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SIGNAL ENHANCEMENT BY SPECTRAL EQUALIZATION OF HIGH FREQUENCY BROADBAND SIGNALS TRANSMITTED THROUGH OPTICAL FIBERS*

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Abstract

A new technique is discussed for enhancing the bandwidth and intensity of high frequency (>1 GHz) analog, spectrally broad (40 nm) signals transmitted through one kilometer of optical fiber. The existing method for bandwidth enhancement of such a signal uses a very narrow (~1 nm) filter between the fiber and detector to limit bandwidth degradation due to material dispersion. Using this method, most of the available optical intensity is rejected and lost.

This new technique replaces the narrow-band filter with a spectral equalizer device which uses a reflection grating to disperse the input signal spectrum and direct it onto a linear array of fibers. The fibers are employed as optical delay lines. Each is cut to the proper length to compensate for material dispersion (at its wavelength) in the given length of input signal fiber. The combined output of the spectrally equalized array is then coupled to the detector and recorded. This technique enhances the acquired signal frequency response by eliminating the wing contributions of narrow-band filters, and significantly increases the signal amplitude by utilizing more of the available input spectrum.

The use of fiber optics in plasma diagnostics[1] is amenable to this technique. A pigtail of radiation resistant plastic clad silica (PCS) fiber is located in the radiation field as a Cerenkov radiation-to-light transducer. The pigtail is connected to one kilometer of high bandwidth graded-index fiber and the high bandwidth, spectrally broad and dispersed signal transmitted to the recording station. The signal fiber is connected to the spectral equalizer for signal enhancement.

Concept

A delta function of white light injected into a kilometer of optical fiber will be spectrally broadened by material dispersion into a pulse over 100 nsec long at the output, and modulated by the attenuation of the fiber. Figure 1 shows a 50-psec FWHM pulse of Cerenkov light so modified by transmission through 1 km of graded-index fiber. The same signal measured through a series of narrow-band filters (FWHM ≤1 nm) would be a series of pulses that are representative of the fiber modal bandwidth for the corresponding wavelengths, each recorded at different relative arrival times.

The problem is how to compensate for material dispersion so that all spectral components will arrive at the same time, avoiding the loss in frequency response and overcoming the loss of light due to filtering one wavelength only.

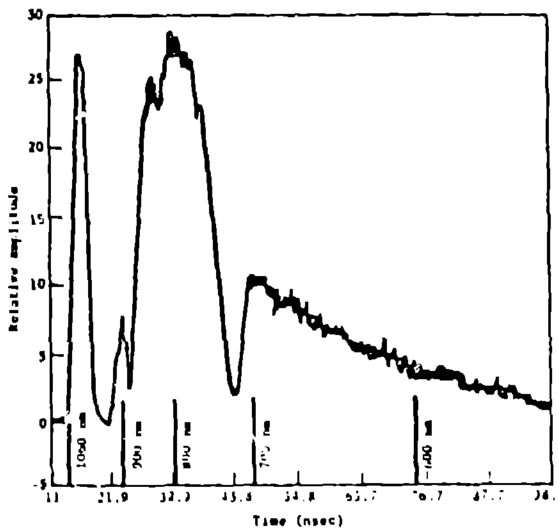

Fig. 1. Broadband Cerenkov spectrum through 1 km of fiber

To achieve this we have developed a spectral equalizer device wherein the high frequency dispersed broadband spectrum is inserted into a spectrograph. The spatially separated wavelengths are collected by a horizontal array of equalizing fibers. Each equalizing fiber is cut in length relative to the rest to adjust for the material dispersion in the original fiber. All signals in the compensating fibers will then be in temporal coincidence with each other. They are all incident on the same photodetector (Fig. 2). The resulting increased photodetector signal relative to that using the single-filter approach is a function of the spectrograph efficiency and the number of fibers used.

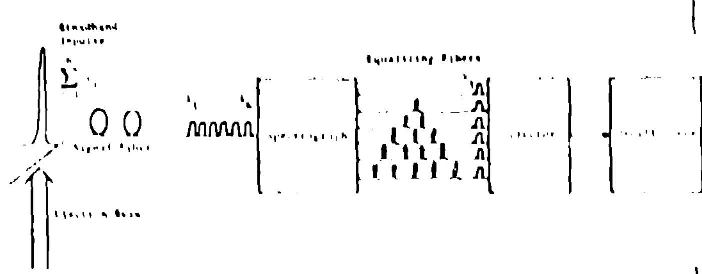

Fig. 2. Conceptual diagram of spectral equalization

Spectrograph Design

The spectrograph must be efficient to be useful. The instrument described here is based on concepts developed by Tomlinsen, Lin, and Aumiller[2,3] and by Kobayashi and Seki.[4,5] The fiber optic input radiation is collimated by a lens onto a high efficiency replica reflection grating (70% in the first order for unpolarized light at 800 nm) in Littrow configuration then refocused onto a linear array of 34 fibers by the same lens (Fig. 3).

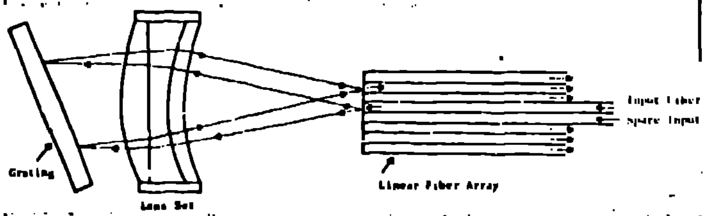

Fig. 3. Schematic of spectrograph

The grating used in the initial spectrograph studies has the following specifications:

Blaze wavelength — 7500 Å

Blaze angle — 26°45'

Grooves per mm — 1200

Relative efficiency at 7500 Å — 74% for unpolarized light

Angular dispersion (in Littrow) — 7.45 Å/mr at 7500 Å

Size (mm) — 50 × 50 × 10

Linear dispersion is dependent on the focal length of the collimating lens. A new two-element lens especially designed for this system will have a paraxial focal length of 77.3 mm. The lens-grating combination will produce a linear dispersion of 94.1 Å/mm at 814 nm, the center of the region of interest for our application.

The linear array of fibers is designed to collect the maximum amount of light in the relatively distortion-free region around the optical axis. There are two input fibers. One is a spare. They are both Corning 63-µm core diameter, graded-index fibers, identical to the main input signal fiber. The 34 equalizing fibers are distributed evenly on either side of the input fibers. They are 100-µm core Corning Short Distance Fibers (SDF). The larger core, numerical aperture, and semi-graded nature of the equalizing fibers relaxes somewhat the stringent requirements placed on the lens.

A computer program designed to model the spectrograph was used to determine the theoretical performance and characteristics of the system with the two-element lens. Figure 4 represents the coupling characteristics for two adjacent channels assuming a "textbook" lens, that is, focal length constant with wavelength, a 70% efficient grating, 0.5% loss at each surface of the lens (8 surfaces) and 4% Fresnel reflections at the fiber ends. The constant coupling over a finite wavelength region is due to the larger core areas of the receiving fiber.

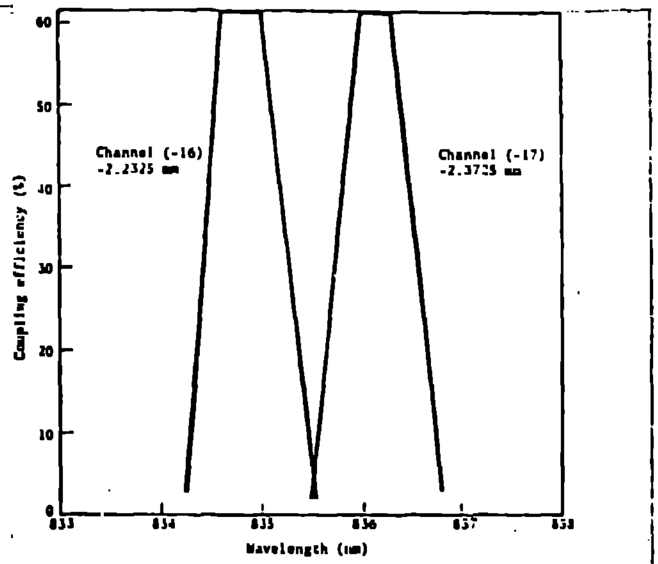

Fig. 4. Theoretical coupling characteristic for spectrograph with perfect lens (focal length 77.3 mm, array at focal point)

The designed two-element lens corrects for a large portion of the spherical aberration but introduces lateral chromatism. The effects of lateral chromatism are demonstrated in Figs. 5 through 9. Figure 5 illustrates the theoretical center wavelength coupling efficiency for the fiber array as a function of focal position. The best coupling at 791.5 nm is for a focal position of 77.20 mm, and for 837.5 nm, a focal position of 77.35 mm, the shortest and longest calculated focal positions.

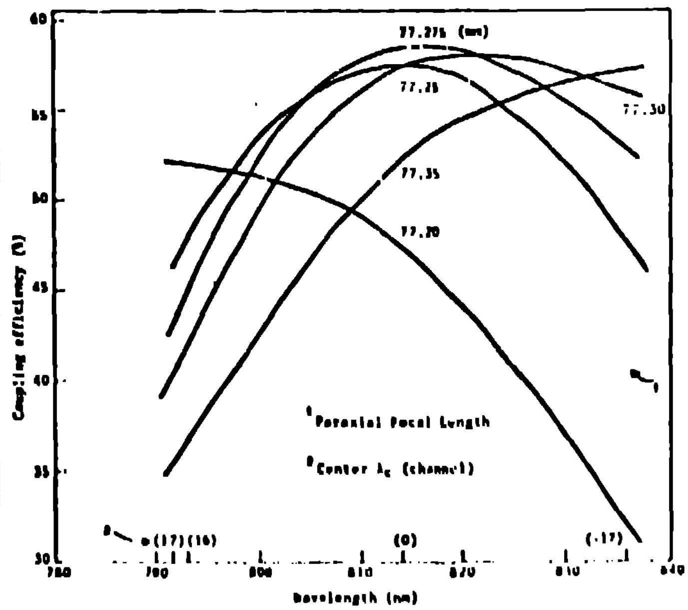

Fig. 5. Peak center wavelength coupling as a function of array paraxial focal position for λ_0 = 814 nm. Fibers are numbered consecutively from 17 to -17

Figures 6 and 8 represent the theoretical coupling characteristics for two channels on each of the two ends of the fiber array, and Fig. 7, for two channels in the center using the two-element lens.

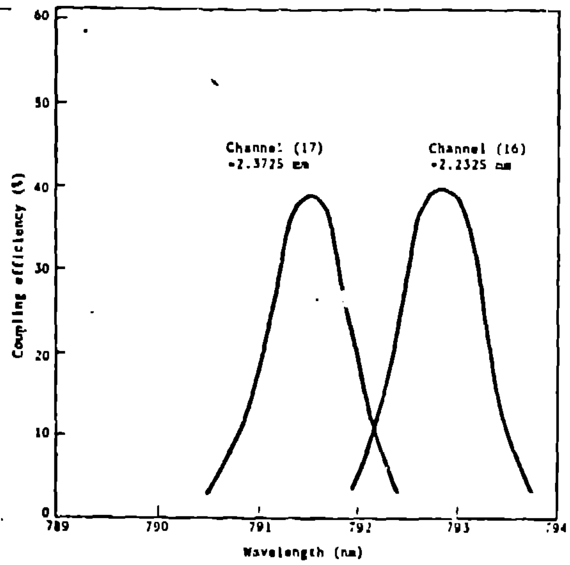

Fig. 6. Theoretical coupling characteristic for spectrograph (77.3 mm paraxial focal position)

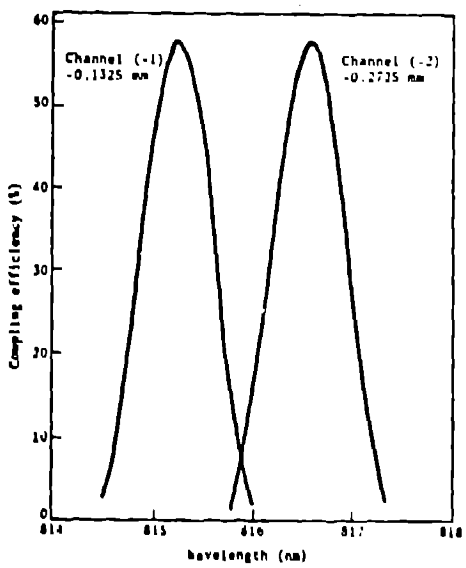

Fig. 7. Theoretical coupling characteristic for spectrograph (77.3 mm paraxial focal position)

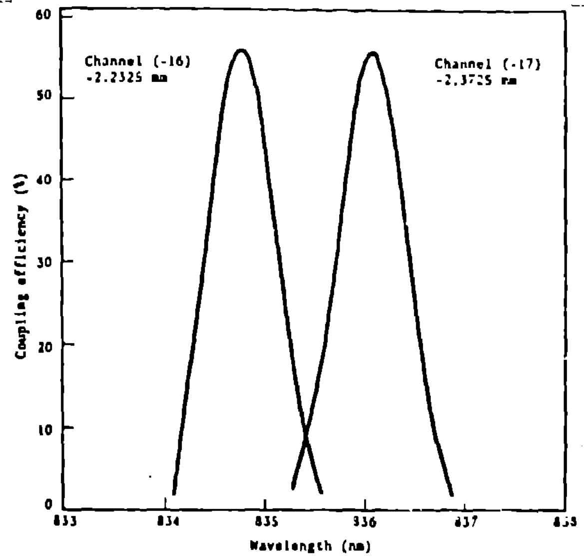

Fig. 8. Theoretical coupling characteristic for spectrograph (77.3 mm paraxial focal position)

Determination of Relative Lengths of Equalizing Fibers

The relative length of each equalizing fiber is dependent on the material dispersion in the input fiber and its length. The portion of spectrum used must be close to the design optimum wavelength of the fiber to minimize modal pulse broadening. Today's high frequency fibers are optimized for 850 nm. Also, since the purpose of the spectral equalization is to increase the signal amplitude, the spectral region should be in the neighborhood of the peak signal from the source-fiber-detector system. For state-of-the-art microchannel plate (MCP) photomultipliers and a Cerenkov source, this system spectrum peaks at 800 nm. The combination of these considerations leads us to use the region from 791 to 817 nm.

The material dispersion of Corning's graded-index fibers has been measured and has been found empirically to follow a power law in the 660 to 850-nm region.[6] (A semi-theoretical expression for material dispersion developed by Wemple could also be used.[7]) Integration of the power law equation yields the relative arrival time difference, Δt (psec), between two channels at wavelengths λ_1 (nm) and λ_2 (nm), for a length L (km) of signal fiber. This relationship is

$$\Delta t = 7.098 \times 10^{12} \left(\lambda_1^{-2.874} - \lambda_2^{-2.874}\right) L. \qquad (1)$$

Multiplication by the velocity of light in fiber (0.02 cm/psec) produces the relative difference in length of equalizing fibers for adjacent channels. The extreme difference in length for the spectral region of interest and 1 km of input fiber is 100 cm.

Construction of the Spectral Equalizer

The spectral equalizer unit has two compartments (Fig. 9), one for the fiber array-lens-grating assembly and one to hold the different lengths of equalizing fibers. The MCP detector is also attached to the second compartment. One of the equalizing fibers is used to verify the use of the appropriate spectral region. The light from this fiber passes through the desired narrow-band filter and is detected by a conventional photomultiplier tube (PMT). Thus, with a white light dc input to the equalizer and a dc measurement of the PMT signal, adjustments of the grating Littrow angle for the proper spectral region can be performed.

The long focal length of the lens and the small size of the fibers dictate a rigid construction with micrometer adjustments for all degrees of freedom. The fiber array is mounted on translation stages that provide adjustments in the x, y, and z directions. The lens is fixed. The grating is mounted in a holder that provides gimbaling about the x and y axis and rotation of the grating about the normal to its ruled surface.

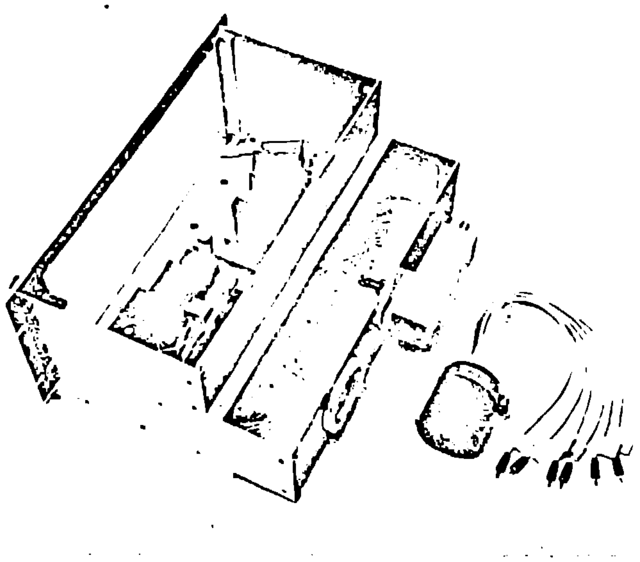

Fig. 9. Top view of spectral equalization unit

All mounts are fastened to a 0.5-inch aluminum plate for stability. The most sensitive adjustments are the grating x-axis gimbaling and rotation, and the fiber z-axis for focusing.

Experimental Results

The prototype spectral equalizer device has been fabricated and characterized using a tungsten lamp to measure efficiency and Cerenkov radiation produced in the fiber by electrons from a linear accelerator, to determine the system response of the combined one kilometer of fiber, the spectral equalizer and microchannel-plate-photomultiplier detector.

The tungsten lamp was used to determine the average efficiency for coupling into each fiber in the following way. Light was coupled directly into the input fiber and the total throughput through all fibers was measured. The input fiber was then broken off near the input end and the throughput of the short piece was measured using a 1-nm filter at the appropriate wavelength.

Using this evaluation technique we measured a mean 12% efficiency per fiber, as compared to the theoretical maximum of approximately 50%. This poor result is attributed to the quality of the lens which is presently in use. It is a photographic achromat, *f*/1.6, 80-mm focal length, and is not corrected for use around 800 nm. The new two-element lens designed for this system, which is in fabrication, should substantially increase the efficiency.

The best system response obtained with the prototype equalizer for a 50-psec input pulse recorded through 1 km of optical fiber, a spectral equalizer and Varian MCP detector, was 300 psec FWHM with an amplitude of 125 mV. This compares with 400 psec FWHM and 10- to 20-mV amplitude measured through a 1-nm narrow-band filter.

The input radiation pulses used for testing are generated at the DOE/EG&G linear accelerator which is capable of producing 50-psec pulses of 6 MeV electrons with a current density of 100 amps/cm^2. When the electrons pass through an optical fiber, the Cerenkov process produces broadband 50-psec impulses of light ideal for these system response measurements.

Conclusion

The concept of spectral equalization has been demonstrated to enhance the signal amplitude and improve the system frequency response to greater than 1 GHz when transmitting a spectrally broad optical signal through a kilometer of optical fiber. A prototype spectral equalizer unit has been constructed that uses this concept. Test results comparing the performance of this prototype with that of the typical narrow-band optical filter show a system time response improvement from 400 to 300 psec, with a factor of eight increase in signal amplitude. A new lens specially designed for this application is being fabricated; it should substantially increase the throughput efficiency of the unit giving considerably larger signal amplitudes and thereby increasing the system dynamic range.

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