Flaw" (with a Sensitivity of 100 mV/div.).