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TITLE: IMPROVEMENTS TO A HIGH-FREQUENCY FIBER-OPTIC SYSTEM FOR PLASMA DIAGNOSTICS

MASTER

AUTHOR(S): J. W. Ogle, P. B. Lyons, L. Looney, P-14
L. Hocker, M. Nelson, P. Zagarino, T. J. Davies, EG&G/Santa Barbara
R. D. Simmons, R. Solk, B. Hopkins, EG&G/Las Vegas

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Improvements to a High-Frequency Fiber-Optic System for Plasma Diagnostics*

J.W. Ogle, P.B. Lyons, L. Looney

Los Alamos National Laboratory, P.O. Box 1663, MS 410, Los Alamos, NM 87545

L. Hocker, M.A. Nelson, P.A. Zagarino, T.J. Davies

EG&G, Inc., Santa Barbara Operations, Santa Barbara, California

and

R.D. Simmons, R. Selk, B. Hopkins

EG&G, Inc., Las Vegas Operations

A system for high-frequency recording of plasma diagnostics has previously been reported. Substantial improvements have been made in the system response, dynamic range, and calibration of the system. Plastic-clad silica fiber is used as a radiation-to-light converter using the Cerenkov process. A spectral equalizer device is used to compensate for the material dispersion in the fiber, increasing the frequency response (≈1 GHz-km) and the dynamic range (a factor of >20 over a FWHM 1 nm, 50% transmitting interference filter). The calibration system uses a pulsed injection laser diode (<100 ps FWHM) injected into the fiber at the radiation end of the fiber and detected by a microchannel plate photomultiplier tube on the recording end. The injection laser diode is triggered by a synchronous trigger delay unit, which also triggers a sampling or real time scope after as much as 10 μs delay with <50 ps jitter. The system improvements will be desribed in more detail and the utility of these components in other plasma diagnostic systems will be discussed.

Introduction

In the last few years, Los Alamos National Laboratory has been developing analog fiber optic systems for gamma and neutron diagnostic measurements at the Nevada Test Site.[1-3] The gamma diagnostics systems have been approaching 1 GHz-km system responses. The neutron systems have been spatially and temporally resolved with a time response of 80-100 MHz-km.

This paper will give an overview of the gamma-diagnostic system with the emphasis on improvements. It will address the light source, the fiber transmission line, the detection system and the calibration system. The system as reported in reference 1 was limited in dynamic range by its overall sensitivity and radiation damage to the optical converter. It was also limited in frequency response by the detector and the material dispersion in the fiber. The system sensitivity and frequency response have both been improved with the development of Spectral Equalizers[4,5] (SPEQ) and third generation microchannel plate (MCP) photomultiplier tubes (PMT).

High bandwidth analog gamma signals derived from nuclear explosions may have components greater than 1 GHz. These will exceed the recording capability of conventional coaxial systems (<400 MHz-km) and may exceed that of state-of-the-art fiber optic systems. However, if the system frequency response is known, mathematical deconvolution can lead to recovery of higher frequency components. To obtain an in-situ system response measurement a calibration system was developed which produces an impulse of light with a full-width-half-maximum (FWHM) less than 100 ps.

System Description

The system, as shown in Fig. 1, consists of an appropriate calibration source, a suitable Cerenkov converter material, optical fibers, a Spectral Equalizer, a fast photodetector and a recording system. Cerenkov light is generated whenever a charged particle traverses a transparent medium with a velocity exceeding the velocity of light in the medium. Cerenkov light is spectrally broad and shows a λ^{-3} dependence on wavelength. For a converter with n = 1.5, an electron with energy exceeding 174 keV will generate Cerenkov light. Cerenkov light is highly directional[6] (for a collimated electron beam) and this requires appropriate alignment of converter, fiber, and electron trajectory. The gamma-electron conversion may occur in the Cerenkov converter or in an external converter.

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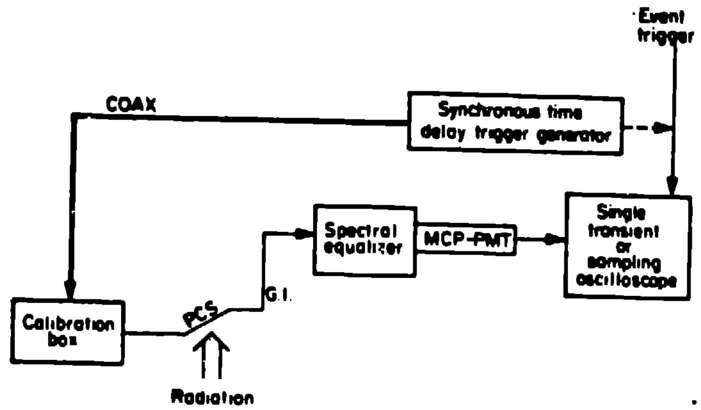

Fig. 1. Schematic of high frequency plasma diagnostic system.

Cerenkov Converter Material

In principle any transparent material can function as the Cerenkov material. In practice, the converter should not develop radiation-induced light absorption. The induced absorption of any converter must be known in order to determine if data corrections are required. Fused silica converters (actually, plastic clad silica (PCS) fibers) have been characterized and fielded. Laboratory studies have indicated that ITT PCS fiber is the most radiation resistant converter measured to this date. Studies have also shown that thermal bleaching increases the recovery rate of transient absorptions. These results are presented in ref.7. We are fielding experiments with the converter at higher temperatures (>100 °C).

Optical Fibers

Systems fielded to date have used the wavelength region from 790 nm to 840 nm, which is near the region where commercial fibers are bandwidth optimized. The bandwidth degradation caused by material dispersion in the region is corrected by spectral equalizers, which are described in Ref. 4 and 5. Siecor cables with Corning Glass fibers have been fielded. The fibers have been single window fibers with 62.5 μm core diameters. Longer wavelengths (1.2μm) would offer advantages in decreased material dispersion and optimized modal dispersion (for commercial double window fibers) and a simplified system, but suitable linear, high voltage, high bandwidth detectors are not yet available at 1.2 μm and longer wavelength.

Fibers are characterized using a Hamamatsu "Picosecond Light Source" with a FWHM <100 ps at 820 nm. The spectral FWHM is 4 nm. The light is optically coupled to a 2 m length of 62.5 μm core step index fiber for mode mixing. The step index fiber is coupled to a 2 m length of 62.5 μm core graded index fiber which is the input to SPEQ. The SPECQ consists of a linear fiber array (input and output fibers), a collimating lens and a moveable diffraction grating mounted in the Littrow configuration. The SPEQ is used as a variable narrowband filter. In this configuration only one of the output fibers is used. This fiber is a Corning Glass short-distance- fiber (SDF) with a step-like profile and a 100 μm core. This fiber is connected to the test fiber, as shown in Fig. 2. At this point the light has been well mode-mixed by the characteristics of the different fibers it has traversed and it has been spectrally limited to a FWHM =0.90 nm, thus minimizing the material dispersion contribution (=100 ps/nm-km @ 820 nm) to the bandwidth. With this configuration all modes of the graded index test fiber are excited. The signal is detected by a Varian VPM-173 MCP PMT with a FWHM = 185 ps and recorded on a computer based sampling system.

The use of a sampling oscilloscope dictates the need for a triggering system with less than 50 ps jitter between the light pulse out of the "Picosecond light source" and the delayed trigger to the sampling oscilloscope. It will be described in more detail in the calibration section. Figure 3 is a typical impulse response for 1 km of high grade Corning Glass fiber, as measured with this system.

In this system, a short length of PCS fiber is required to transfer data out of the high radiation environment. A transition to high bandwidth grade-index fiber is then required to maintain high system bandwidth. Some types of transitions (poor welded joints, for example) can introduce serious mode mixing. When such mixing occurs between a low bandwidth (high N.A.) and a high bandwidth fiber, the anticipated bandwidth of a link can be seriously degraded, even with very short PCS lengths. Carefully designed transitions do not severely mix modes and will sample only the modal volume of the PCS fiber within the N.A. of the graded fiber (typically ~0.2). With such a clean transition the PCS fiber will contribute only ~20 ps/m to the system bandwidth. Some welded PCS-graded systems have shown ~150 ps dispersion for each meter of PCS fiber; the same value observed for observation of only PCS fiber (with all modes observed) over few meter lengths. Properly welded systems have shown 20-30 ps/m disperions. To properly make this transition IT&T Cannon connectors have been used. If the PCS is installed in the ferrule with the cladding intact it is hard to achieve a satisfactory polished end. The cladding can be removed for a short distance, the core cleaned and reclad with a 5 to 10 μm thickness of optelecon recladding polymer after which procedures are followed. With this type of connector the excess loss over the geometrical loss (0.40 to 0.2 NA and 125 μm to 62.5 μm core should yield a ~12 db loss) is 1 to 2 db.

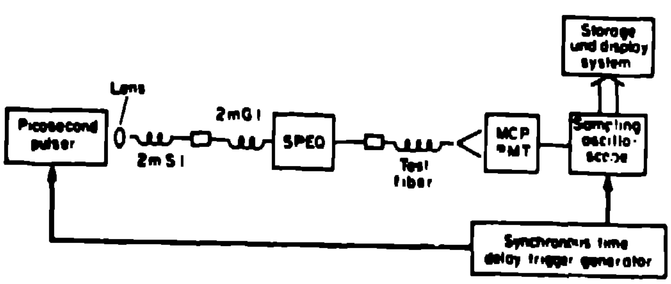

Fig. 2. Pulse response characterization system.

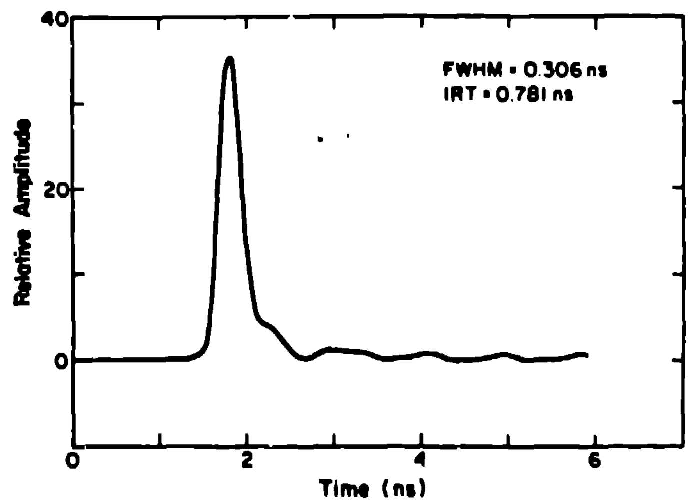

Fig. 3. Impulse response of 1.015 Km of Corning graded index fiber.

Detection System

The detection system consists of three parts: (1) a spectral equalizer (SPEQ), (2) a photodetector, and (3) a high bandwidth oscilloscope.

Spectral Equalizer

Material dispersion in the fiber broadens a spectrally wide pulse (~115 ps/nm-km @ 800 nm) making it necessary to spectrally limit the detected signal when operating in a non-zero dispersion region. One method is to use a narrow band interference filter which spectrally limits the pulse, thus preserving the modal frequency response at the expense of signal amplitude. A preferable method is to use a SPEQ to commensate for material dispersion over a larger spectral region (40 nm $< \Delta\lambda <$ 80 nm). This method, when properly implemented, detects about 30% of the available light within $\Delta\lambda$ and has an effective FWHM of 0.9 nm. The use of SPEQs has made it possible to field systems with higher bandwidth and larger dynamic range than are possible with narrowband filters.

Detectors

A detector with high quantum efficiency, bandwidth, and peak linear current is necessary for high frequency, single transient, analog systems. A gain of 10^4 is required. Micro-channel plate (MCP) photomultiplier tubes (PMT) are ideal for this applicaton. MCP PMTs from IT&T and Varian have been fielded. Most of the MCPs used are of the proximity focus type with 18 mm photocathodes. Gain on all the tubes is about 1-3 x 10^4.

Data on the IT&T F4126X MCP PMT [with 60/1 channel length/channel diameter (L/D)] were reported with an impulse response of about 300 ps FWHM.[8] The quantum efficiency is about 4% at 800 nm for this extended red photocathode. This MCP PMT is reported to be linear when evenly illuminated until the MCP has been depleted of 1.4 nC of charge.

Interest in the use of MCP PMTs in fiber optic applications has led to a need for IR-sensitive photocathodes. Two new third generation tubes, the ITT F4141 and the Varian VPM-225 have a GaAs photocathode along with a filmed MCP. These have been reported to have pulse responses of 365 ps and 191 ps, respectively.[8] Quantum efficiency on both of these detectors is about 20% at 800 nm.

Oscilloscope

Direct deflected oscilloscopes are used which have a 2.5 GHz bandwidth and 0.7 V/cm deflection sensitivity.[9]

Calibration System

The calibration system has been designed to address five functions: 1) loss measurements during system hook-up, 2) system integrity checks, 3) SPEQ adjustment checks, 4) system pulse response measurements, and 5) total system dry run capability.

The calibration system is in two sections, separated in distance by the length of the cable run as shown in Figure 1. At the recording station is a trigger generator, delay box, and the aforementioned detection and recording system. In the area of the experiment are a calibration box containing laser diodes, light emitting diodes, and STAR splitters. Triggers are transmitted to the calibration box through coax cable equalized to 100 MHz.

The calibration box is schematically shown in Fig. 4. The LED is used in the dc mode to check connector attenuation during hook-up, optical system continuity, and SPEQ alignment adjustments. The two pulsed laser diodes are used for system impulse response measurements and as the light source in a dry run system. Only one laser diode is used at a time. The other is a spare unit which can be used by activating the coaxial switch. The laser diodes have a FWHM equivalent to Hamamatsu's Picosecond light source when measured with a 0.5 inch IT&T 4014 photodiode. The unfolded FWHM is less than 100 ps. The peak power emitted from a 1 m length of 62.5 μm graded index pigtail is >0.05 watts.

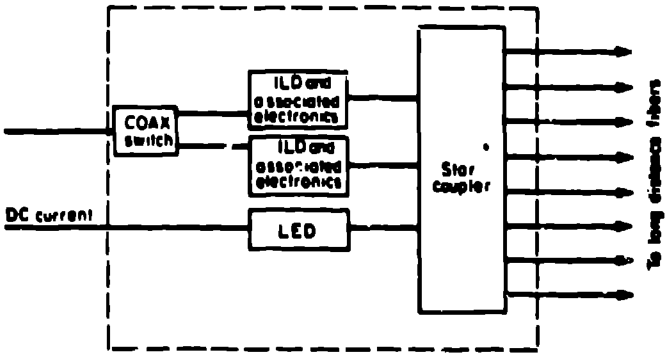

Fig. 4. Schematic diagram of calibration box.

The STAR couplers have been manufactured by both CANSTAR and HUGHES. They are of the fused biconical taper types with three input fibers and 8 output fibers. The fibers have been 100 μm core, step index fingers. Both manufacturers chose Cornings Short Distance Fiber (SDF).

The interest in measuring the pulse response of the high frequency system with a sampling system constrains the delayed trigger (≤10 μs) to have jitter less than ±25 ps. This requirement led to the development of a synchonous trigger delay generator. The instrument was designed as three modules in one rack-mountable box: an ultra-stable oscillator (~54 MHz), a countdown unit (single shot to 1 KHz) and a digital delay unit (capable of 18.500 μs in 0.0185 μs steps). The oscillator is the clock for both the countdown unit and the digital delay module. The pulse from the countdown unit has been resynchronized with the oscillator frequency and is used to initiate the delay unit. The delay unit has a prompt output, which is synchronized with the oscillator, and a delayed output which is again synchronous. Figure 5a illustrates the experimental arrangement used to measure the jitter. The delayed trigger out is used to trigger a Tektronix 7854 sampling oscilloscope. The clock frequency is recorded. Figure 5b is a trace of the clock pulse with 10 μs delay. Figure 5c is a single sweep of the expanded section of the sine wave. The total jitter is less than ±25 ps.

The prompt trigger is sent through coaxial cable to the laser diode pulsing network in the calibration box. The delayed trigger is used to trigger oscilloscopes, or a sampling scope, at the proper time.

There is one drawback to the calibration system. The SPEQs use a broad "white" spectrum (>40 nm), but the pulsed laser diodes are <5 nm at FWHM. Therefore the calibration system does not completely include the equalization range of the SPEQ and does not sample the fiber modal bandwidth over the full spectral range. Preshot comparison of the calibration pulse response can identify the magnitude of this effect. To the amount that the SPEQs are staple and give repeatable results, this limitation maybe negligible.

(a)

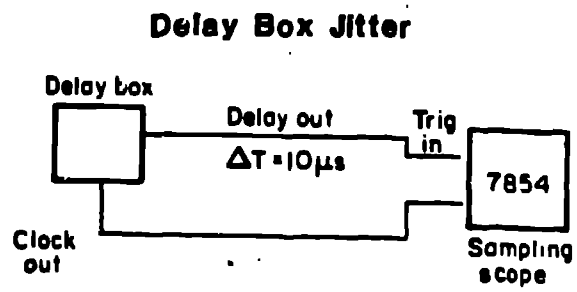

Fig. 5a. The experimental arrangement used to check the jitter of the synchronous delay trigger generator.

(b)

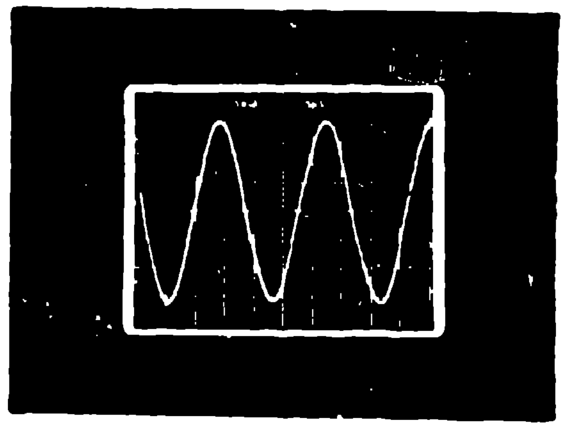

Fig. 5b. Using μs of delay the clock is sampled.

(c)

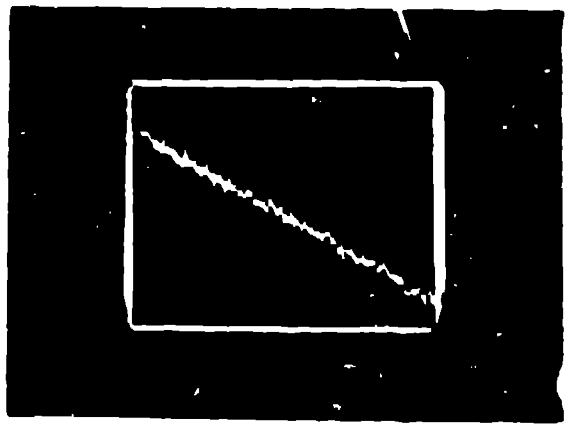

Fig. 5c. A single sweep of an expanded portion of the clock frequency. The jitter is less than ±25 ps.

System Performance

The best performance obtained to date with the MCP detectors and spectral equalizers is shown in Fig. 6 where a 0.50 km link demonstrated 226 ps FWHM. Anticipated link performance for a 0.5 km distance of 1.35 GHz-km fiber predicted using equations of reference 10 is 244 ps. The accuracy of the measurement is ±10 ps and the measurement of the fiber bandwidth is limited by the detector response (~1.6 GHz). The detector was a VPM-225 which gave us a signal of 1 volt when using a linear accelerator (LINAC) as the electron source for generation of the Cerenkov effect in the fibers. A comparable bandwidth measurement using a narrowband interference filter would have a signal level less than 100 mv and a larger FWHM caused by material dispersion contributions. The narrowest interference filter we have been able to purchase is 1.1 nm at 800 nm with 50% transmission. Furthermore, filters have much more transmission outside their FWHM passband than SPEQ.

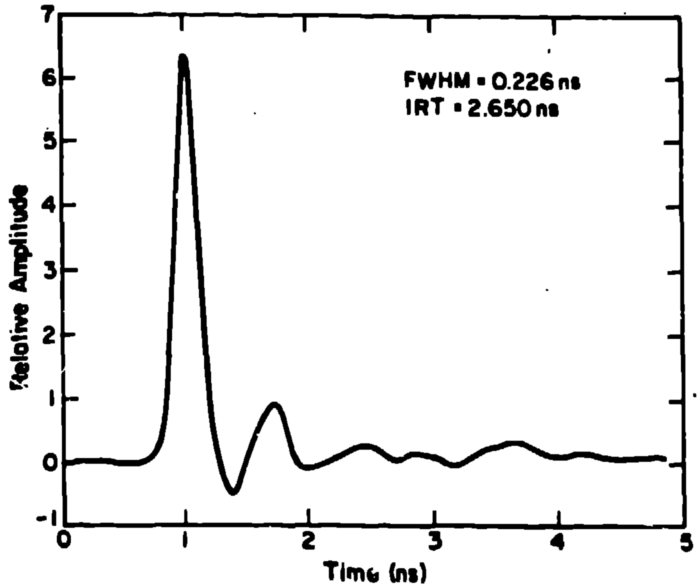

Fig. 6. Impulse response of a 0.5 Km fiber link with a 50 ps Cerenkov light source, a SPEQ, and a VPM-225 MCP PMT detector recorded with a sampling system.

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