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TITLE: MICROSHELL®-TIPPED OPTICAL FIBERS AS SENSORS OF HIGH-PRESSURE PULSES IN ADVERSE ENVIRONMENTS

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Microshell®-tipped optical fibers as sensors of high-pressure pulses in Adverse Environments

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Abstract

We have developed and used an optical-fiber sensor for detecting the arrival of strong pressure pulses. The sensor consists of an optical fiber, tipped with a gas-filled microballoon. They have been used successfully in adverse environments including explosives, ballistics and electromagnetic pulses (EMP). The sensor produces a bright optical pulse caused by the rapid shock-heating of a gas, typically argon or xenon, which is confined in the spherical glass or plastic microballoon. The light pulse is transmitted via the optical fiber to a photo detector, usually a streak camera or photomultiplier tube.

The microballoon optical sensor (called an optical "pin" by analogy to standard electrical "pins"), was originally developed for diagnosing an explosive, pulsed-power generator. Optical pins are required due to the EMP. The optical pins are economical arrival-time indicators because many channels can be recorded by one streak camera.

The generator tests and related experiments, involving projectile velocities and detonation velocities of several kilometers per/sec have demonstrated the usefulness of the sensors in explosives and ballistics applications. We have also measured the sensitivity of the optical pins to slowly-moving projectiles and found that a 200 m/sec projectile impacting the microballoon sensor produces a flash having a risetime less than 100 ns and a pulse duration (FWHM) of less than 300 ns.

The technical and cost advantages of this optical pin make it potentially useful for many electromagnetic, explosive, and ballistics applications.

Introduction

We describe an optical fiber sensor that reliably detects a high-pressure pulse in a harsh electromagnetic environment. The "Microshell®[1] optical pin"[2] also functions well in a number of other adverse environments, including ballistics and explosives experiments. We initially developed this pin for diagnosing explosive pulse-power devices, where it has been extremely successful. In addition, other experiments that we report here indicate how it can be used for other high-pressure applications.

We first describe how the pin converts a high-pressure pulse into a pulse of visible light. Then we discuss how the pins are fabricated and deployed in an array. We then describe three experiments where the pins have been successfully used and we show the results from experiments with: (1) explosively-driven pulse-power, (2) explosives, and (3) direct impact by a projectile. Finally, we consider the technical and economic advantages of this pin as compared to other detection schemes.

Principle of operation

The Microshell® optical pin, shown in Fig. 1, is a simple sensor that converts a high-pressure pulse into an optical pulse. The pin functions as a microscopic "flash gap."[3] A flash gap is a confined volume of gas that rapidly shock-heats under impulsive pressure loading. The shock-heated gas produces a bright flash. The gas in a conventional flash gap is typically confined in a volume 0.1 mm thick by tens of centimeters in lateral dimensions. The duration of the flash is less than the time required for the shock to traverse the gap's thickness due to the rapid heating caused by reverberating shock waves. A flash gap's information is usually detected by a streak or framing camera via a lens-imaging system, although some researchers are using optical fiber links.

Leave space for Figure 1 and its captions.

By contrast, the gas in the Microshell® optical pin is confined in a spherical, transparent Microshell®, typically 200 μm diameter, which is a far smaller volume than a conventional flash gap. Since the Microshell® is so small, it is used in remote places of a target assembly with minimal intrusion, whereas conventional flash gaps are quite bulky. Argon is the usual fill gas because of its high luminosity with shock-heating. Increased luminosity is attained by filling the Microshell® to higher pressure, up to an optimum pressure which has yet to be determined. An earlier attempt to entrap gas at the tip of an optical fiber without using a pre-loaded gas vessel did produce a flash gap,[4] but the apparatus was too costly to use routinely.

The pin's principle of operation is the same as that of a conventional flash gap: When a shock wave or projectile impacts the argon-filled, transparent Microshell®, the induced pressure pulse causes the entrapped argon to become shock-heated. Reverberating shock waves in the confined argon heat the argon, causing a pulse of optical radiation. The optical pulse is significantly less duration than the transit of the shock wave through the gas volume. This optical pulse is a time-of-arrival sensor. The optical pulse is transmitted via the attached optical fiber to a photo detector. The Microshell® is destroyed in the process of producing the optical pulse since the pressures involved are quite high (above a few kilobars).

Measurements show that the optical signal level varies with the impact velocity as expected from simple, ideal-gas equation-of-state considerations. By assuming blackbody radiation from the gas, we estimate the light output.[5] For velocities greater than ~8 × 10^4 cm/sec, the signal can be recorded on a photodiode or streak camera if the optical fiber link is not excessively long and the Microshell®-optical fiber coupling is good. For lower velocities a detection system with optical gain, such as a photomultiplier or intensified streak camera, will be required. However, the threshold velocity at which optical gain is needed depends on other factors. For example, xenon produces brighter flashes than does argon. (Xenon is generally not used because it is more expensive and difficult to diffuse into Microshells®.) The brightness is also a function of the gas fill pressure.

Fabrication

The Microshell® is a small, transparent, spherical shell made of glass or plastic. The technology for fabricating and characterizing these shells has evolved as part of the world-wide effort to produce inertially confined fusion since such shells are used as the targets containing fusionable fuel. A pin usually uses a Microshell® about 200 μm diameter but smaller ones have been tested. The dimensional tolerance of the Microshell® for optical pin application is far less exacting than for fusion applications. Thus optical pins use Microshells® which are less expensive than fusion targets since the selection and quality control processes are less rigorous.

The gas-filling is done by diffusion.[6] Diffusive filling requires a batch of Microshells® to be heated in a pressurized canister of the filling gas, usually argon. The heating enhances the diffusion. Then cooling to room temperature causes the argon to be entrapped in the Microshell®. The diffusion filling works especially well for plastic Microshells®.

The argon-filled Microshell® is glued onto the tip of an optical fiber using an index-matching adhesive to maximize the optical coupling. The fiber's tip is polished or cleaved before the Microshell® is glued on. Since the Microshell® is transparent, one may illuminate the Microshell® while checking at the photo-detector end of the optical fiber to test the optical coupling.

When the gas flashes in response to a pressure pulse, the induced optical pulse is transmitted to a photo-detector via the optical fiber. A streak camera is the preferred photo-detector due to its multi-channel capability. Other photo-detectors such as photomultipliers or photodiodes are also suitable. As shown in Fig. 1, shielding is needed to protect the Microshell® and to prevent light from reaching the optical fiber. Typical shielding materials are metal tubing, shrinkable tubing, and metal foil.

In a typical application, we use an array of pins to measure the dynamic deformation of the object under study. Pins are placed throughout the object. Since the pins are so small, they do not perturb the event significantly. As each pin is impacted, it reports time-of-arrival datum. These data provide a time-resolved profile of the pressure pulse traversing the sample.

Applications

The initial application for these pins was to diagnose an explosive, pulse-power source, known as a magnetic flux compression generator. This device works by using the chemical energy of an explosive to compress a magnetic field in order to amplify an electrical current. Thus a probe diagnosing this device is subjected to a harsh electromagnetic and explosive environment as well as undesirable weather elements. One design under study has a coaxial geometry, shown in figure 2, in which the cylindrical "armature" is explosively driven against the conical "stator", thereby compressing the magnetic flux trapped between the two surfaces. We used the pins to examine the hydrodynamics of the armature-stator collision. The pins were imbedded in the wall of the copper stator, an inert material. When the armature collides with the stator, the induced shock wave in the stator causes the pins to flash. Figure 3 shows a streak record of a typical event. We obtained similar streak records on the other three events of the series of four generator tests. Further details and results are described in a paper elsewhere in the Proceedings.[7]

Leave space for figures 2 and 3.

The Microshell® optical pins have been used to measure the detonation speed in small cylinders of PETN high-explosive. Here the pins function in an explosives environment. Figure 4 shows four optical pins imbedded in the wall of an acrylic plastic container. The explosive is ignited through a glass window on one end of the cylinder. As the detonation front passes the optical pins, they "flash." The four optical fibers are multiplexed onto an EG&G Model FND 100 photodiode, and Fig. 5 shows the oscilloscope record of the output pulses. This detonation event was relatively slow moving at 4×10^5 cm/sec as measured by the shock arrival times at the four optical pin locations (separated by about 1 mm). The optical signal rise-time and full-width at half maximum are a function of the shock speed and for this speed the FWHM's were below 10 nanoseconds.

Leave space for figures 4 and 5.

Another optical pin experiment examined direct projectile impact. Figure 6 shows a schematic of an experiment where a flat-nosed, "BB" pellet accelerated by an air rifle is impacted on an optical pin which is mounted flush with the surface of an aluminum plate. The BB speed is only about 200 m/sec, and traverses the 200 μm diameter Microshell® in 1 μsec. The optical pulse recorded by a RCA 8644 photomultiplier, however had a rise-time of ~0.08 μsec and a pulse width of less than 300 nsec. The short risetime and pulse width relative to the shock transit time suggests that the optical pulse is due to a multiple-shock excitation. This test was performed at a projectile velocity that is relatively slow compared with many ballistics' applications. For high velocities, the pin's optical signal will be brighter and shorter duration.

Leave space for figure 6.

Advantages

The Microshell® optical pin has several advantages when compared with electrical pins. First, in pulse-power environments, optical pins are immune to electromagnetic noise that would overwhelm electrical pins. Second, optical pins are completely passive, whereas electrical pins are energized with a bias voltage. Thus optical pins are better suited for electrically sensitive environments such as explosives where an electrical arc could have undesirable effects. In addition, the Microshell® optical pin has a significant economic advantage when compared with electrical pins. Optical data is less expensive to transmit and record than is electrical data. For example, the cost of a streak camera capable of simultaneously recording about 100 channels of optical data with subnanosecond resolution is only a few hundred dollars per channel, which is significantly less than 100 channels of an electrical recording. The cost of maintaining and operating a single streak camera is also less than that for several dozen oscilloscopes or fast digitizers.

Conclusion

The Microshell® optical pin is a useful probe for detecting strong pressure pulses in adverse environments due to pulse-power generators (electromagnetic noise), explosives and ballistics. The pin is being used at Los Alamos routinely to study the hydrodynamics of explosive, pulse-power generators. The pin is a simple and economical probe for diagnosing a wide range of phenomena involving dynamic deformations.

Acknowledgements

We are grateful to Bob Caird, Jim Goforth, and Denny Erickson for early discussions and encouragement about developing this probe. We acknowledge the technical assistance of Vivian Gurule, Clint Findley, and Connie Gomez at Los Alamos, and Diana Schroen, Nancy Schmerberg, Paul Anderson, Dennis Cielaszyk, and Matt Ebner at KMS Fusion. The early development of the pin, the co-axial generator application and some of the ballistics tests were carried out at the Los Alamos National Laboratory under the auspices of the U. S. Department of Energy.

References

1. Sometimes referred to as "microballoons," the Microshell® is a registered trademark of KMS Fusion, Inc.

2. Robert F. Benjamin, Patent Application DOE Docket Number S-59, 360, "Optical Pin Using a Microballoon Flash-Gap," filed October 1983.

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4. L. L. Shaw, R. R. Donaldson, J. R. Murchie and T. J. Ramos, SPIE Vol. 97, High Speed Photography (Toronto 1976), p. 256-262.

5. Frederick J. Mayer, KMS Fusion, Inc., Internal Memorandum FJM-146, December 7, 1983.

6. D. E. Solomon and T. M. Henderson, "Laser-Fusion Targets," J. Phys. D: Appl. Phys. 8, L85-L86 (1975).

7. Results of the pulsed power experiments are discussed elsewhere in these proceedings in the paper, "Application of Optical-Fiber Pins to Explosive, Pulse-Power Generators." by R. S. Caird, R. F. Benjamin, R. C. McQueen, and D. J. Erickson.

Figure captions

1. This cutaway view of a pin shows the Microshell®-tipped optical fiber and the shielding used in the pulse-power application.

2. This schematic, cross-sectional view of the co-axial magnetic flux compression generator shows the pins imbedded in the stator's wall.

3. Increasing time is toward the right in this streak record of the pins' signals from a flux-compression generator experiment. Each streak corresponds to a single pin.

4. Acrylic plastic explosive showing Microshell® optical pin fibers mounted perpendicular to the detonation direction. Detonation is laser initiated through the glass plate affixed to one end of the cylindrical container. The optical pins are mounted 100 µm below the inner cylinder wall.

5. Oscilloscope output trace from two photodiodes. The left-most pulse is a photodiode time marker coincident with laser ignition of the PETN cylindrical explosive sample. The four succeeding pulses are from the four Microshell® optical pins recording the detonation arrival at approximately 1 millimeter separations. All four fibers are multiplexed onto the face of one photodiode.

6. A schematic of the "BB" impact projectile experiment and a photomultiplier output voltage trace into a 50 Ω load.

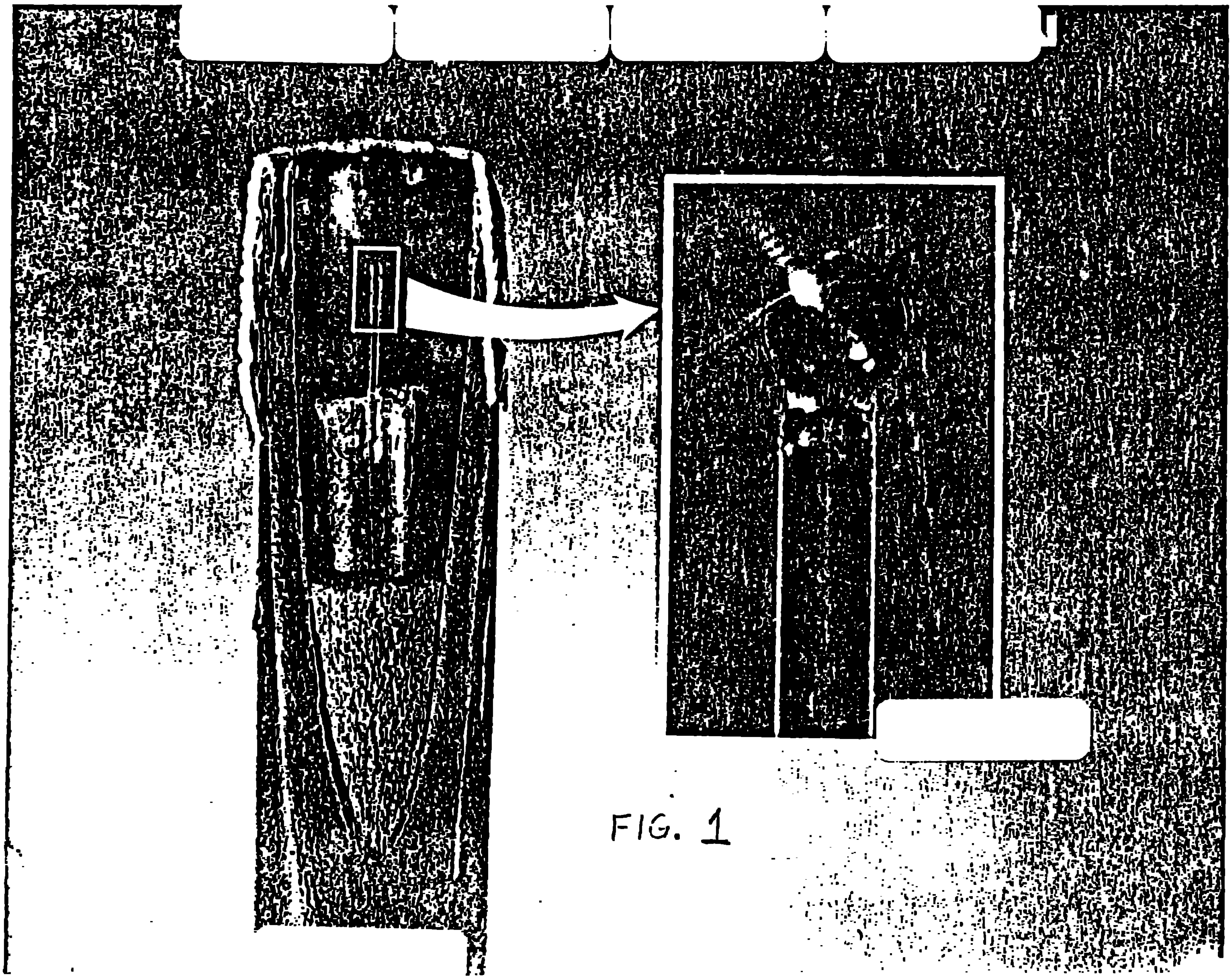

FIG. 1

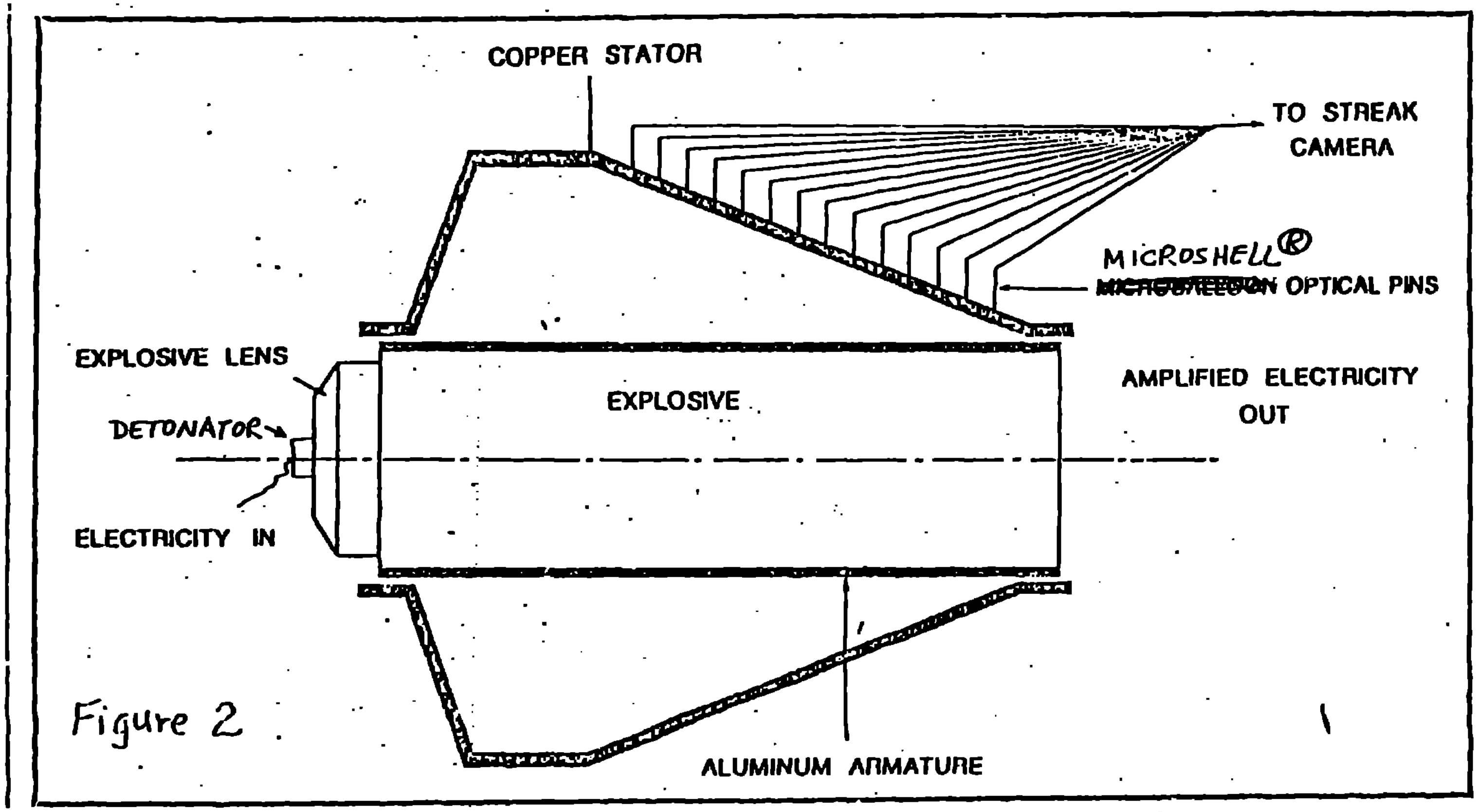
COPPER STATOR
TO STREAK CAMERA
MICROSHELL® OPTICAL PINS
EXPLOSIVE LENS
DETONATOR
EXPLOSIVE
AMPLIFIED ELECTRICITY OUT
ELECTRICITY IN
ALUMINUM ARMATURE

Figure 2

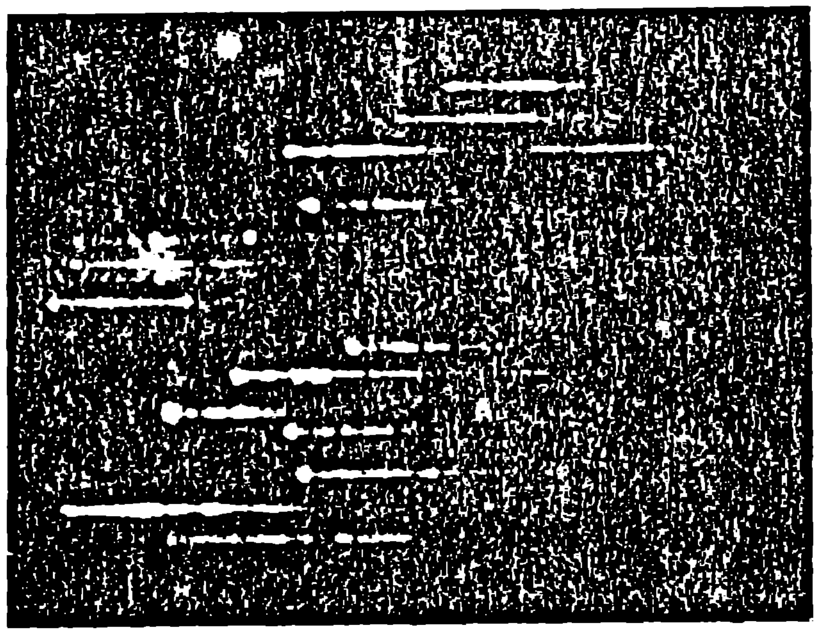

FIG 3

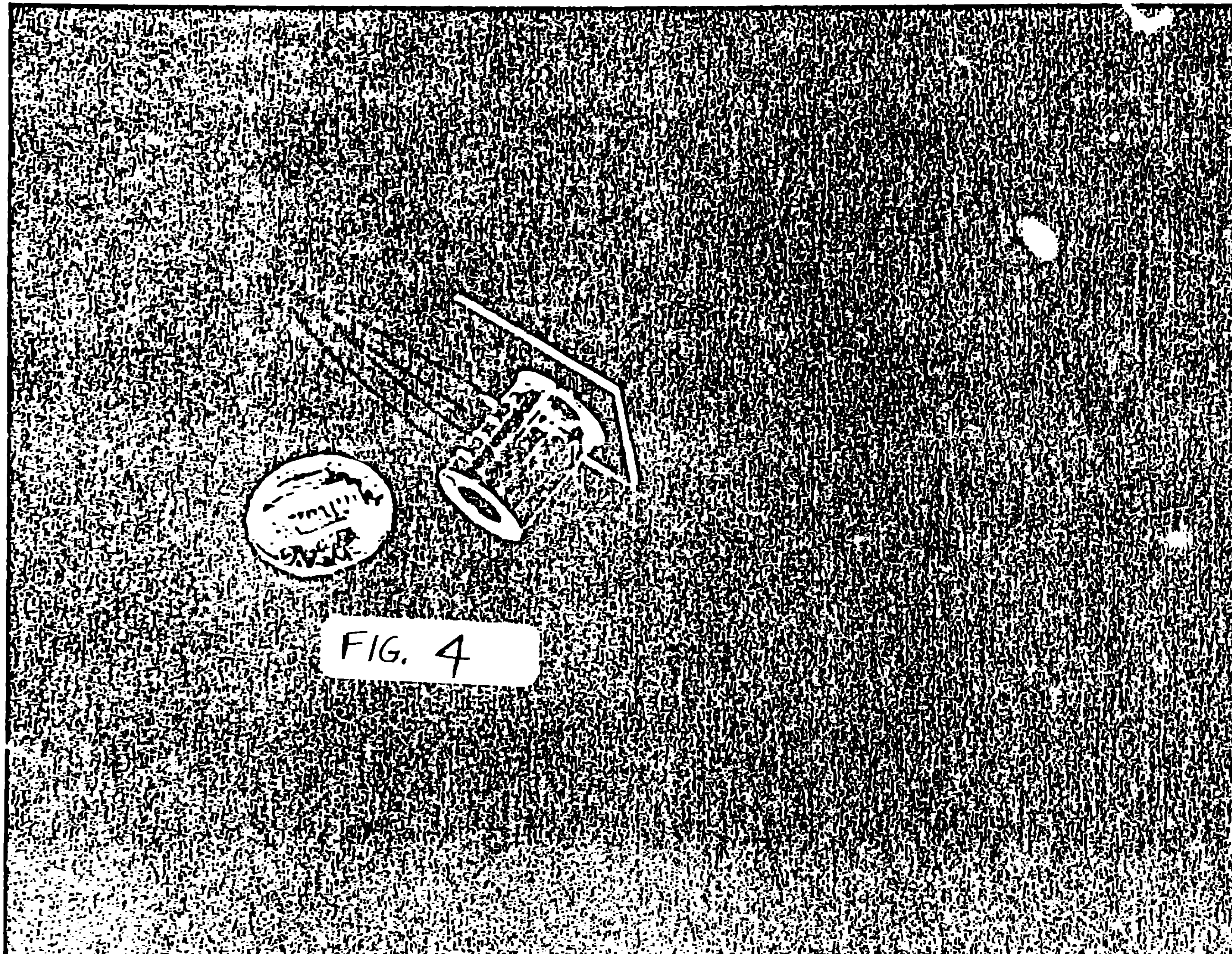

FIG. 4

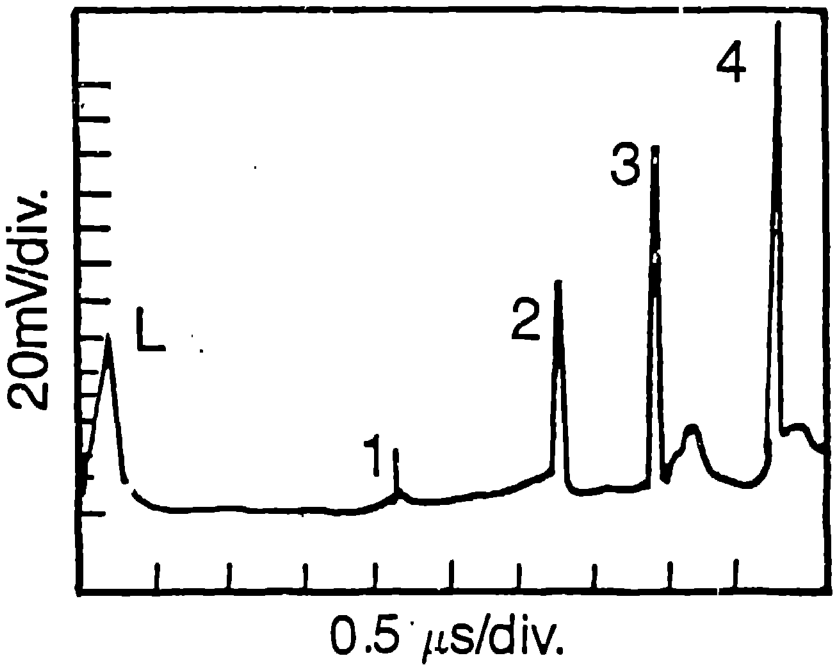

FIG. 5

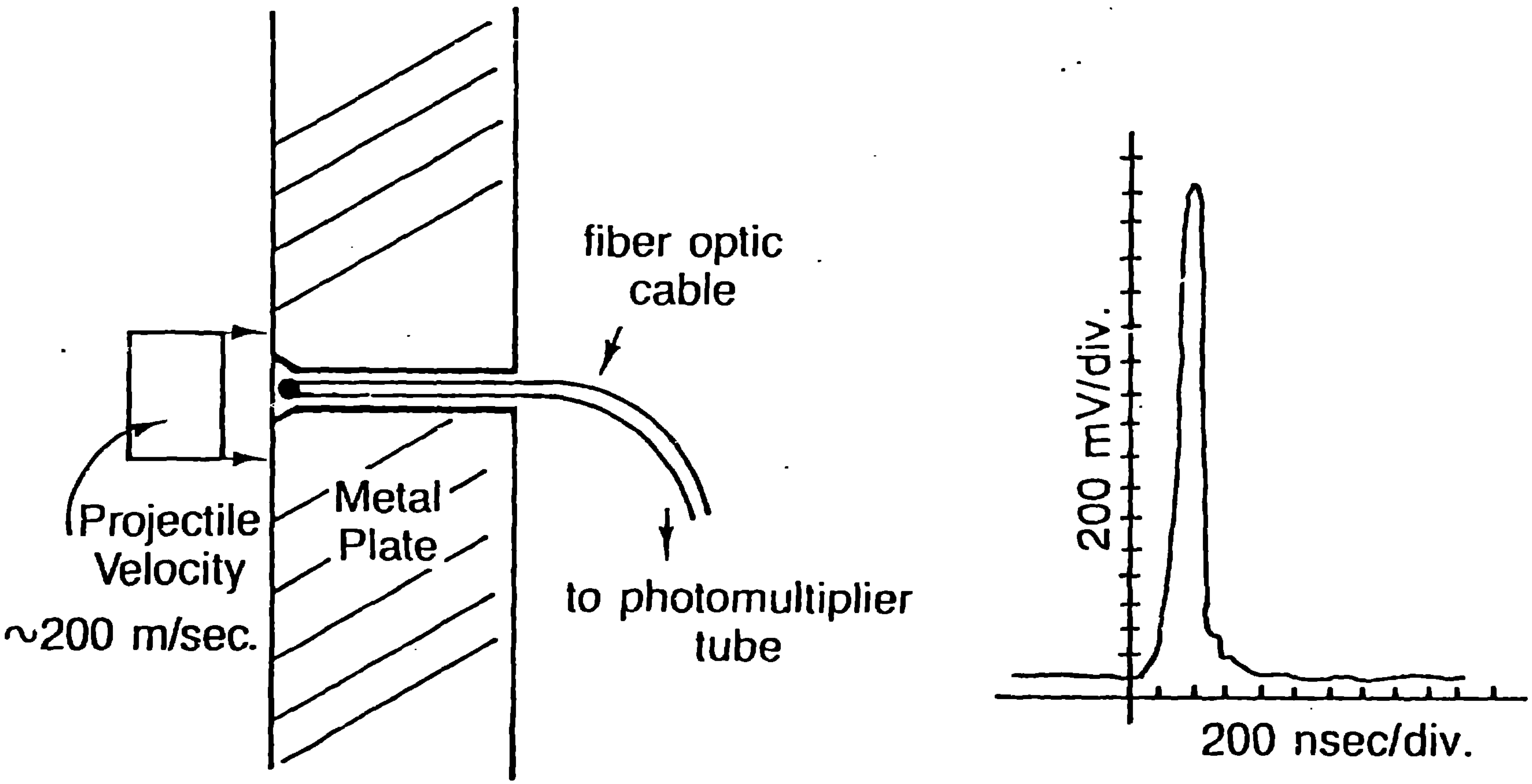
fiber optic
cable
Projectile
Velocity
~200 m/sec.
Metal
Plate
to photomultiplier
tube
200 mV/div.
200 nsec/div.

FIG. 6