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A FIBER-OPTIC TIME DOMAIN REFLECTOMETER*

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Abstract

An optical time domain reflectometer is described which combines in one instrument the basic capability to analyze several important fiber characteristics. The device uses the polarization properties of light to enable high sensitivity fault detection close to the fiber input end; its probe pulse temporal characteristics and high gain photodetector in combination provide excellent discontinuity location resolution in long lossy fibers, and give an indication of fiber dispersion at large bandwidths.

Introduction

An optical time domain reflectometer (OTDR) has been developed which can measure a combination of important optical transmission properties of fiber lightguides. The OTDR can detect faults at lengths as short as 0.4 m and, depending on fiber loss, as long as 5 km to 10 km. It can measure, without signal averaging, discontinuities in fiber with losses >65 db. Average fiber attenuation can be measured. Fiber dispersion is indicated to 5 ns resolution limit. The significant difference in this OTDR over those previously reported[1-3] is the means used to achieve high sensitivity fault detection close to the input end of the fiber.

The inherent polarization of some semiconductor lasers is used in conjunction with the isolation properties of polarizing beamsplitters to reduce the problem of large initial reflections that would saturate the analyzing photodetector.

Description

The OTDR's previously reported have a configuration similar to that shown in Figure 1.

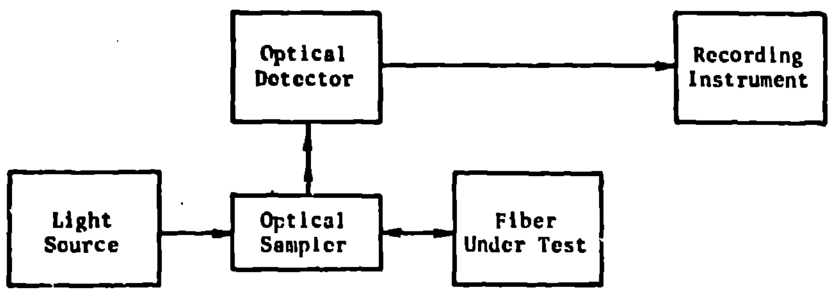

Fig. 1. Block diagram of typical optical time domain reflectometer.

An optical probe pulse is injected into the fiber to be measured. A fraction of the injected pulse is sampled by an analyzing photodetector and is displayed on an oscilloscope as a "start" pulse, or it may be used to initiate a time interval meter count sequence. The probe light injected into the fiber is partially reflected at internal discontinuities in the fiber, such as cracks, small fractures, connectors or splices, and from the extreme fiber end. The reflections are transmitted back to the input end of the fibers where they, too, are detected by the photodetector and recorded. The time interval between the start pulse and the reflection pulse indicates the location of the fault.

The probe pulse undergoes scattering continuously along the length of the fiber, producing a low-level reflected signal. The degree of this scattering is dependent on the amount of transmission loss in the fiber and is caused by scattering from microscopic inhomogeneities. Analysis of the backscatter gives a measurement of average fiber attenuation.

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Design Considerations

Two primary goals in the design of an OTDR are high sensitivity and high resolution. High sensitivity can be achieved by using a high intensity light source and a high gain detector. High resolution can be achieved by using a fast rising or short duration light source and a fast response detector.

In the present system a semiconductor GaAlAs injection laser was chosen as the probe pulse source for its high peak intensity and fast rise, short duration output. A photomultiplier detector was selected[4] over an avalanche photodiode (APD) because of its high sensitivity and large noise-free gain.

A serious problem can arise with this combination of components. Photodetector saturation can result from reflections of the initial probe pulse. These reflections are from the sampling optics, the fiber holder, and the Fresnel reflection at the fiber input. Their combined intensity can be many times greater than a discontinuity intensity. When hard saturation of the photodetector occurs, the detector can "hang up" (produce an output signal of microseconds duration from an optical input pulse of a few nanoseconds). While the detector is in saturation it is insensitive to low-level reflections from fiber discontinuities.

Several techniques have been suggested to overcome this problem. One is the use of a special gated photomultiplier which can be gated to reduce the photomultiplier gain for the duration of the initial probe pulse.[3] Another technique is the use of a Y fiber optical directional coupler,[2] wherein the probe pulse is coupled to the test fiber through a fiber pigtail. The reflected pulses are coupled back into the pigtail and to a second fiber which terminates at the photodetector and is welded to the pigtail. Using this technique the detector collects only that portion of probe pulse which is reflected from the test fiber input face. Both these techniques, and others, have been reported in the literature.

A property of some semiconductor lasers has made possible another effective method. Certain lasers, such as some RCA types, produce light that is more polarized in one direction than the other. The degree of this polarization may range from 2:1 to 7:1. Using this property in conjunction with a polarizing beamsplitter, it is possible to transmit significantly more than 50% of the laser output to the fiber input. A conventional beamsplitter, on the other hand, using either unpolarized or polarized light, will have maximum efficiency at a 50% - 50% splitting ratio.

System Technique

The system described here uses the properties of polarized lasers and beamsplitters, and other commercially available components, to achieve improved optical coupling efficiency and greatly reduced reflection of the initial probe pulse at the detector. The system, shown in Figure 2, works in the following way. The polarized probe pulse emitted by a GaAlAs injection laser is collimated by a lens, passes through a polarizing beamsplitter adjusted for maximum transmission, and is focussed by a second lens into the test fiber. The test fiber is positioned in a glass capillary tube[5] which is furnished at one end to accept it. This entry configuration reduces the possibility of damaging the cleaved fiber end. In addition the stationary capillary provides automatic positioning of the test fiber at the focus of the probe pulse. Polarization of the GaAlAs laser is in the plane of Figure 2.

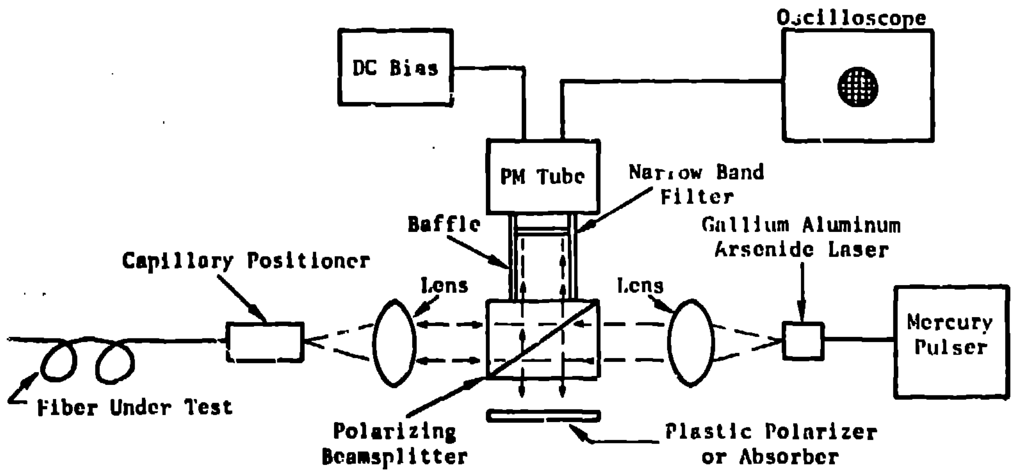

Fig. 2. Configuration of improved optical fiber analyzer system.

The polarized probe light scattered from the lens and the fiber end retains its direction of polarization. This light passes back through the beamsplitter to the laser where it is further scattered and lost. Only a small part of it is scattered sufficiently to reach the phototube, constituting the "start" pulse. This pulse triggers the oscilloscope sweep and is recorded, or it may trigger a time interval meter or similar interval measuring apparatus.

The probe pulse injected into the fiber rapidly loses its polarization due to multiple internal reflections. The discontinuity reflections coming out of the fiber are therefore principally unpolarized. As they are emitted into the beamsplitter they are separated into two polarization components, one being reflected into the phototube and recorded, and the other passing through the beamsplitter to the laser source area, where it is scattered and lost.

A polarizing element may be used at the beamsplitter surface opposite the phototube to absorb undesired laser emission of the proper polarization which leaks through the polarizing element. This further decreases unwanted light that might be scattered and detected by the phototube. The pickup of scattered light in this system is further reduced by restricting the viewing angle of the PM tube to see only the appropriate part of the face of the beamsplitting polarizer. The restriction is accomplished by coupling the phototube and beamsplitter with an opaque-wall cylinder.

Results

Minimum resolvable lengths are less than 40 cm. A typical measurement is shown in Figure 3. For fiber length less than 3 m long, as in the above case, a neutral density filter is used in front of the laser to improve the system resolution. Figure 3 indicates that the amount of detected scattered light from the initial probe pulse is only twice that of a 4% Fresnel reflection from the end of the fiber. This is quite small and leaves little room for improvement.

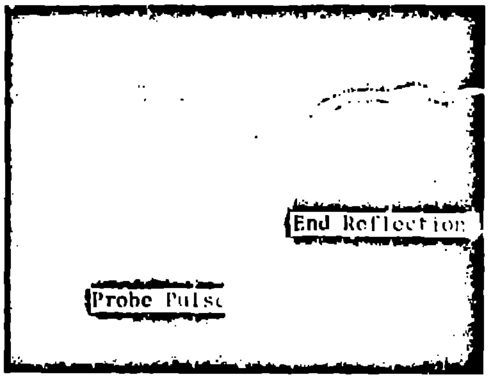

Fig. 3. Fault detection of a 60-cm-long lightguide. Filter of optical density 3.0 used at the laser output; sweep speed: 5 ns/div.

The 60-cm section used in Figure 3 was also connected (using Thomas & Betts connectors) to the end of two similarly connected 500-m sections of Corning high frequency graded-index fiber to give the reflections shown in Figures 4a and 4b.

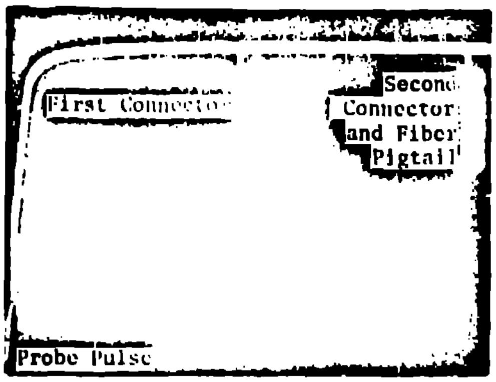

Fig. 4a. Optical reflectometry of two 500-m lengths of connectorized high frequency graded-index fiber, with 60-cm pigtail connected to second length. Sweep speed: 1 μs/div.

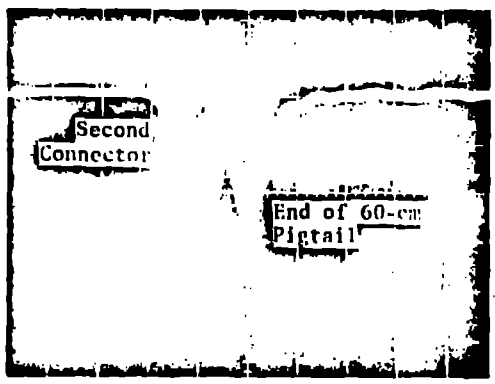

Fig. 4b. Detail of second connector and fiber pigtail at end of 1-km of fiber. Sweep speed: 5 ns/div.

In Figure 4a the first reflection is from the initial probe pulse. The second reflection is from the connector between the 500-m sections. The third reflection, which is actually two reflections not resolvable at

1 μs/div. sweep speed, is from the 60-cm fiber connector and fiber end. An expanded view of the third reflection is shown in Figure 4b at 5 ns/div. sweep speed. It shows the connector and the end of the 60-cm section, still well resolved with little pulse broadening after two-way transmission through 1 km of fiber. These particular 500-m sections had previously been radiated by a cobalt source and are very lossy, hence the greatly attenuated reflection signals from the 60-cm section.

Pulse broadening due to dispersion is an inherent fiber property that limits the potential bandwidth of information that can be transmitted through a fiber at any given wavelength. An example of pulse broadening, measured with this system at 850 nm, is shown in Figures 5a and 5b for a 500-m length of Corning step-index fiber. Figure 5a shows the initial 5-ns FWHM probe pulse injected into the fiber. After two-way transmission in the fiber the pulse is broadened to 8 ns FWHM, as shown in Figure 5b.

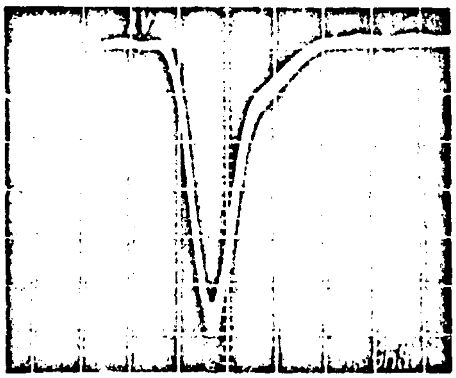

Fig. 5a. Narrow pulsewidth characteristic (5 ns FWHM) of probe pulse input to test fiber. Sweep speed: 5 ns/div.

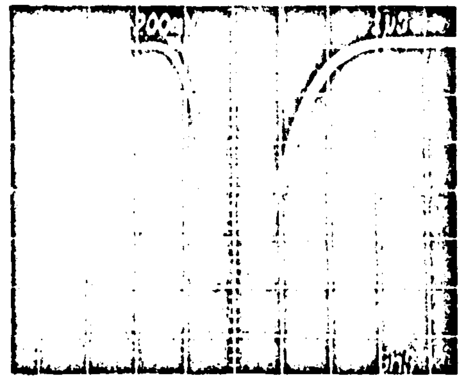

Fig. 5b. Reflected probe pulse showing width degraded to 8 ns by two-way transmission through 500-m fiber, from which fiber bandwidth is derived. Sweep speed: 5 ns/div.

Fiber Attenuation

The high probe pulse intensity plus the sensitivity and large S/N ratio of the photodetector provide quantitative data showing fiber attenuation due to Rayleigh scatter in the fiber at the probe pulse wavelength. In some fiber types, such as low-loss, only a small proportion of incident light is backscattered and the measurement is less precise.

Analysis of backscatter requires a time-continuous recording display such as provided by an oscilloscope, rather than use of a time interval meter. The technique is to adjust the oscilloscope sweep speed and gain as needed to display the test fiber backscatter characteristic, as shown in the lower trace of Figure 6a. This recording is of a 500-m step-index fiber that exhibits loss irregularities over its length. Then, with all but 10 cm of test fiber removed,* the reference probe pulse characteristic is recorded at the same oscilloscope settings, illustrated by the upper trace in Figure 6a. A semilog plot of amplitude difference between the traces at selected times produces a line whose slope enables direct calculation of average attenuation.

A typical analysis of attenuation using this technique is shown in Figure 6b, where the data plotted are from the traces of Figure 6a. The calculational technique for determining attenuation is:

$$P_2/P_1 = e^{-\alpha ct} \quad (1)$$

$$\alpha = (1/ct)\ \ln\ (P_1/P_2) \quad (2)$$

$$\alpha = (1/0.3)\ \ln\ (18/6.5) = 3.39\ \text{nepers/km}$$

$$db = 10\ \log\ e^{\alpha} \quad (3)$$

$$db = 10\ \log\ e^{3.39}$$

$$db = 14.9\ \text{db/km}$$

*The end of fiber is index matched to suppress reflections.

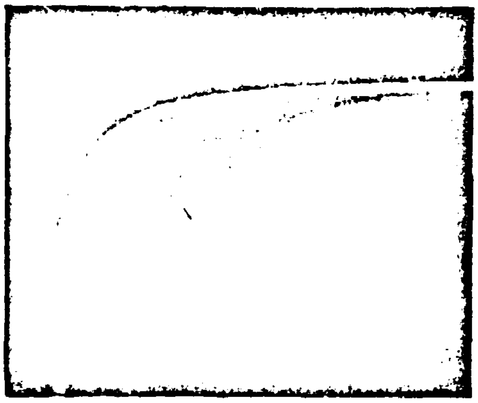

Fig. 6a. Reference (upper trace) and backscatter characteristic (lower trace) from a low-loss 500-m length of step-index fiber. Sweep speed: 0.5 μs/div.

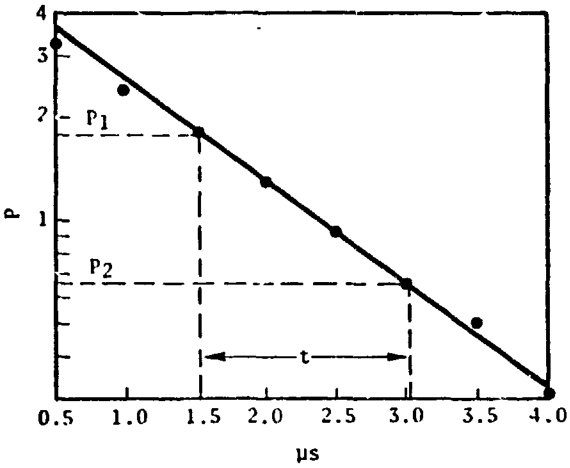

Fig. 6b. Fiber backscatter data plotted from curve of Figure 6a.

where

c = velocity of light in fiber

t = light transmission time through fiber

P = backscatter power

α = loss factor of fiber

In this case the average loss is determined to be 14.9 db/km at the 850-nm probe pulse wavelength, compared to a value of 12 db/km at 900 nm reported by the fiber manufacturer.

Acknowledgment

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2. "Fiber Waveguides: A Novel Technique for Investigating Attenuation Characteristics," by M.K. Barnoski and S.M. Jensen, *Appl. Optics, Vol. 15, No. 9* (September 1976).

3. "Photon Probe — An Optical Fiber Time-Domain Reflectometer," by S.D. Personick, *Bell System Technical Journal, Vol. 56, No. 3* (March 1977).

4. An RCA type C31034 photomultipler tube was used to acquire the data in this paper.

5. The capillary tube is manufactured for EG&G by Wilmad Glass Company, Buena, New Jersey.