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Inventors: Larry Fabiny et al.

PATENT APPLICATION
Navy Case No. 78,315

INTERFEROMETRIC FIBER OPPIC DOPPLER VELOCIMETER WITH HIGH DYNAMIC RANGE

SPECIFICATION

Background of the Invention

1. Field of the Invention

The present invention relates to velocity sensors and more particularly to a fiber optic laser Doppler velocity sensor (or velocimeter) which performs non-contact measurements of the velocity of a moving surface.

2. Background of the Invention

Optical techniques for measuring the motion of moving surfaces can offer significant advantages over conventional electro-mechanical accelerometers and strain gauges. For instance, optical sensors can operate in a non contact manner, thereby eliminating distortion of surface motion caused by mechanical loading from attached sensors. Among the optical sensing techniques, wavelength encoded sensors are often preferred over intensity based sensors because the sensed information is carried by the wavelength or optical frequency of the output light, and as such is not directly affected by extraneous losses or optical power changes in the system. Several methods have been developed for the detection of small wavelengths shifts associated with wavelength encoded sensors, ranging from conventional heterodyne detection, to more recently developed schemes for decoding fiber Bragg grating devices. However, such prior art techniques do not provide high sensitivity to weak dynamic frequency shifts, and as such are not particularly useful for monitoring transient events.

Summary of the Invention

It is therefore an object of the invention is to provide an improved velocity sensor.

Another object of the invention to provide a fiber optic laser Doppler velocity sensor which performs non-contact measurements of the velocity of a moving surface.

Another object of the invention is to provide an interferometric fiber optic Doppler velocimeter with high dynamic range.

A further object of the invention is to provide a fiber optic velocity sensor for measuring the Doppler shift in the optical frequency of light reflected from a moving surface.

These and other objects of this invention are achieved by providing a fiber optic velocity sensor system for measuring the Doppler shift in the optical frequency of light reflected from a moving surface. The velocity sensor system comprises: a source of coherent light; a sensor for directing the coherent light to a moving surface and collecting a Doppler-shifted return signal from the moving surface; an unbalanced optical interferometer for changing the Doppler-shifted return light into an optical phase shift; and a processor for converting the optical phase shift from the interferometer into a voltage signal proportional to the velocity of the moving surface.

Brief Description of the Drawings

These and other objects, features and advantages of the invention, as well as the invention itself, will become better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein like reference numerals designate identical or corresponding parts throughout the several views and wherein:

Fig. 1 is a schematic block diagram of a preferred embodiment of the interferometric fiber optic Doppler velocimeter (velocity sensor) system of the present invention;

Figs. 2 and 3 show the performance of the fiber optic velocimeter of the invention in comparison to conventional sensing devices under various testing conditions in a laboratory.

Fig. 2 shows a typical comparison between the output signal from the fiber optic Doppler velocity sensor system and the integrated output signal from an accelerometer;

Fig. 3 shows the measured velocity amplitudes from the fiber optic Doppler velocity sensor system and the accelerometer as a function of applied acceleration;

Fig. 4 shows a velocity measurement of the fiber optic Doppler velocity sensor to a plate impact test;

Fig. 5 shows a velocity measurement of a magnetic coil velocity sensor to a plate impact test;

Fig. 6 shows a velocity measurement of the surface of an aluminum cylinder in response to an explosive charge;

Fig. 7 is a second embodiment of the fiber optic Doppler velocity sensor system with enhanced dynamic range;

Fig. 8 is a third embodiment of the fiber optic Doppler velocity sensor system with selectable responsivity; and

Fig. 9 is a fourth embodiment of the fiber optic Doppler velocity sensor system with multiple optical pickup heads.

Detailed Description of the Preferred Embodiments

Before the invention is described in detail, a few general comments about velocimeters, as well as the invention, will now be made.

The invention to be described is a fiber optic Doppler velocity sensor (or velocimeter) which performs non-contact measurements of the velocity of a moving surface or moving target. Sensor operation is based on interferometric processing of a wavelength encoded signal. The range of the fiber optic velocimeter is scalable from less than 1 mm/s to more than 1000 m/s through changes in the optical path imbalance in the fiber optic interferometer. A dynamic velocity resolution of < 80 $\mu m/s/\sqrt{Hz}$ has been demonstrated.

The fiber optic velocity sensor of the invention measures the Doppler shift in the optical frequency of light reflected from a moving surface. Unlike conventional heterodyne Doppler-based velocimeters, the system to be described operates through fiber optic interferometric decoding of the optical frequency shift. Interferometric processing of wavelength encoded sensors has been demonstrated previously, e.g. with Bragg grating devices. In previous work, the use of a readout interferometer has been demonstrated for decoding Bragg grating wavelength shifts by transposing the wavelength change into a phase shift at the output of an unbalanced Mach-Zehnder interferometer. This technique provides extremely high sensitivity to weak dynamic frequency shifts, and as such is particularly useful for monitoring transient events.

The system of the invention extends this highly sensitive interferometric decoding technique for wavelength encoded sensors to the measurement of surface velocities. Interferometric processing of the Doppler-induced frequency shift allows the detection of the velocity profile in the baseband by transposing the Doppler induced frequency shift in laser light reflected from a moving target into the phase shift of an interferometer. The technique has the added advantage that the system responsivity is scaled directly by the optical path difference of the interferometer used to process the Doppler-shifted light, and thus can be used for a wide range of velocities. As the long term phase stability of the readout interferometer limits the 'DC' sensing capability of the system, the present invention has been designed for, and tested with short duration transient effects, but could be modified to allow quasi-static monitoring.

Schemes currently exist for the optical measurement of the velocity of a moving target through detection of the Doppler shift of reflected light. For normal incidence, the optical frequency shift Δv is related to the target velocity V by

$$\Delta v = 2V/\lambda \tag{1}$$

where λ, is the wavelength of the incident light. The most common Doppler-based velocity measurement technique is heterodyne detection, where the Doppler shifted light is mixed with light at a fixed reference frequency at the optical detector, and the difference frequency is monitored. To avoid the problem of ambiguity in measuring the sign of the velocity, the heterodyne reference signal has an offset frequency (beat signal frequency at zero velocity) that is greater than the maximum frequency shift generated by the moving target. Heterodyne Doppler velocimeters are generally limited in velocity range by the large frequency shifts associated with high target velocities. For instance, velocities in the hundreds of meters per second have corresponding frequency shifts approaching GHz levels.

The detailed description of the preferred embodiment of the invention will be discussed by now referring to the drawings.

Fig. 1 is a schematic block diagram of a preferred embodiment of the interferometric fiber optic Doppler velocimeter (velocity sensor) system 11 of the present invention. As shown in Fig. 1, light from a coherent source or a single frequency laser 13, such as an Nd:YAG laser operating at 1.319 microns, is passed along single mode optical fiber 15 to a sensor head or exemplary rod lens 17 by way of input and output ports 19 and 21 of a fiber optic coupler 23. Although not absolutely required for the practice of the present invention, an isolator 25 can be inserted between laser 13 and port 19 of the coupler 19 in order to reduce feedback to the laser 13.

The sensor head 17 can comprise a collimating lens (or a focusing lens) which directs the laser light to a moving surface or moving target 27 and collects the frequency-shifted, or Doppler-shifted reflected return light 29. The lens 17 that is preferrably used is a simple GRIN (graded index) rod lens, with a low inherent back reflection of < - 40 dB. Low back reflection at the GRIN lens surface is necessary to prevent the creation of an additional interferometric signal in the system 11.

A small strip of retroreflecting tape 31 can be used on the moving surface 27 to ensure that a sufficient signal is returned as the moving surface 27 undergoes angular deviations. Typical working distances between the lens 17 and the surface 27 have been on the order of 5 cm, but experimentally it has been found that the system 11 operates at distances up to ~ 20 cm. Beyond 20 cm, the system 11 becomes limited by the reduced optical power collected by the GRIN lens from the retroreflecting surface 27 though the distance could be increased by switching to a laser 13 with greater power than the one used in this system (14 mW).

Light reflected from the target 27 is collected by the rod lens 17 and directed via the single mode optical fiber 15 and ports 21 and 22 of the optical coupler 23 to an unbalanced Mach-Zehnder interferometer 33. The interferometer 33 has a preselected path difference between its arms 33A and 33B such that, for example, the arm 33B is slightly longer than the other arm 33A. The interferometer 33 takes the return light 29 and, when that return light 29 is frequency modulated by the moving surface 27, converts the optical frequency shift in the Doppler-shifted light into phase shift at the interferometer 33 output.

The output of the interferometer 33 produces two outputs which are respectively detected by balanced detection by way of detecters 37 and 39.

It should be understood that the system 11 could be implemented to use any other suitable type of interferometer, such as, for example, a Michelson or a low reflection Fabry-Perot interferometer to perform this operation to obtain a phase term at the output of the interferometer 33 that is proportional to the velocity of the moving surface 27. So now when a velocity transient is produced due to a shock wave on the moving surface 29, the transient can be observed by looking at the phase at the output of the system 11. No frequency measurements have to be performed.

This becomes extremely important if high frequency transients have to be measured. For example, if transients due to very high intensity shock waves are of interest, motions of surfaces in kilometers per second could be involved. Of course, such such high speed motions do not last very long. So if something moves at a kilometer per second for a microsecond, it only moves 1 milimeter (1 mm). But it is still moving very quickly for a very short period of time and that is very difficult to determine when, for example, the conventional heterdyne technique is used.

Decoding of the Doppler-shifted return light is accomplished in the exemplary Mach-Zehnder unbalanced interferometer 33 in the following manner. The path imbalance imparts an optical phase shift that is a function of both the optical frequency shift and the length of the path imbalance.

The phase change of the interferometer output is determined by

$$\Delta\phi = \frac{4\pi nd}{c\lambda} V \qquad (2)$$

where d is the interferometer path imbalance, n is the index of refraction of the fiber (n = 1.45) and c is the speed of light. Of particular interest is the fact that the system responsivity, e.g. $\Delta\phi/V$, is directly proportional to the optical path imbalance (nd) of the interferometer. Therefore, the path imbalance can be adjusted to provide the desired scale factor for a range of target velocities. For this system, interferometers have been built with path imbalance ranging from 3 cm to 80 m in order to measure velocities ranging from more than 1000 m/s to less than 1 mm/s.

For this system, the interferometric phase shift is decoded though the use of the well-known phase-generated-carrier method.

A carrier signal is applied to either a piezoelectric transducer or an integrated optical phase modulator 35 located in one arm (arm 33B) of the interferometer 33 to generate a sinusoidal phase shift in the interferometer 33.

The outputs of the Mach Zehnder interferometer 33 are photodetected in photodetectors 37 and 39 and combined in a difference amplifier 41 to produce the cosine of the Doppler shift, cos $\{\Delta\phi(v)\}$. This output from the difference amplifier 41 is not just the phase itself, but is the cosine of the phase. So the signal cos $\{\Delta\phi(v)\}$ must be phase demodulated in a phase demodulator 43 to recover the phase of the Doppler shift.

In the preferred embodiment of Fig. 1, the phase demodulator 43 generates a carrier signal or carrier demodulator signal which is applied to to either a piezoelectric transducer or an integrated optical phase modulator 35 located in one arm (arm 33B) of the interferometer 33 to generate a sinusoidal phase shift in the interferometer 33. This carrier signal modulates the phase of the interferometer resulting in a modulated interferometric output at the output of the difference amplifier 41. The output of the difference amplifier 41 is fed to the phase demodulator 43 to yield the phase $\Delta\phi$.

It is possible to perform this phase demodulation by a variety of techniques well known to thos skilled in the art.

The electronic processing performed by the phase demodulator 43 converts the modulated interferometric output into a voltage signal which is proportional to the target velocity. As presently configured, the system responds to velocity-induced optical phase changes at frequencies up to 100 kHz.

The performance of the fiber optic velocimeter 11 was compared to conventional sensing devices under various testing conditions. First, small sinusoidal target velocities (<0.1 m/s) were generated by an electrically driven mechanical shaker. The motion was monitored simultaneously by the fiber optic velocity sensor and a small piezoelectric accelerometer which was mounted to the shaker surface.

Fig. 2 shows a typical comparison between the output velocity signal from the fiber optic velocity sensor 11 compared to an integrated output signal from the accelerometer (with an offset added for clarity), with a test signal at 200 Hz applied when they were used to monitor the motion of a shaker table or shaker platform. And the agreement in terms of the velocity and the time trace of the two signals can be readily seen.

Fig 3 shows the measured velocity amplitudes from the fiber optic Doppler velocity sensor system and the accelerometer as a function of the acceleration applied to the shaker. In general, there is excellent agreement between the velocities measured by the two sensors. The fiber optic velocity sensor noise floor corresponds to a minimum detectable velocity resolution of < 80 $\mu m/s/\sqrt{Hz}$. For this test the path imbalance of the interferometer was d = 80 m.

To generate a more severe test of the fiber optic velocity sensor than was possible with the mechanical shaker, both in terms of transient signal content and higher peak velocities, a vertical impact plate with a horizontal hammer on a pendulum was constructed. This system could produce transient velocities on the order of a few meters per second. The plate was 50 cm x 76 cm, and was clamped along all four edges. A magnetic coil velocity sensor was mounted to the center of the plate on the side opposite the impact, and the light from the fiber optic sensor was incident on a strip of retroreflecting film attached to the end of the magnetic coil velocity sensor. The use of the coil velocity sensor in place of the piezoelectric accelerometer eliminated the need to integrate the output signal for comparison with the fiber optic sensor.

Figs. 4 and 5 show the typical responses of the two sensors for a rear impact test or transient shock event applied to the plate. The fiber optic velocity sensor response is shown in Fig. 4, and the magnetic coil velocity sensor response is shown in Fig. 5. Although the agreement between the two responses is quite good, a small difference appears approximately 15 ms after the impact. The most likely source of the difference would be any transverse motion induced in the center of the plate through any small asymmetries in the mechanical system.

Measurement of surface velocity during an explosive shock test was performed in order to test the performance of the fiber optic velocity sensor in response to high-velocity (100 m/s) short time scale (150μs) events.

In Fig. 6, the velocity signal generated by the fiber optic sensor from such a test is compared to the velocity record derived from the surface displacement recorded with a high-speed streak camera. Figs 2-6 show that there is good agreement between the fiber optic sensor and conventional sensors over a wide range of target velocities and time scales.

Referring briefly back to Fig. 1, the sensitivity of the system 11 of the invention depends on the optical path difference (OPD) between the arms 33A and 33B of the interferometer 33. since the arm 33B of the interferometer is a distance d longer than the other arm 33A, the optical difference is d times the refractive index, n, of the glass. And so there is an optical path difference nd which can be anything from millimeters to meters (mm to m) difference. If that path difference is made smaller, then the system 11 responds to higher velocities. If that path difference is made longer, then the system 11, becomes sensitive smaller velocities. So by changing that optical path difference (OPD), if it is desired to look at mm of displacement, then ten's of meters of path difference could be used. If, on the other hand, it is desired to look at velocities of kilometers per second, then only centimeters of path difference could be used.

ALTERNATIVES

A single fiber optic system 11A could be fabricated to operate simultaneously over the entire velocity range between 1 mm/s and 1000 m/s. As shown in Fig. 7, several interferometers 33 and 34 with different path imbalances could operate in parallel by splitting the reflected frequency-shifted light into each of the interferometers 33 and 34. Each interferometer would process the velocity data over a particular velocity range.

It is also possible to create a system 11B with a variable velocity range by incorporating an optical switch 45 in one arm 36A of the interferometer 33, as shown in Fig. 8. The system 11B would switch different optical path lengths d_1 and d_2 into the one arm 36A of the interferometer 33.

In order to avoid potential problems with signal fading or damp out as the target surface 27 moves, multiple detection heads or pickup lenses 17A and 17B could be positioned near the surface 27, as shown in Fig. 9. Each of the pickup lenses 17A and 17B would be fiber coupled to a separate one of two interferometers 33 and 33.

ADVANTAGES AND NEW FEATURES OF THE INVENTION

A fiber optic interferometrically decoded laser Doppler velocimeter sensor system has been described and demonstrated. Such a sensor can be scaled to operate over a wide range of velocities, from less than 1 nm/s up to 1000 m/s, by properly scaling the path imbalance in the decoding interferometer. The sensor is capable of resolving velocity signals to 80 μm/s. Interferometric processing of the Doppler-induced frequency shift allows direct detection of the velocity profile in the baseband by transposing the Doppler induced frequency shift in laser light reflected from a moving target into the phase shift of an interferometer. Baseband detection reduces some of the difficulties associated with the high speed detection necessary in Doppler heterodyne detection.

A single optical fiber serves as the source and return paths for the laser light, a feature which permits simplified deployment and ease of use. The detector head assembly and target surface can be located a significant distance from the optical source, the interferometer, and the processing electronics.

Therefore, what has been described in preferred embodiments of the invention is a fiber optic velocity sensor system for measuring the Doppler shift in the optical frequency of light reflected from a moving surface is disclosed. The velocity sensor system comprises: a source of coherent light; a sensor for directing the coherent light to a moving surface and collecting a Doppler-shifted return signal from the moving surface; an unbalanced optical interferometer for changing the Doppler-shifted return light into an optical phase shift; and a processor for converting the optical phase shift from the interferometer into a voltage signal proportional to the velocity of the moving surface. Other embodiments of the fiber optic Doppler velocity sensor system of the invention include an embodiment with enhanced dynamic range, an embodiment with selectable responsivity, and an embodiment with multiple optical pickup heads.

It should therefore readily be understood that many modifications and variations of the present invention are possible It is therefore to be understood that the invention may be practiced otherwise than as specifically described.

ABSTRACT

A fiber optic velocity sensor system for measuring the Doppler shift in the optical frequency of light reflected from a moving surface is disclosed. The velocity sensor system comprises: a source of coherent light; a sensor for directing the coherent light to a moving surface and collecting a Doppler-shifted return signal from the moving surface; an unbalanced optical interferometer for changing the Doppler-shifted return light into an optical phase shift; and a processor for converting the optical phase shift from the interferometer into a voltage signal proportional to the velocity of the moving surface. Other embodiments of the fiber optic Doppler velocity sensor system of the invention include an embodiment with enhanced dynamic range, an embodiment with selectable responsivity, and an embodiment with multiple optical pickup heads.

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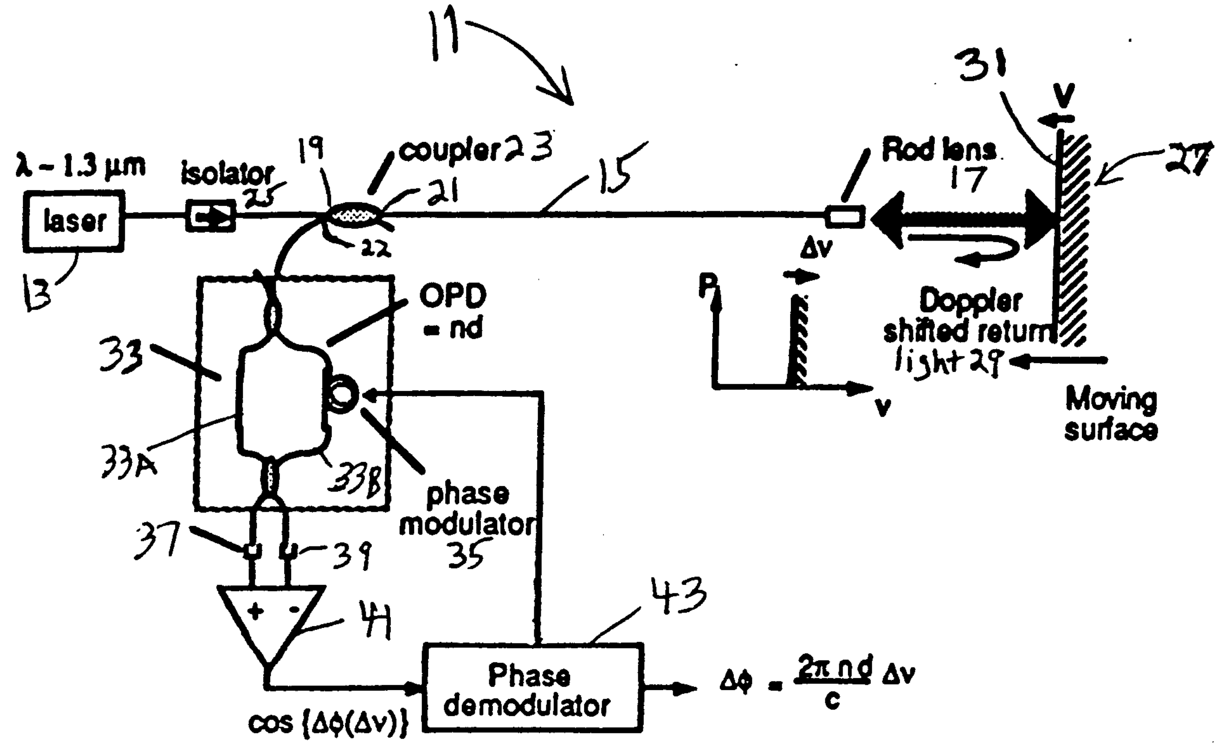


FIG. 1

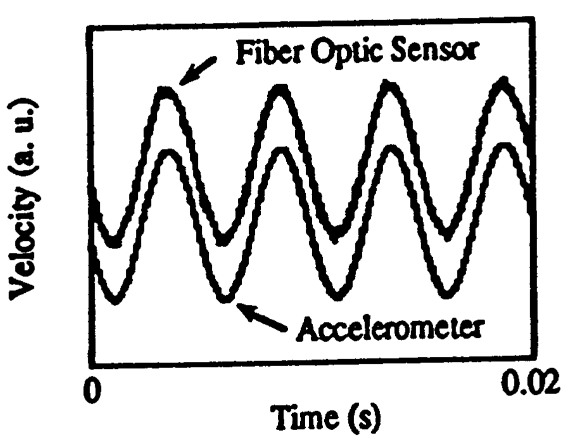


FIG. 2

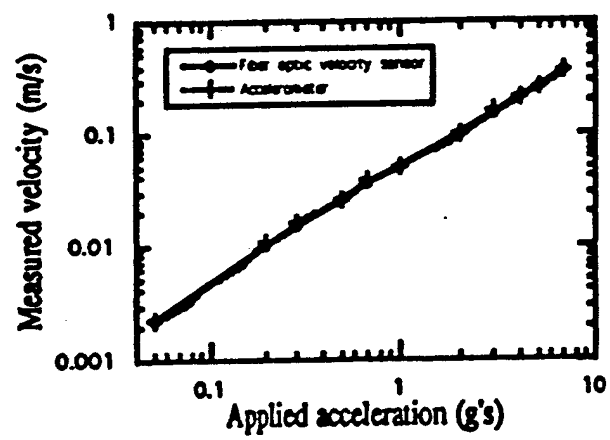


FIG. 3

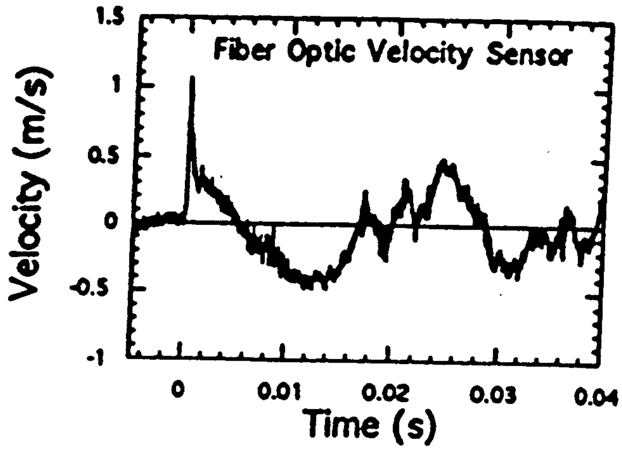


FIG. 4

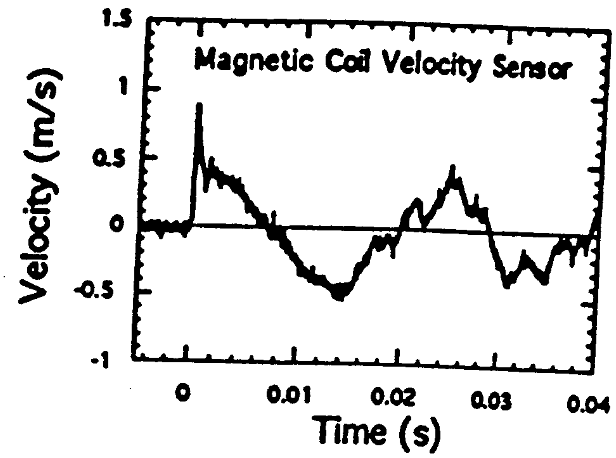


FIG. 5

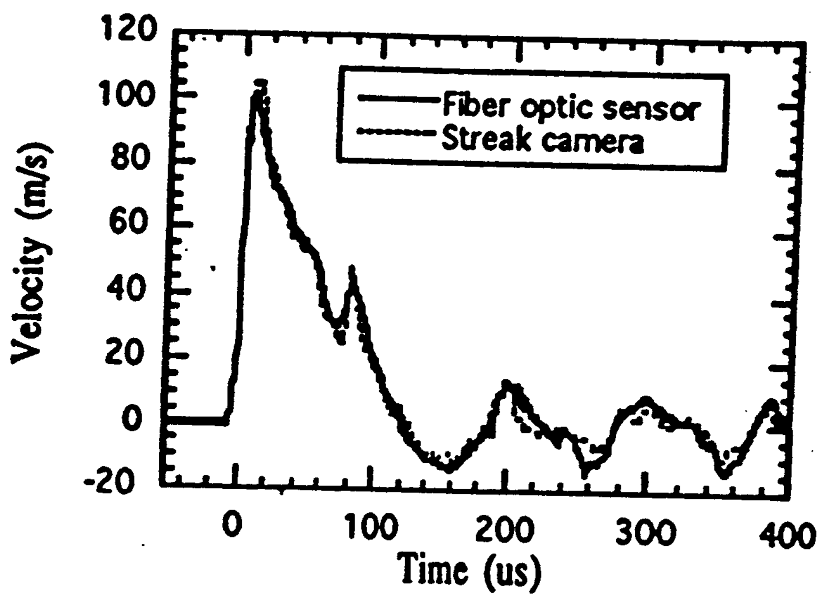
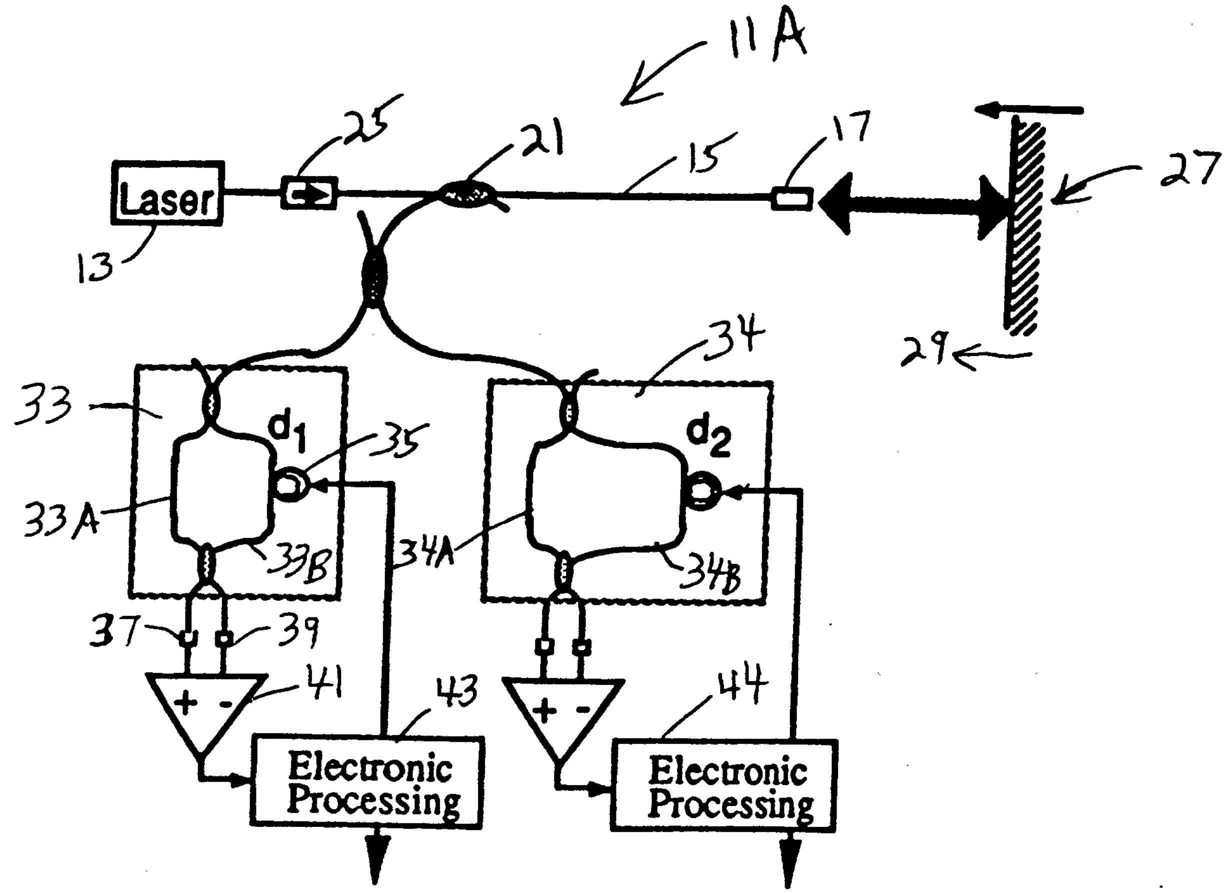


FIG. 6


11A
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21
15
17
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33
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d1
d2
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33A
33B
34A
34B
37
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43
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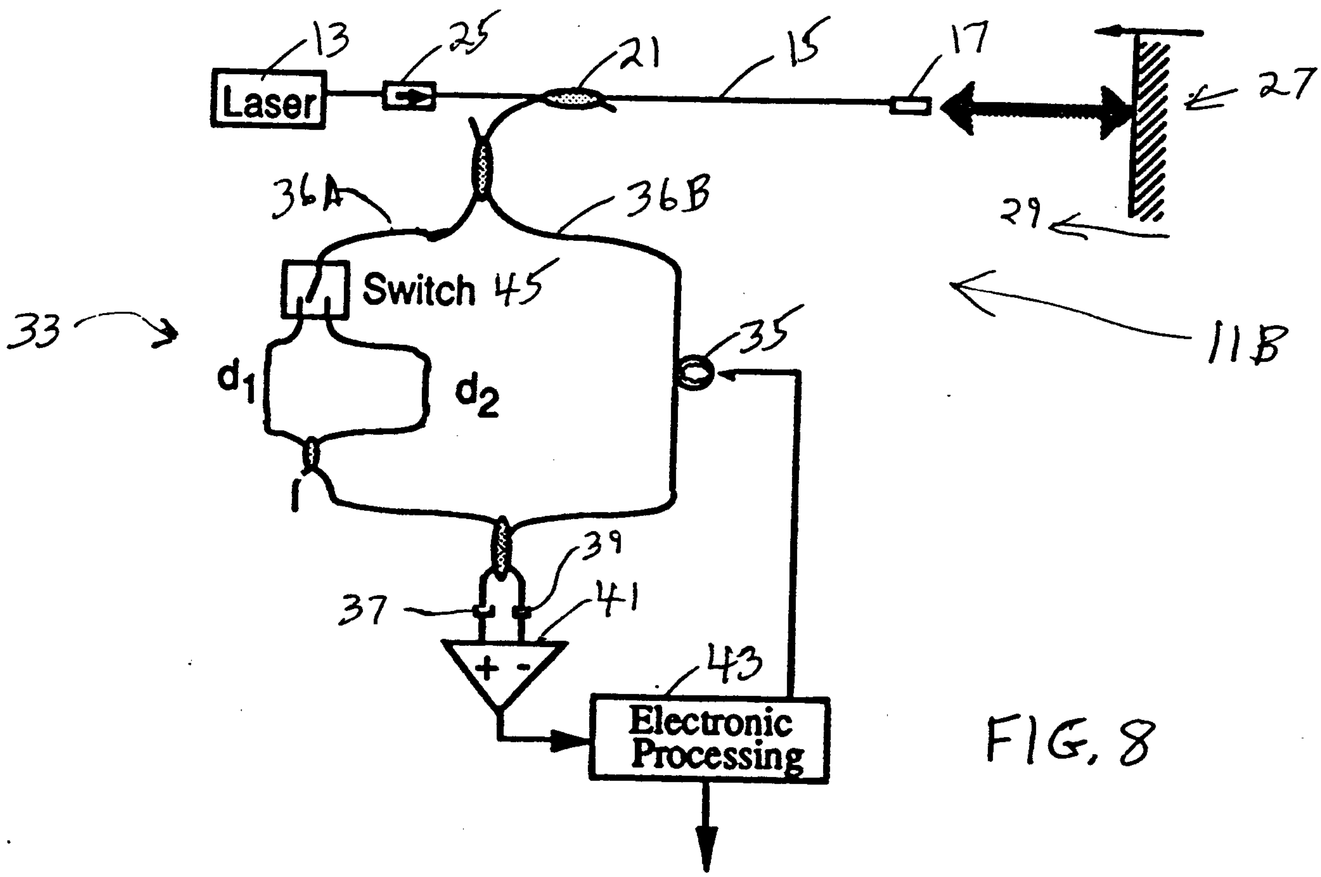
Electronic Processing
Electronic Processing

FIG. 7


Laser
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Switch 45
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11B
d1
d2
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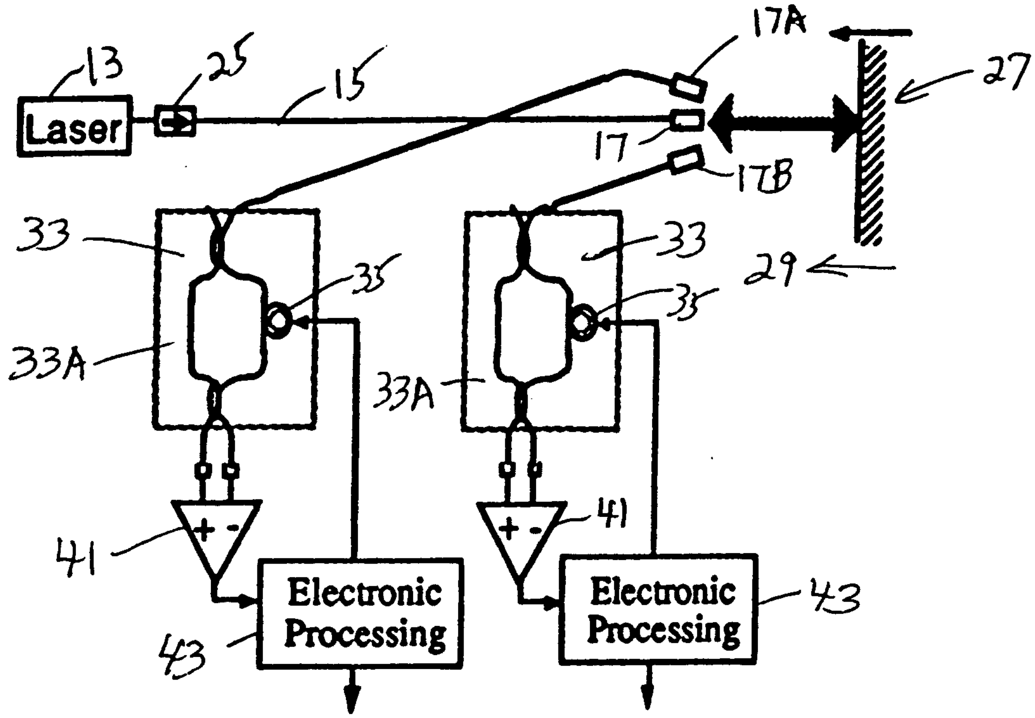
41
43
Electronic Processing

FIG. 8



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Electronic Processing
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FIG. 9