A DISTRIBUTED FORCE-SENSING OPTICAL FIBER
USING FORWARD TIME DIVISION MULTIPLEXING

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ABSTRACT

A new optical fiber capable of sensing distributed forces along its continuous length comprises a small central core and a non-contiguous second light-guiding region of longer optical path length. When interrogated with sufficiently short light pulses launched into the central core at the fiber launch end, mechanical forces acting at different points along the fiber cause the deflection of a fraction of the intensity of the interrogating light pulses propagating along the fiber at each point from the central core to the second light-guiding region, where they generate positive pulsed light signals reaching the fiber distal end separated in the time domain from the interrogating light pulses and from the signals generated at other sensing points along the fiber, and with an intensity several orders of magnitude stronger than that of Rayleigh-backscatter signals. In addition to its potential use as a distributed force sensor, the fiber could serve as a telecommunications line allowing the non-invasive coupling of information at many points, simultaneously or in any arbitrary sequence, without the need for time-sharing protocols.

1. INTRODUCTION

Mechanical forces acting at different points on an optical fiber can cause the ejection of light propagating along the fiber out of the fiber core, and can thus be sensed with optical time domain reflectometry (OTDR) techniques by the decrease they cause on the intensity of the Rayleigh-backscatter from the interrogating light pulses[1]. A serious shortcoming of this technique, including its polarization variant[2], is that it 'throws away' the ejected light, and instead it provides an estimate of its intensity *indirectly* from a difference between two usually much larger, but still weak and noisy backscatter signals the intensity of which is typically about -50 dB relative to the intensity of the forward interrogating light beam.

In this paper we discuss a variety of approaches for measuring directly the fraction of the intensity of the interrogating light deflected out of a fiber core under the action of a measurand, with emphasis on the use of a novel optical fiber which allows the capture and *direct* measurement, by forward time division multiplexing, of the light deflected out of the fiber core under forces acting at different points along the fiber length. The new fiber could be used as a sensitive distributed force-sensor, generating signals several orders of magnitude stronger than Rayleigh backscatter signals, and/or for the non-invasive coupling of information from the side at any point or, simultaneously or in any arbitrary sequence, at a multiplicity of points along its length.

2. APPROACHES TO THE DIRECT MEASUREMENT OF THE INTENSITY OF LIGHT DEFLECTED OUT OF THE FIBER CORE AT A MULTIPLICITY OF POINTS IN A LONG OPTICAL FIBER.

The *direct* measurement, by time division multiplexing techniques, of light deflected out of a fiber core under the action of a measurand at a multiplicity of

sensing points along the fiber requires that the light deflected at each point generate an optical signal reaching the photodetection system in a form separable from the light propagating along the core at that point. The approaches we have considered for effecting the separation include both a separation in the spectral domain --by luminescence or Raman conversion techniques--, and a separation in the time domain by forward time division multiplexing (FTDM) techniques. These are described below, including experimental results with the FTDM technique.

2.1 Luminescence and Raman Techniques.

One way of measuring directly the intensity of the interrogating light deflected from the fiber core to the fiber cladding under the action of a force is to convert that light into a light of wavelengths different from those of the interrogating light, for example by luminescence conversion[3] or Raman scattering. In contrast to other modal separation techniques, once the wavelength-shifted signal is generated, it cannot 'fade' by subsequent reconversion to the modes or the wavelength of the interrogating light. Luminescence conversion is the more efficient of these processes and, therefore, it is described in greater detail below.
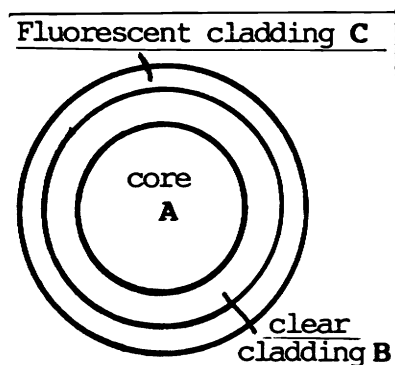

Fluorescent cladding C

core A

clear cladding B

FIGURE 1

Cross-section of fiber with fluorescent cladding

Consider an optical fiber probe as described in **Figure 1,** comprising a glass core **A** with an index of refraction n_1 and a glass cladding **B** with an index of refraction n_2 lower than n_1, as in most commercial single mode or multimode fibers. Around and in contact with cladding **B** there is an outer cladding **C** comprised of an optically homogeneous plastic with an index of refraction n_3 lower than n_2 and having dissolved therein a dye with a fluorescence quantum efficiency ϕ greater than 0.5. When interrogated by standard OTDR techniques with light pulses of pulse width of the order of 10^{-8} seconds or shorter, and of wavelengths λ_s within an absorption band of the fluorescent dye, a lateral force acting at any point along the fiber will deflect a fraction of the intensity of the interrogating light propagating along the core at that point to cladding **B**, where it will generate fluorescence light pulses of mean wavelengths λ_f at the *evanescent* region of cladding C. The time of arrival of the fluorescence light pulses at the fiber launch end identifies the location along the fiber of the lateral force, while their intensity is indicative of the magnitude of the force. Since the fluorescence decay times of most fluorescent dyes are typically shorter than 10^{-8} seconds, spatial resolutions better than 1 fiber-meter should be obtained. The method could be made ratiometric by referencing the fluorescence intensities to the intensities of the Rayleigh-backscattered pulses from the same sensing point.

The method should provide a large improvement in signal strength compared to Rayleigh backscatter methods. Let us label the numerical aperture of the fiber core as $(NA)_1$ and that of the region comprising the core and the first cladding as $(NA)_2$. A moderately high micro- or macrobending sensitivity requires a relatively low $(NA)_1$, preferably about 0.15 or smaller for ease of core-to-cladding light coupling, and a relatively high $(NA)_2$ value, preferably not smaller than 0.40, for maximizing the collection of the generated fluorescence light signals. If the concentration of the fluorescent dye is sufficiently high to absorb most of the deflected light per resolvable fiber length, it can be shown that the intensity of the fluorescence force

signals will be stronger than the force-induced change in the intensity of the light Rayleigh-backscattered from the sensing point by a factor F approximately given by

$$F \; > \; [(NA)_2 n_1/(NA)_1 n_2]^2 [\phi \, (1 - \alpha_f)/\beta] \qquad \ldots \ldots (1)$$

where β is the Rayleigh backscatter coefficient per resolvable fiber length, and α_f is the fraction of the intensity of the generated fluorescence light which is absorbed along its fiber path to the photodetector. The use of the sign ">" is justified in that the collection efficiency of evanescent fluorescence is greater than that of bulk fluorescence. For resolvable fiber lengths of the order of 1 meter, equation (1) predicts that the fluorescence force signals should be between two and three orders of magnitude stronger than the Rayleigh backscatter signals.

One attractive feature of this system is that it does not require any changes in the commercially available fiber preforms. Another one is that the guided fluorescence light pulses travel almost entirely within low attenuation glass in their way to the photodetector, even though they are generated within a medium of higher attenuation. One may thus use fiber probe lengths of the order of one kilometer despite the use of plastic claddings of relatively high **bulk** attenuation.

The luminescence conversion techniques described above are not restricted to the measurement of forces, and should be suitable for sensing any measurand which produces a variable attenuation of the interrogating light. For example, if the interrogating light pulses are launched into the region comprising **both** the core and the first cladding, and the temperature coefficient of the index of refraction of the plastic second cladding is much greater than that of the glass cladding, then the intensity of the fluorescence back-directed to the fiber launch end from any point along the fiber will be temperature-dependent, and the fiber could be used as a distributed temperature probe. Alternatively, the fiber could be interrogated with light of wavelengths at which the light absorption is temperature-dependent, thus generating fluorescence pulse signals with an intensity indicative of the fiber temperature.

2.2 Distributed sensing based on backward-stimulated light amplification processes.

Distributed sensing by backward-stimulated light amplification processes is a variant of the wavelength conversion system described above. A representative system using backward-stimulated Raman scattering (BSRS) is shown schematically in **Figure 2**.
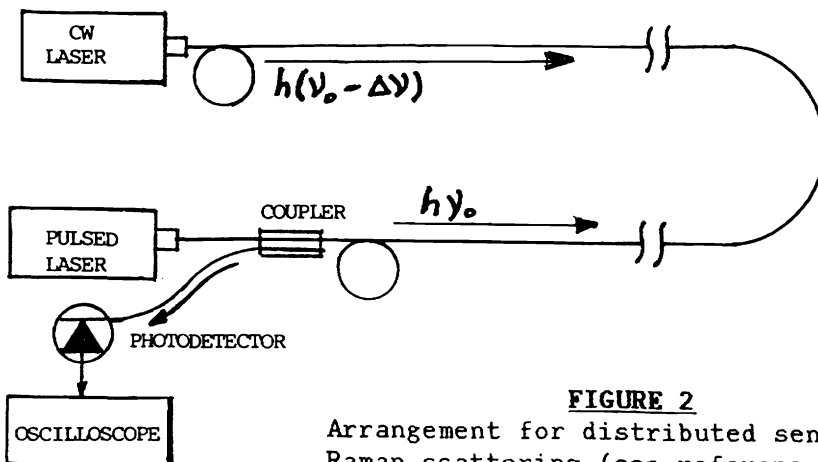

FIGURE 2
Arrangement for distributed sensing using backward-stimulated Raman scattering (see reference 4)

A relatively high power laser pulse of photon energy $h\nu_0$ interacts with a low power counterpropagating CW laser beam (wave) of photon energy $h(\nu_0-\Delta\nu)$, where $\Delta\nu$ is the main Stokes Raman shift of the pump pulse by the glass of the fiber core. At the region of interaction the CW beam is pulse-amplified with a gain which is made dependent on the measurand. An actual force-sensing system based on force-induced polarization-selective stimulated BSRS changes *within the fiber core* has been described by Farries and Rogers[4], but the system is flawed in that the state of polarization of the light at any sensing point affects the state of polarization of the light at other points, which makes it difficult to derive unambiguous measurand values at a multiplicity of sensing points. This problem could be eliminated by using an arrangement wherein the intensity of the pump pulses is distributed between two light-guiding regions of different chemical composition and different Raman gain properties at a preselected Stokes shift, the relative distribution varying in a known manner with the magnitude of the measurand at each sensing point and independently of the relative distribution of the pump radiation at other sensing points. Then the Raman gain at that Stokes shift should be determined at each sensing point by the magnitude of the measurand at that point, independently of the magnitude of any measurand acting at other sensing points along the fiber.
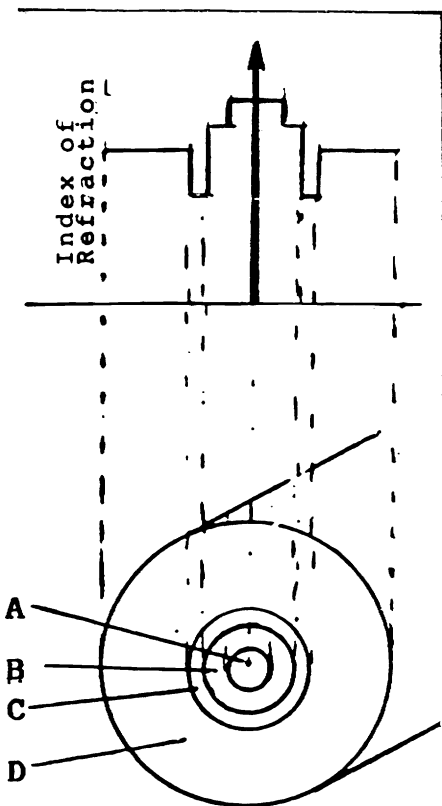

FIGURE 3

Refractive index profile of proposed 'segmented core' fiber sensor based on backward-stimulated Raman scattering.
(see text on right)

In one proposed arrangement, shown in **Figure 3**, the probe is a long optical fiber comprising a small core **A** with a diameter of, say, 3.5 micrometers (μm), an index of refraction n_1, and made of glass comprised of a material having a relatively high Raman-scattering coefficient at a Stokes shift of $\Delta\nu$ cm^{-1}. Around this core there is a thin first cladding **B** having a diameter of, say, 6.0 μm, an index of refraction n_2 slightly lower than n_1, and substantially different Raman gain at said Stokes shift. Around cladding **B** there is a second thin cladding **C** with an index of refraction n_3 substantially lower than n_2. Around cladding **C** there is an outer cladding **D** with an index of refraction n_4 higher than n_3 and only slightly lower than n_2. Regarding its index profile, the fiber is essentially a single mode "W" fiber where core **A** and cladding **B** can be regarded as the inner and outer segments, respectively, of a 'segmented core'. Core **A** and cladding **B** are the two light-guiding regions between which the intensity of the interrogating (pump) light pulses is distributed. If the value of $[n_1-n_2]$ (henceforth referred to as Δn) is lower than 0.01, then an appreciable fraction α of the intensity of the interrogating (pump) light launched into core **A** (or into the light guide comprising both core **A** and cladding **B**) will propagate along cladding **B** even in the absence of any external force on the fiber, due to the penetration into region **B** of the evanescent field of the guided light beam[5]. Thus, small changes of Δn should produce a relatively large change in the value of α. Relatively weak lateral forces should produce the same effect, due to the low value of $(NA)_1$.
Since the fiber is essentially a "W" fiber, strains or other forces which may cause a substantial optical

power redistribution between regions **A** and **B** should not cause excessive light losses from the segmented core comprising these two regions.

Because of the different Raman scattering coefficients of regions **A** and **B**, any measurand which affects the relative distribution of the interrogating (pump) between regions **A** and **B** should produce Raman gain at each sensing point indicative of the magnitude of the measurand.

Instead of stimulated Raman amplification one could use stimulated light amplification in an optical fiber doped with a laser material, for example Nd^{3+}-doped fibers. If the fiber is pumped with light pulses of wavelengths near 880 or 810 nanometers (nm), a pulse width of the order of 10^{-8} seconds and energy sufficient to generate a population inversion at different sensing points along the fiber, a counterpropagating CW beam of wavelength of about 1.06 μm will be pulse-amplified at the fiber sensing points, the amplified pulses having a risetime approximately equal to the pulse width of the pump pulses, even if the decay time of the *spontaneous* luminescence is much longer.

2.3 Distributed Sensing by Forward Time Division Multiplexing.

2.3.1 Theory.-

While the luminescence-based techniques for distributed sensing can provide a direct measurement of the intensity of the light deflected out of the fiber core at different points along the fiber, and generate much stronger signals and lower noise than Rayleigh backscatter loss techniques, signal separation without wavelength conversion or other lossy processes should provide a more efficient means *if* the light deflected out of the fiber core could be separated in the time domain from the interrogating light. This can be accomplished by capturing the deflected light within a light-guiding region of the fiber having a different effective optical path length from that of the fiber core. What follows is a description of a new method and a new fiber which allow said separation.

Figure 4 shows a representative refractive index profile of the subject fiber *as designed*. The fiber comprises a small single or near single mode central core **A** having an index of refraction n_1, a first cladding **B** around the core having an index of refraction n_2 lower than n_1, a second light-guiding region **C** around cladding **B**, having a graded near parabolic refractive index the highest value of which, n_3, is substantially higher than n_1, and an outer cladding **D** having an index of refraction n_4 substantially lower than n_2. The fiber is designed to work as follows:

When a train of interrogating light pulses of subnanosecond duration (depending on the spatial resolution desired) is launched into the fiber core **A** at the fiber launch end, a lateral mechanical force applied at any point along the fiber will deflect a fraction of the intensity of each interrogating light pulse from core **A** to the graded index region **C**. Because of the refractive index profile of the fiber, the deflected light should be captured within this graded index core **C** and transmitted to the fiber distal end. Because n_3 is substantially greater than n_1, the light pulse carried by the graded index region **C** will arrive at the fiber distal end after a resolvable time interval Δt *after* the arrival of the undeflected light pulse transmitted by the central core **A**. This interval identifies the location along the fiber at which the force is applied, according to the relation

$$\Delta t = (z/c)(n_3 - n_1) \quad \text{seconds} \quad \ldots\ldots\ldots (2)$$
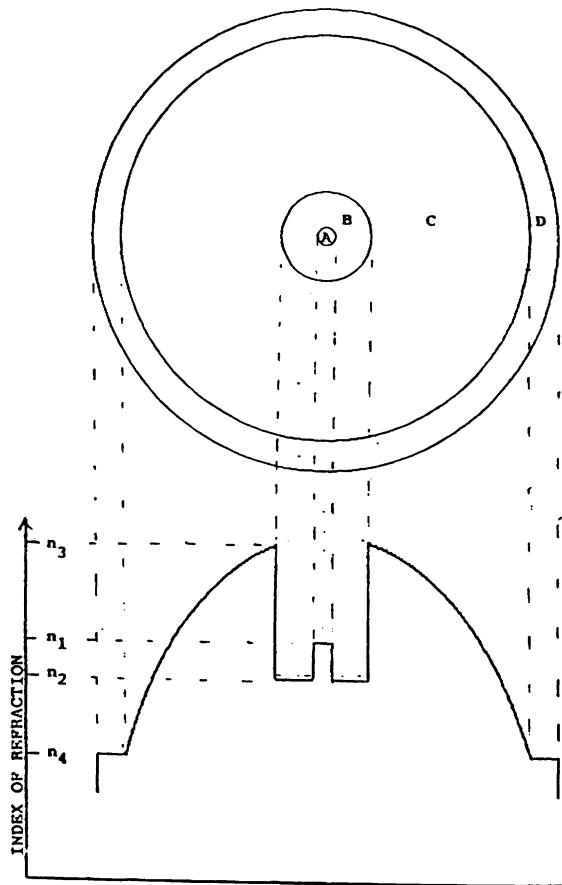
where z is the fiber distance from the fiber distal end of the point at which the force is applied, and c is the velocity of light in free space. Forces applied at a multiplicity of points along the fiber length will generate optical signals arriving at the fiber distal end at different times indicative of the locations of the forces, regardless of whether the forces are applied simultaneously or in any arbitrary sequence. Thus, no time-sharing protocols are needed to demultiplex the signals. If the difference $(n_3 - n_1)$ is, for example, 0.025, and the fiber probe is, for example, 500 meters long, then the difference in the times of arrival at the fiber distal end of the interrogating light pulse and the force signal from a sensing point nearest the fiber launch end will be shorter than 4.2×10^{-8} seconds, and the pulse repetition frequency (PRF) of the interrogating light could be greater than 2×10^7 pulses per second (pps). Such a high PRF should allow the use of signal integration and averaging techniques to an extent sufficient for compensating for the frequency-dependent detection noise per pulse. In order for the signals to be resolved, the multimode graded index region C must have a sufficiently low time dispersion, which should be achievable with the graded index parabolic profile. The rms dispersion δt of a parabolic graded index fiber of length L is given by the relation

FIGURE 4

Cross-section and refractive index profile of force-sensing fiber of this work, as designed.

$$\delta t = [(n_a - n_b)/n_a]^2 . n_a L / [3^{1/2} . 20c] \; sec ...(3)$$

where n_a and n_b are the highest and the lowest values of the graded index of refraction (corresponding to n_3 and n_4 in the fiber of this paper). The actual dispersion is expected to be somewhat greater in practice.

2.3.2 Experimental

A preform of GeO_2-doped silica was fabricated for us by SpecTran, Inc., with the refractive index profile shown in **Figure 5**. While the profile of the graded index region is short of being parabolic, fibers drawn from this preform could be used for testing the principles set forth in section 2.3.1. The fibers, with a central core diameter of 7 μm, were interrogated with light pulses with a pulse width of about 280 picoseconds (ps) and a PRF of about 1 MHz from an NEC visible (675 nm) diode laser model **NDL3210** driven by an AVTECH AVM-2-C-M pulse generator. The time evolution of the signals was monitored with a Mitsubishi Si avalanche photodetector (APD) model FU-25AP and a Tektronix sampling oscilloscope model 7854 fitted with plug-in units 7T11A (time base) and 7S11 (sampling unit), the latter including a sampling head S4.

2.3.3 Results

Figure 6(a) shows the relative times of arrival, at the fiber distal end, of

SpecTran
Corporation

INDEX

PROFILE

+.06

n_3 -

n_1 -

n_2 -

n_4 (1.458)
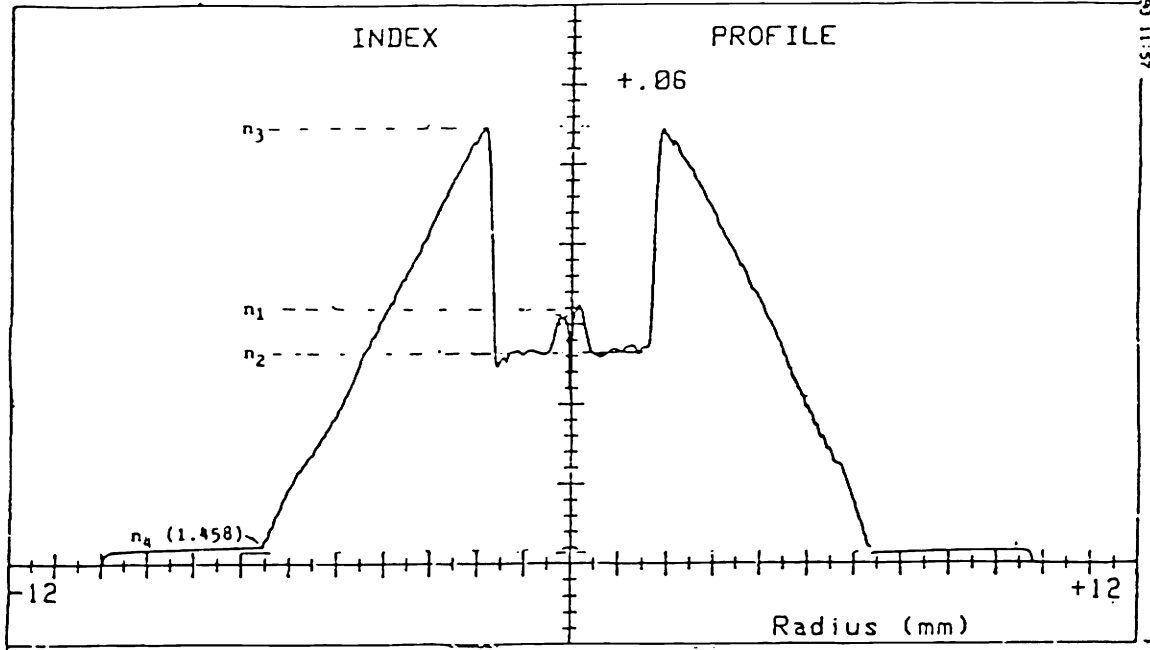
-12

+12

Radius (mm)

FIGURE 5

Refractive index profile of fiber preform used in this work (section 2.3.2)
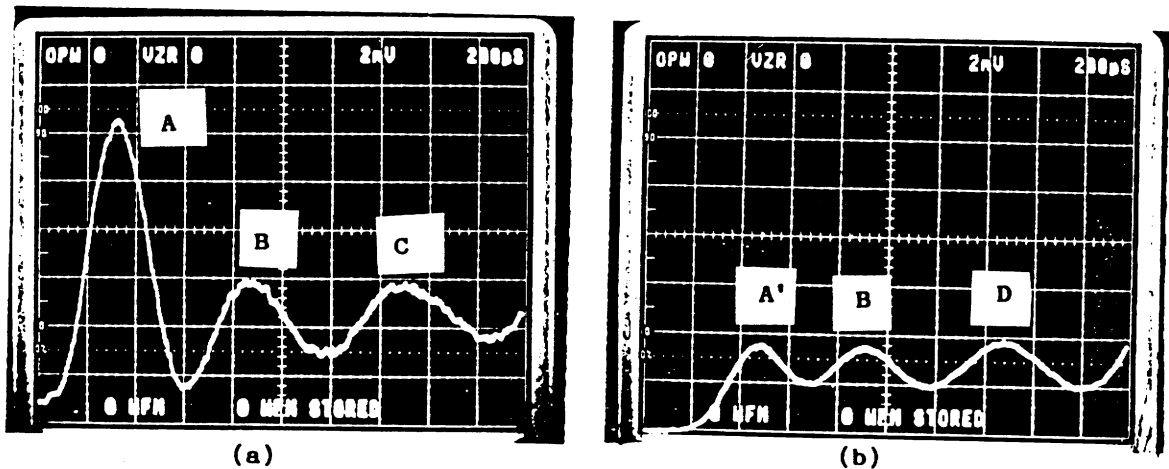
(a)

(b)

Figure 6

Relative times of arrival at the distal end of a 42 meter long force-sensing fiber (see section 2.3.3), on a time scale of 200 picoseconds per division, of
(a) Interrogating light pulses (A) and force signals generated by bending forces acting simultaneously at points B and C located at 9.25 and 19.8 fiber meters from the fiber distal end, respectively; and
(b) Force signals similarly generated at points A', B and D located at 1.7, 9.25 and 21.2 fiber meters from the fiber distal end, respectively.

the interrogating light pulses launched into the subject fiber at the fiber launch end, and the signals generated by macrobending forces at two different points along the fiber, and **Figure 6(b)** shows the relative times of arrival of signals generated by bending forces acting simultaneously at three different points along a 42 meter long fiber. The smallest separation of sensing points in these tests (**Figure 6(b)**) was 7.5 meters in our non-optimized fiber, and the data indicate that smaller distances should be resolvable. These results demonstrate the feasibility of measuring distributed forces by fiber optic forward time division multiplexing.

In preliminary experiments, a static macrobending force of 10 g on a fiber loop of a bias radius of 0.46 cm, and perpendicular to the fiber loop, caused an increase of the light intensity deflected from core **A** into the graded index region **C** of about 12 percent, and a decrease of the loop radius to 0.40 cm. This suggests that static forces of the order of 0.1 g or less, and much weaker oscillatory forces, should generate measurable signals.

2.3.4 ALTERNATE CONFIGURATIONS.

The fiber configuration tested in this work was chosen mainly for purposes of rapid demonstration of the principle discussed in section **2.3.1**. If fiber lengths of the order of 1 Km or greater are needed, or high spatial resolutions are required, it would be advantageous if the higher index light-guiding region were a single mode core, for lower time dispersion. This may require a more elaborate design to ensure efficient coupling to the high index core of the light deflected from the low index core. In one possible configuration the higher index core has a substantially smaller diameter than that into which the interrogating light pulses are launched (core **A**). Alternatively, the core with the longer optical path length could be off axis and follow a helical path around core **A**.

3.0 POTENTIAL USES.-

3.1 Sensing applications.-

As a distributed sensor, the new fiber should find many applications in the sensing of distributed forces. Each spatially resolvable point along the fiber is a force sensor, and a long fiber could monitor strain changes at any or all sensing points along the fiber simultaneously, generating signal strengths up to about 50 dB greater than with light loss Rayleigh-backscatter OTDR systems, and clean separation of the pulse signals from the interrogating light pulses. Examples of sensing applications where the new fiber should be particularly useful are as follows:

'Smart skins' diagnostics. Embedded in the skins of composite materials in aerospace structures, the fiber could monitor stress distributions within said structures. Because of the greatly increased sensitivity compared to Rayleigh backscatter OTDR methods, incipient stresses should be readily detected before significant damage occurs, allowing for appropriate corrective action.

Distributed vibration sensors.- Any and many points along the new fiber could be positioned under a suspended proof mass within any large structure subject to vibration, like aircraft, spaceships, bridges, buses, etc. Such an arrangement should be far more economical than the use of a multiplicity of discrete accelerometers.

Hydrophones and hydrophone arrays.- While not achieving the highest sensitivity

possible with interferometric sensors, hydrophones based on the new fiber could offer a more desirable combination of adequate sensitivity with ruggedness and reliability. One way to look at the acoustic detection capability of the new fiber is to regard it as an irreversible force-sensing optical coupler many meters long and sensitive to acoustic pressure over its whole length.

Other potential uses include the monitoring of the integrity of large structures like bridges and pipelines, and as perimeter intrusion sensors.

3.2 Fiberoptic Bus-organized Systems for Data Communications and Sensor Data Acquisition

Any sensor signals which are in the form of or can be converted into acoustical or other mechanical forces could be coupled noninvasively to the fiber. For example, numerous existing sensors and devices with a mechanical frequency output include flowmeters and pumps, whose signals could be coupled to the subject fiber through a fiber bending frequency proportional to the flow rate or the rate of rotation of the pump impeller. Owing to recent advances in micro-machined Si sensors, and their suitability for constructing 'intelligent' sensors, it can at least be argued that the main attraction of fiber optics will increasingly lie in the electrically-passive transmission of noninvasively coupled signals from sensors and/or any other devices to a remote processing unit, rather than in the generation of the signals. It is already economically viable to incorporate just enough processing capability into a microchip sensor to convert the sensor signal into a pulse rate or frequency output. This could drive an inexpensive microvibrator attached noninvasively to the fiber of this work, allowing the essentially error-free transmission to a remote station of the signal from that sensor and, simultaneously or in any arbitrary sequence, the signals from numerous other sensors so coupled to the fiber. Since the interrogating light pulse rate for a 1 Km long fiber can be of the order of 10^7 Hz, each vibration period will be sampled by thousands or more interrogating light pulses, more than enough to accurately reproduce the instantaneous sensor signal and to measure rapid signal changes *in real time*, including voice microphone signals.

The technology subject of this project allows the real time collection, storing and integration of the electrical signals produced by **each and all photons** or group of photons per signal pulse arriving at the photodetector from each force-sensing point along the fiber. Since the fiber is so constructed as to automatically demultiplex and time-resolve the optical signals from each sensing point, these signals, and their time evolution, could **all** be captured, stored and integrated as a two-dimensional distribution of electrical charges in a scan converter or any other image storage tube or solid CCD array, each resolvable spot in the two-dimensional array representing the time-integrated charge within a 'TV' frame. Referring to **Figure 7**, each horizontal line contains information on the light intensity generated at a given instant from each spatially resolvable element of the fiber, and the location of each all sensing points. Each point could include the signals from hundreds, or thousands, or more interrogating light pulses, depending on the PRF of the interrogating light. The PRF can be any chosen frequency up to the order of about 10^7 Hz. Each vertical line represents the intensity changes as a function of time for each corresponding, fixed point along the fiber. For example, the rotor of a turbine flow meter or pump will produce an oscillatory signal as illustrated in **Figure 7**, the period of oscillation being indicative of the flow rate. Another vertical scan line could reproduce human speech picked up by a voice microphone. The number of 'TV' frames per second (the refresh rate) could be adjusted at will, so that
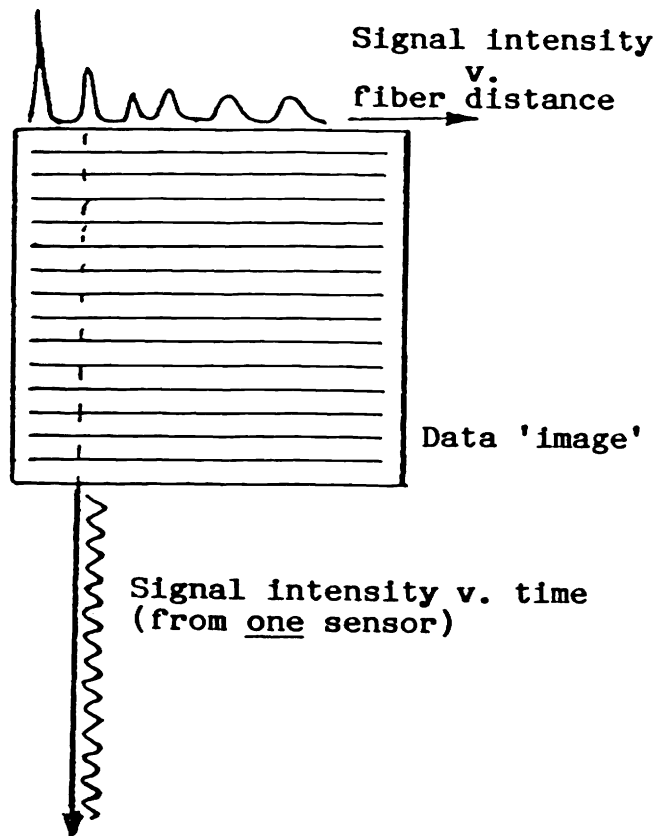
Signal intensity
v.
fiber distance

Data 'image'

Signal intensity v. time
(from one sensor)

FIGURE 7
Representation of a two-dimensional charge distribution on an image storage device,
or scan converter, generated by numerous sensors or other devices non-invasively
coupled to the sensing fiber subject of section 2.3 et seq. A horizontal scan
reveals the instantaneous optical signals as a function of fiber distance from a
reference point (i.e. one of the fiber ends), while a vertical scan reconstructs the
time evolution of the signal from one specific device, for example changes in the
speed of rotation of a pump impeller.

each resolvable spot in the two-dimensional charge distribution can be the sum of
numerous pulse signals.

4.0 CONCLUSION

We have demonstrated the feasibility of sensing distributed forces by forward
time division multiplexing techniques, using a novel optical fiber comprising two
light-guiding regions of different optical path length. In addition to its
suitability for sensing distributed forces, the fiber could be used as a
telecommunications line by allowing the non-invasive coupling of information from the
side at any point or, simultaneously or in any arbitrary sequence, at a multiplicity
of points.

5.0 ACKNOWLEDGMENTS

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