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NASA CASE NO. LAR 14640-1-CU

PRINT FIG. 1

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INTERFEROMETER HAVING FUSED OPTICAL
FIBERS, AND APPARATUS AND METHOD
USING THE INTERFEROMETER Patent
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AN INTERFEROMETER HAVING FUSED OPTICAL FIBERS,
AND APPARATUS AND METHOD USING THE INTERFEROMETER

The present invention relates to an interferometer and method using the interferometer, for sensing physical phenomenon such as pressure or stress.

As shown in FIG. 2, the interferometer 1 includes a first optical fiber 2 coupled to a second optical fiber 3 by fusing. At a fused portion, the first and second optical fibers 2 and 3 are cut to expose respective cores. The cut or fused end of the first and second optical fibers 2 and 3 is arranged to oppose a diaphragm or surface against which a physical phenomenon such as pressure or stress, is applied. Interference between a reference and reflected light from the diaphragm 12 or the surface occurs in the second optical fiber 3 so that an output light has an intensity which depends upon the positional relationship between the interferometer 1 and the diaphragm 12 or the surface. Accordingly, the intensity of the output light represents the amount of the physical phenomenon such as pressure or stress, applied to the diaphragm or surface.

The interferometer is expected to provide several advantages. The interferometer is less sensitive to temperature and does not require thermal compensation associated with prior art devices and techniques. Also, the interferometer can detect small displacements and is suitable for miniaturization. In addition, the interferometer may be provided with a cooling structure so that the interferometer can be operated in relatively high-temperature and/or high-vibration environments.

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PATENT APPLICATION

AN INTERFEROMETER HAVING FUSED OPTICAL FIBERS,
AND APPARATUS AND METHOD USING THE INTERFEROMETER

Origin of the Invention

5 The invention described herein was jointly made in the performance of work under NASA Grant No. NAS 1-18471 and an employee of the U.S. Government. In accordance with 35 U.S.C. §202, the contractor elected not to retain title.

10 Background of the Invention

1. Field of the Invention

15 The present invention relates generally to an interferometer having fused optical fibers, and an apparatus and method using the interferometer, or more specifically, to a pressure-sensing interferometer using fused optical fibers and a diaphragm for sensing pressure, and an apparatus and method using the pressure-sensing interferometer.

20 2. Description of the Related Art

25 Many types of pressure sensors have been developed for high-temperature and/or high-acoustic environments such as turbojets and rocket engines. Such pressure sensors are required to withstand relatively high heat flux and/or high vibrations.

30 One conventional sensor for high-temperature and/or high-acoustic environments uses optical fibers in conjunction with a diaphragm sensor. One optical fiber is arranged to face a diaphragm having a reflective surface. The diaphragm receives pressure at one side thereof so that the position of the diaphragm relative to one end of the optical fiber depends upon the amount of pressure applied to the diaphragm. Therefore, the intensity of the light reflected

from the reflective surface of the diaphragm and received by the optical fiber (or, alternatively, received by a second optical fiber) represents the amount of pressure applied to the diaphragm. A photodiode may be used to convert the optical signal into an electrical signal representing the amount of pressure applied to the diaphragm.

The conventional sensor described above suffers from difficulties in calibration for time-dependent, high heat flux environments. In addition, sensors of this nature lack sensitivity, and therefore, are not well-suited for many applications.

Various interferometric sensors have been described. While these sensors, particularly those based on the Michelson interferometer, are expected to be highly utilized, most presently known interferometric sensors require thermal compensation to account for temperature differences in the optical systems associated with such sensors. While Fabry-Perot interferometric sensors may not require thermal compensation, such sensors do not have a flat response to, for example, acoustic frequencies.

Summary of the Invention

It is an object of the present invention to provide an apparatus and method using coupled optical fibers to sense displacement of a diaphragm or surface.

Another object of the present invention is to provide a pressure transducer and method using coupled optical fibers to sense a pressure exerted on a diaphragm or surface.

Another object of the present invention is to provide an apparatus and method using coupled optical fibers to sense displacement of a diaphragm or surface with high sensitivity.

Another object of the present invention is to provide an apparatus and method using coupled optical fibers, which can be operated in relatively high-temperature and/or relatively high-vibration environments.

5 Another object of the present invention is to provide an apparatus and method using coupled optical fibers suitable for miniaturization.

In order to achieve the foregoing and other objects, in accordance with the purposes of the present invention as described herein, an apparatus is provided with a first optical fiber which is coupled to a second optical fiber by fusing. A fused portion of the first and second optical fibers is cut cross-wise
10 to expose a fused end. In the fused end, the respective claddings of the first and second optical fibers are integrated together while the respective cores of the first and second optical fibers remain distinct. The fused end may be polished or ground, and in a first embodiment, a reflective surface is selectively deposited on the fused end to cover the core of the first optical fiber, but not
15 the core of the second optical fiber.

In operation, the first embodiment of the present invention uses the first optical fiber to receive a source light which is preferably a monochromatic, coherent light such as is generated by a laser. By evanescence, reference light based on the source light, effectively crosses from the first optical fiber to the
20 second optical fiber at the fused portion, and is transmitted to a diaphragm or a surface situated to oppose the fused end of the first and second optical fibers. Light which reflects from the diaphragm or the surface is received at the fused end. The reflected light interferes with the reference light reflected from the reflective surface, in the second optical fiber so that light output from the
25 second optical fiber has an intensity which depends upon interference of the reference light and the reflected light, and therefore, which depends upon a positional relationship between the fused end and the diaphragm or surface. Accordingly, a physical phenomenon such as a pressure, applied to the diaphragm or surface may be sensed.

Alternatively, in the first embodiment, the source light may include light having substantially first and second wavelengths. The source light having the substantially first wavelength is used to generate output light indicating the positional relationship or displacement between the fused end and the diaphragm or the surface, while the source light having the substantially second wavelength is used to generate output light indicating a direction of change of the positional relationship or displacement.

In the first embodiment, the reflective surface is provided on the fused end to cover the core of the first optical fiber. However, in a second embodiment, the reflective surface is not provided on the fused end. In operation, the second embodiment uses the first and second optical fibers to transmit source light to a diaphragm or surface. Source light from the first and second cores of the first and second optical fibers, respectively, reflects from first and second portions of the diaphragm or surface. The intensity of the output light of the end of either of the first and second optical fibers opposite the fused end, depends upon interference between reference light and reflected light reflected from the first and second portions of the diaphragm, respectively, and accordingly, depends upon the positional relationship or displacement between the first and second portions of the diaphragm or surface approximately relative to a direction from which the reference light and reflected light are received from the diaphragm or surface. Accordingly, as with the first embodiment of the present invention, a physical phenomenon such as pressure or stress, applied to the diaphragm or the surface, may be sensed.

Alternatively, in the second embodiment, the source light may include light having substantially first and second wavelengths. The source light having the substantially first wavelength is used to generate output light indicating the positional relationship or displacement between the first and second portions of the diaphragm or surface, while the source light having the substantially second wavelength is used to generate output light indicating a direction of change of the positional relationship or displacement.

A third embodiment utilizes the structure of the first embodiment or the second embodiment, but operates by utilizing input light of substantially first and second wavelengths to determine an absolute positional relationship or displacement between the fused end and the diaphragm in the first
5 embodiment, or the first and second portions of the diaphragm or surface in the second embodiment.

These and other features and advantages of the present invention will become more apparent with reference to the following detailed description and drawings, wherein like numerals refer to like parts throughout. However, the
10 drawings and description are merely illustrative in nature and not restrictive.

Brief Description of the Drawings

The accompanying drawings illustrate various aspects of the present
15 invention, and together with the detailed description serve to explain the principles of the present invention. In the drawings:

Figure 1 is a schematic view of an interferometer in accordance with the present invention;

Figure 2 is a schematic view of an apparatus employing an
20 interferometer in accordance with a first embodiment of the present invention;

Figure 3 is a graph illustrating intensity of output light as a function of phase difference between the reference light and the reflected light for the apparatus of Figure 2;

Figure 4 is a cross-sectional view of a diaphragm in accordance with the
25 present invention;

Figure 5 is a schematic view of a protective housing for the interferometer in accordance with the present invention;

Figure 6 is a cross-sectional view of a cooling structure for cooling the diaphragm in accordance with the present invention;

Figure 7 is a cross-sectional view of an assembled mounting cylinder and cooling structure for an apparatus in accordance with the present invention;

Figure 8 is a graph of the output of the apparatus of Figure 7 as a function of sound pressure level; and

5 Figure 9 is a graph of the output of the apparatus of Figure 7 as a function of acoustic frequency.

Detailed Description of the Preferred Embodiments

10 Figure 1 is a schematic view of an interferometer 1 in accordance with the present invention. The interferometer 1 includes a first optical fiber 2 which is coupled to a second optical fiber 3 by fusing. Preferably, the first optical fiber 2 includes a first core 4 having a first cladding 5 while the second optical fiber 3 includes a second core 6 having a second cladding 7. The first and second
15 optical fibers 2 and 3 may be formed of quartz, silicate, sapphire or plastic, for example, and are available from many commercial sources such as Corning Glass. The interferometer 1 is completed by cutting along the cleavage plane 8, for example, by using a diamond scribe to etch an imperfection which propagates along the cleavage plane 8 upon bending the first and second
20 optical fibers 2 and 3 at the imperfection, or by placing the interferometer 1 in epoxy and polishing or grinding the resulting structure back to the cleavage plane 8. By cutting along the cleavage plane 8, however, it will be recognized that a second optical fiber system 9 which is similar to the optical fiber system 1, is formed.

25 Figure 2 is a schematic view of an apparatus employing an interferometer in accordance with a first embodiment of the present invention. In Figure 2, the interferometer 1 has a fused end 10 corresponding to the cleavage plane 8. The fused end 10 is the surface which results from cutting and/or polishing or grinding the first and second optical fibers 2 and 3 of Figure
30 1 along the cleavage plane 8. In the first embodiment of the present invention,

a reflective surface 11 is provided on a portion of the fused end 10. Preferably, the reflective surface 11 is formed such that an entire cross-section of the first core 4 exposed at the fused end 10 is covered by the reflective surface 11. The reflective surface 11 may be formed by masking a portion of the fused end
5 10 including a cross-section of the second core 6 and depositing a reflective material such as aluminum on the fused end 10 using, for example, a chemical vapor deposition or sputtering technique. Further, it is believed that organometallic paint could be used to form the reflective surface 11 by painting the organometallic paint on the portion of the fused end 10 including the cross-
10 section of the first core 4, and baking the organometallic paint to deposit reflective material to form the reflective surface 11. Such organometallic paint is available from Engelhard, Inc.

Alternatively, in the second embodiment of the present invention, the reflective surface 11 is not provided on the fused end 10. The second
15 embodiment will be described in a later section.

The fused end 10 is arranged to oppose a diaphragm 12. The diaphragm 12 has a first side opposing the fused end 10 which is reflective, and a second side which receives a physical phenomenon, such as a pressure or stress, to be sensed. Particularly in high temperature environments, the
20 diaphragm 12 is preferably formed of copper due to its relatively high thermal conductivity and relatively low modulus of elasticity, as will be explained in more detail in a later section.

The operation of the apparatus of Figure 2 will now be described. The first optical fiber 2 receives a source light 13 at an end opposite the fused end
25 10. Preferably, the source light 13 is single-mode monochromatic, coherent light such as that produced by a laser. While it is preferred that the source light 13 be single-mode (e.g., linearly polarized $LP_{0,1}$), it is presently believed that the interferometer 1 would function properly if other modes are present. In any event, the source light 13 must be substantially monochromatic, coherent light
30 to generate interference.

Due to a phenomenon known as "evanescence," the coupling of the first and second optical fibers 2 and 3 results in a portion of the source light 13 effectively crossing from the first optical fiber 2 to the second optical fiber 3. This portion of the source light 13 propagates from the second core 6 to the first side of the diaphragm 12 and is reflected as reflected light 14 back to the fused end 10. The reflected light 14 received at the fused end 10 propagates to the left in the second core 6 of Figure 2.

The source light 13 also reflects from the reflective surface 11. The source light 13 reflected from the reflective surface 11 is termed 'reference light' 36 because the reflective surface 11 defines a reference arm of the interferometer 1. By evanescence, the reference light 36 effectively crosses from the first optical fiber 2 to the second optical fiber 3. An output light 15 has an intensity which depends upon interference of the reference light 36 and the reflected light 14, which in turn depends upon the positional relationship or distance between the fused end 10 and the diaphragm 12. Accordingly, a physical phenomenon such as pressure applied to the second side of the diaphragm 12 affects the distance between the fused end 10 and the diaphragm 12, and the resulting phase difference between the reference light 36 and the reflected light 14 causes the output light 15 to have an intensity which depends upon the amount of the physical phenomenon, such as pressure, applied to the second side of the diaphragm 12. The output light 15 may be provided to an optical/electronic converter such as a photodiode to convert the output light 15 into an electronic signal representing the amount of the physical phenomenon applied to the second side of the diaphragm 12.

In general, light propagating in an optical fiber will have a phase at a given point within the optical fiber which depends upon the temperature of the optical fiber. In many interferometric sensors, temperature differences between different parts of the same optical fiber or more than one optical fiber, must be compensated to obtain valid measurements of a physical phenomenon. Such compensation is especially necessary in sensors for use in high-temperature

environments since relatively high temperature differences may be applied to different parts of the same optical fiber or different optical fibers. The interferometer 1 of the present invention greatly reduces or eliminates the need to provide temperature compensation between the first optical fiber 2 and the second optical fiber 3 since the first optical fiber 2 and the second optical fiber 3 are fused together at the portion of the first and second optical fibers 2 and 3 (i.e., the fused end 10) which transmits the reference light 13 to the diaphragm 12 and receives the reflected light 14 from the diaphragm 12. Therefore, since the first optical fiber 2 and the second optical fiber 3 are fused together, no significant temperature difference occurs in the fused portion of the first optical fiber 2 and the second optical fiber 3. Accordingly, the output light 15 generated by the interferometer 1 is relatively unaffected by the temperature in which the interferometer 1 is operated. For this reason, the interferometer 1 is referred to as a temperature insensitive Michelson interferometer (TIMI).

As an alternative, the interferometer 1 of the first embodiment of the present invention can be operated using a source light 13 having substantially first and second wavelengths. The substantially first wavelength can be used to generate output light 15 as described above, to detect an amount of change of a positional relationship or displacement between the fused end 10 and the diaphragm 12 or surface. Similar to the generation of the output light 15 as described above, the substantially second wavelength of the source light 13 can be used to indicate the direction or sense of change of the positional relationship or displacement between the fused end 10 and the diaphragm 12 or surface by generating interference in a similar manner to that obtained with the substantially first wavelength. Accordingly, the output light 15 includes light of the substantially first wavelength having an intensity which depends upon the positional relationship or displacement between the fused end 10 and the diaphragm 12 or surface, as well as light of a substantially second wavelength having an intensity which can be used to determine the direction of change of the positional relationship or displacement by obtaining an absolute value of the

difference between intensity of the substantially first wavelength and the substantially second wavelength. If the difference increases, the displacement between the fused end 10 and the diaphragm 12 or surface, has increased. On the other hand, if the difference decreases, the displacement between the

5 fused end 10 and the diaphragm 12 or surface, has decreased. The output light 15 can be provided to a prism, a diffraction grating, or split by a beam splitter, and each of the split beams can be filtered appropriately, to obtain a first optical signal corresponding to the positional relationship or displacement between the fused end 10 and the diaphragm 12 or surface, and a second

10 optical signal used to indicate the direction of change of the positional relationship or displacement.

The second embodiment of the present invention is similar to the first embodiment, except that the reflective surface 11 is omitted. Also, in the second embodiment, the first core 4 of the first optical fiber 2 is arranged to

15 oppose a first portion of the diaphragm 12, which preferably is relatively stationary such as, for example, near a fixed-edge of the diaphragm 12. The second core 6 of the second optical fiber 3 is arranged to oppose a second portion of the diaphragm 12, which preferably undergoes maximum deflection upon exertion of a physical phenomenon such as pressure or stress. In

20 operation, the source light 13 is provided to the first optical fiber 2. The source light 13 is transmitted from the first optical fiber 2 to the first portion of the diaphragm 12 and reflected back to the first optical fiber 2 as the reference light 36. By evanescence, the reference light 36 effectively crosses to the second optical fiber 3. The source light 13 transmitted from the second optical fiber 3

25 to the second portion of the diaphragm 12, is reflected back to the second optical fiber 3 as the reflected light 14. In the second optical fiber 3, the output light 15 has an intensity which depends upon interference of the reference light 36 and the reflected light 14, which in turn depends upon the positional relationship or displacement between the first portion and the second portion

30 of the diaphragm 12 relative to a direction in which the reference light 36 and

reflected light 14 are received from the diaphragm 12. The output light 15 could also be derived from the first optical fiber 2 since interference between the reference light 36 and the reflected light 14, also occurs in the first optical fiber 2.

5 Alternatively, in the second embodiment, the source light 13 can include light of substantially first and second wavelengths. The source light 13 of the substantially first wavelength can be used to generate output light 15 having the substantially first wavelength an intensity representing the positional relationship or displacement between the first and second portions along the direction in
10 which the reference light 36 and reflected light 14 are received from the diaphragm 12, and having the substantially second wavelength an intensity which can be used to determine a direction of change of the positional relationship or displacement. The output light 15 can be applied to a prism, a diffraction grating, or a beam splitter and each split beam can be appropriately
15 filtered, to extract a first optical signal indicating positional relationship or displacement, and a second optical signal which can be used to indicate a direction or sense of change of the positional relationship or displacement as explained above with respect to the first embodiment.

 In either of the first and second embodiments of the present invention,
20 the diaphragm 12 may be replaced by any surface receiving a physical phenomenon to be sensed.

 The first and second embodiments of the present invention utilize a differential interferometer since a measurement of displacement or positional relationship is relative to an initial positional relationship or displacement
25 between the fused end 10 and the diaphragm 12 or surface in the first embodiment, and the first and second portions of the diaphragm 12 or surface in the second embodiment. A third embodiment of the present invention can be used to detect absolute measurements of the positional relationship or displacement between the fused end 10 and the diaphragm 12 or surface in the
30 first embodiment, and the first and second portions of the diaphragm 12 or

surface in the second embodiment. In operation the third embodiment of the present invention utilizes a source light 13, which has substantially first and second wavelengths λ_1 and λ_2 , respectively. Assuming the substantially first wavelength λ_1 is less than the substantially second wavelength λ_2 , the phase of either the first or second wavelengths λ_1 and λ_2 is defined by equation (1) as:

$$(1) \quad \Phi_{1,2} = \frac{4\pi \cdot L}{\lambda_{1,2}},$$

where $\phi_{1,2}$ is the phase of either the substantially first or second wavelengths λ_1 or λ_2 , L is the displacement or positional relationship between the fused end 10 and the diaphragm 12 or surface in the first embodiment, or the displacement or positional relationship between the first and second portions of the diaphragm 12 or surface in the second embodiment, and $\lambda_{1,2}$ is the wavelength of the substantially first or second wavelengths λ_1 and λ_2 .

The phase difference between the substantially first and second wavelengths λ_1 and λ_2 is defined by equation (2) as:

$$(2) \quad \Delta\phi = \phi_1 - \phi_2 = \frac{4\pi \cdot L \cdot \lambda_1 \cdot \lambda_2}{\lambda_2 - \lambda_1}.$$

Therefore, the displacement or positional relationship between the fused end 10 and the diaphragm 12 or surface in the first embodiment, or the first and second portions of the diaphragm 12 or surface in the second embodiment, is defined by equation (3) as:

$$(3) \quad L = \frac{\Delta\phi \cdot \lambda_1 \cdot \lambda_2}{4\pi \cdot \Delta\lambda},$$

where $\Delta\lambda$ is the difference between the substantially first and second wavelengths. Accordingly, by using a prism, a diffraction grating or a beam splitter with appropriate filters, the intensities of the substantially first and

second wavelengths λ_1 and λ_2 can be extracted from the output light 15. By subtracting the intensities of the substantially first and second wavelengths λ_1 and λ_2 , a value proportional to the phase difference $\Delta\phi$ is obtained. This value can be used in conjunction with equation (3) to determine the positional relationship or displacement between the fused end 10 and diaphragm 12 or surface in the first embodiment, or the first and second portions of the diaphragm 12 or surface in the second embodiment. Therefore, equation (3) can be used to determine the absolute positional relationship or displacement in either the first or second embodiments of the present invention.

Figure 3 is a graph illustrating intensity of the output light 15 as a function of the phase difference between the reference light 36 and the reflected light 14 for the first embodiment of the present invention. At zero radians (i.e., a situation in which the reference light 36 and the reflected light 14 are in phase), the respective intensities of the reference light 36 and the reflected light 14 add to cause the output light 15 to have a maximum intensity. On the other hand, at π radians, the reference light 36 and the reflected light 14 are out of phase such that the output light 15 has a minimum intensity. While relatively large displacements of the diaphragm 12 relative to the fused end 10 can be measured by "fringe counting" (i.e., observing the number of times the intensity of the interference pattern 15 passes through some reference intensity in one direction as the diaphragm is displaced from some reference position to a given position under influence of a physical phenomenon such as pressure), relatively small displacements of the diaphragm 12 may also be measured using the interferometer 1. Preferably, when measuring small displacements of the diaphragm 12 relative to the fused end 10, the interferometer 1 is operated in a linear region such as that shown in Figure 3. To best attain operation in the linear region, an operation point of the interferometer 1 is adjusted by changing the frequency of the source light 13 so that the output light 15 has an intensity about equal to half of the difference between the maximum and minimum intensities. Small displacements of the

diaphragm 12 result in an approximately linear change in the intensity of the output light 15. Operation of the interferometer 1 in the linear region as shown in Figure 4, is particularly well-suited to applications which require relatively high sensitivity, such as the sensing of acoustic pressure. Since the minimum detectable displacement of the diaphragm 12 is a function of the wavelength and signal-to-noise ratio (SNR) of the source light 13, and since SNR values of 70 to 80 decibels are theoretically possible, it is expected that the interferometer 1 could be used to detect displacements as small as one Angstrom (10^{-10} m).

Figure 4 is a cross-sectional view of the diaphragm 12. In Figure 4, a pressure P is applied to the second side of the diaphragm 12. The maximum displacement of the diaphragm along an axis normal to the surface of the diaphragm 12 and along a direction in which the pressure P is applied to the diaphragm 12, is defined by the following equation:

$$(4) \quad y_0 = \frac{3(1-\mu^2)Pa^4}{16Eh^3}$$

where y_0 is the maximum deflection of the diaphragm 12, μ is Poisson's ratio, P is the pressure exerted against the diaphragm 12, a is the radius of the diaphragm 12, E is Young's modulus of elasticity and h is the thickness of the diaphragm 12. For sensitive measurements of the displacement of the diaphragm 12, it is important for the deflection of the diaphragm 12 to be within a quarter of the operating wavelength of the interferometer 1 to maintain an approximately linear relationship between the displacement y_0 of the diaphragm 12 and the intensity of the output light 15. For example, assuming that the diaphragm 12 is formed of copper with $a=.625\text{mm}$ and $h=.05\text{mm}$, an estimate is made of the maximum pressure to which the diaphragm 12 will be subjected. For example, a maximum pressure of 1.4 kiloPoise produces a maximum center defection of 39nm. Thus, the wavelength of the source light 13 should be at least $39\text{nm} \times 4 = 156\text{nm}$.

Another constraint upon the material and dimensions of the diaphragm 12 relates to the natural frequency of the diaphragm 12. The natural frequency is defined by:

$$(5) \quad f_n = 9.22 \frac{h}{a^2} \left[\frac{E}{w(1-\mu^2)} \right]^{1/2}$$

5 where w is the specific weight of the material composing the diaphragm 12 (in this case, copper). While equation (5) does not take into account damping due to gases to which the diaphragm 12 may be exposed or due to edge-mounting adhesive which may be applied around the edges of the diaphragm 12, equation (5) is sufficient to obtain an estimate of the natural frequency of the
10 diaphragm 12. In this case, the natural frequency $f_n = 208\text{kHz}$. The maximum acoustic frequency which can be transferred to a 1.25mm diameter diaphragm 12 is limited to about 100kHz. Since this frequency is well above the desired working range of several kilohertz for use in, for example, structural acoustic load testing, and since the natural frequency of 208kHz is above the desired
15 working range, the dimensions and material of the diaphragm 12 as selected above are appropriate for an application such as structural acoustic load testing. In any event, it is important to keep the natural frequency of the diaphragm 12 above the working range of frequencies to maintain a linear relationship between the displacement of the diaphragm 12 and the intensity
20 of the output light 15.

While other materials may be used for the diaphragm 12, copper has a relatively high thermal conductivity and relatively low modulus of elasticity. The low modulus of elasticity of copper allows for a relatively thick diaphragm (i.e., a relatively large h in Figure 4) which provides better thermal conduction for
25 heat removal while maintaining a useable natural frequency and deflection suitable for use with the interferometer 1. By using a relatively small diameter (i.e., relatively small a in Figure 4) and relatively thick diaphragm, more symmetrical temperature distributions are obtained for the diaphragm 12.

When the temperature distribution is symmetrical, the temperature difference between the center and the edge of the diaphragm 12 is proportional to the heat flux, and temperature-dependent physical characteristics of the diaphragm 12 such as the modulus of elasticity, thermal growth and tension, are more
5 predictable. Also, the relative thickness of the diaphragm 12 helps to provide structural, thermal and/or acoustic durability, while the relatively small diameter of the diaphragm 12 enables a sensor employing the diaphragm to be relatively miniaturized.

Another advantage of using copper as the material for the diaphragm 12
10 is that copper is a relatively reflective material, and so will reflect a relatively large amount of the reflected light 14 to the fused end 10. It should be noted, however, that copper will oxidize, and therefore limit the length of time a copper diaphragm may be employed.

While tension may be applied to the diaphragm 12 to increase its
15 frequency response, the diaphragm 12 is preferably secured by its edge without tension so that a relatively high maximum center deflection is obtained to increase the sensitivity of the diaphragm 12.

Figure 5 is a schematic view of a protective housing 16 for the interferometer 1. The protective housing 16 includes a protective tube 17. The
20 interferometer 1 is fixed within the protective tube 17 with an epoxy 18. An end of the protective housing 16 may then be ground so that the fused end 10 of the interferometer 1 is formed or exposed. In any event, the protective tube 17 may be formed of a variety of materials such as stainless steel. Also, the epoxy 18 may be of any conventional variety for many applications.

25 Figure 6 is a cross-sectional view of a cooling structure 19 for cooling the diaphragm 12 and/or the interferometer 1. Cooling of the diaphragm 12 helps to stabilize its temperature-dependent physical characteristics, and also provides thermal protection for the diaphragm 12 and the interferometer 1. Also, the cooling structure 19 allows the diaphragm 12 and interferometer 1 to
30 be calibrated at a certain temperature such as room temperature since the

cooling structure 19 effectively maintains the diaphragm 12 and interferometer 1 at the certain temperature regardless of the heat flux to which the diaphragm 12 and/or interferometer 1 is subjected. Although a particular cooling structure 19 is described below with reference to Figure 6, other configurations of the
5 cooling structure 19 may be employed.

Referring to Figure 6, the cooling structure 19 has a circular face plate 20 with a circular aperture in which the diaphragm 12 is situated. Connected to the face plate 20 concentrically with the circular aperture, are first and second tubes 21 and 22. The first and second tubes 21 and 22 may be
10 connected to the face plate 20 by welding or an adhesive, for example. Preferably, the first tube 21 has a step formed at an end opposite the face plate 20 by machining, for example.

To the left of Figure 6, a third tube 23, a fourth tube 24 and a fifth tube 25 are arranged and fixed concentrically by member 26. Connected to the
15 member 26 are a first coolant tube 27 for providing a coolant to the cooling structure 19, and a second coolant tube 28 for removing coolant from the cooling structure 19. Preferably, the cooling structure 19 includes a swirler 29 which may be formed by threading the outside of the first tube 21, the third tube 23 and/or the inside of the fourth tube 24, or by using a wire coil spirally
20 wrapped about the outside of the first tube 21 and the third tube 23. The swirler 29 serves to control the flow of coolant to avoid or reduce stagnation of the coolant flow at any point in the cooling structure 19. By preventing stagnation of the coolant, heat can be removed from the diaphragm 12 more effectively.

25 Preferably, all components of the cooling structure 19 are formed of hardened copper. Since copper is widely available and has a relatively high thermal conductivity, heat can be more effectively removed from the diaphragm 12 if the cooling structure 19 is formed of copper. Hardening of the copper serves to increase structural strength, and may be accomplished by heating
30 and relatively slow cooling of the copper.

The coolant circulated in the cooling structure 19 may be of any conventional variety such as water. In any event, the cooling structure 19 maintains calibration of the system by maintaining the diaphragm 12 at a constant temperature regardless of the heat flux therethrough.

5 Referring to Figure 7, a mounting cylinder 30 is fit within the cooling structure 19. Specifically, the mounting cylinder 30 is fit within the inside of the first tube 21 and the third tube 23, and may be fixed therein by an adhesive such as cyanoacrylate. Adhesives such as cyanoacrylate wick into the space
10 between the mounting cylinder 30 and the inside of the first tube 21 and the third tube 23 by capillary action, and are anaerobic so that they cure in the absence of air. Such adhesives are available, for example, from Loctite Corporation.

The mounting cylinder 30 may be formed of copper, for example, and is provided with a bore hole which receives the protective housing 16. The
15 protective housing 16 is fixed within the mounting cylinder 30 using an adhesive such cyanoacrylate, for example, so that the interferometer 1 opposes the diaphragm 12. Preferably, the output of the interferometer 1 is monitored so that the operating point may be adjusted while the adhesive is curing, by moving the protective housing 16 relative to the diaphragm 12. Also, the
20 amount of adhesive used to fix the protective housing 16 within the mounting cylinder 30 must be monitored. If too much adhesive is used, the diaphragm 12 and the end of the protective housing 16 may be bonded together. On the other hand, if too little adhesive is used, the protective housing 16 including the
25 interferometer 1 may be loose so that the interferometer 1 is more susceptible to adverse affects caused by vibration, for example.

For absolute pressure measurements, the mounting cylinder 30 is provided with a passage 31 which communicates with a vacuum source tube 32 and a space between the interferometer 1 and the diaphragm 12. A vacuum may be generated between the interferometer 1 and the diaphragm 12

by connecting the vacuum source tube 32 to a vacuum source which is sealed using a valve 33.

In any event, the first optical fiber 2 is connected to a source light generator 34 for generating the source light 13. The second optical fiber 3 may
5 be connected to a photovoltaic converter 35 which includes, for example, a photodiode to generate an electronic signal or output representative of the displacement between the diaphragm 12 and the fused end 10 of the interferometer 1.

Figure 8 is a graph of the output of the apparatus of Figure 7 operated
10 with a source light 13 of a wavelength of 1300nm, when subjected to 1600°F and white noise of up to 2000 Hertz at 126 and 150 decibels sound pressure level. As expected, an approximately linear relationship appears between the acoustic level and the output since the apparatus was operated in the linear region indicated in Figure 3.

Figure 9 is a graph of the output of the apparatus of Figure 7 operated
15 with a source light 13 of a wavelength of 1300nm, when subjected to a single frequency of 372 Hertz at 160 decibels and 1600°F. The output level was analyzed using a power spectral density analyzer which indicates power at 372 Hertz as well as the second and third harmonics at 744 Hertz and 1116 Hertz.
20 Additional outputs denoted by a triangular symbol in Figure 9 were also measured, but are not presently understood.

Numerous modifications and adaptations of the present invention will be apparent to those skilled in the art and thus, it is intended by the foregoing claims to cover all modifications and adaptations which follow in the true spirit
25 and scope of the invention and the equivalence thereof.

What Is Claimed Is:

AN INTERFEROMETER HAVING FUSED OPTICAL FIBERS,
AND APPARATUS AND METHOD USING THE INTERFEROMETER

Abstract

An interferometer includes a first optical fiber coupled to a second optical
5 fiber by fusing. At a fused portion, the first and second optical fibers are cut to
expose respective cores. The cut or fused end of the first and second optical
fibers is arranged to oppose a diaphragm or surface against which a physical
phenomenon such as pressure or stress, is applied. In a first embodiment, a
source light which is generally single-mode monochromatic, coherent light, is
10 input to the first optical fiber and by evanescence, effectively crosses to the
second optical fiber at the fused portion. Source light from the second optical
fiber is reflected by the diaphragm or surface, and received at the second
optical fiber to generate an output light which has an intensity which depends
upon interference of reference light based on the source light, and the reflected
15 light reflected from the diaphragm or surface. The intensity of the output light
represents a positional relationship or displacement between the interferometer
and the diaphragm or surface.

FIG. 1

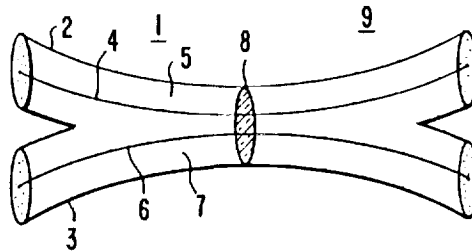


FIG. 2

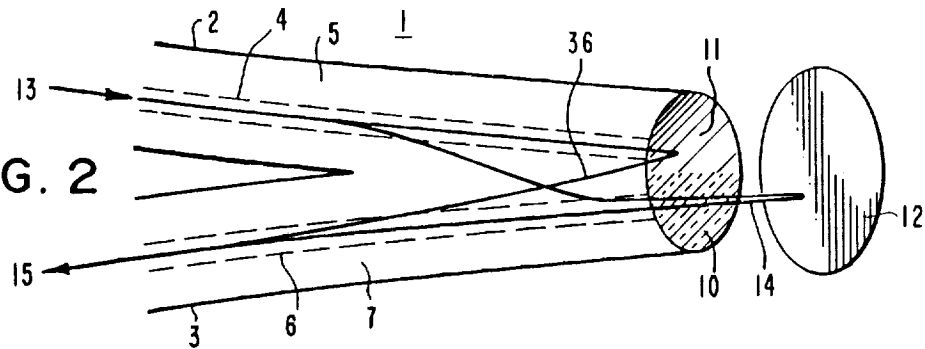


FIG. 3

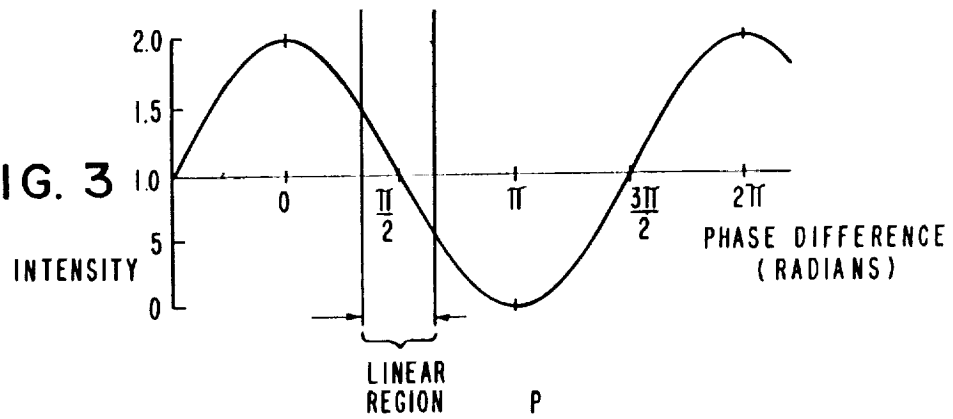


FIG. 4

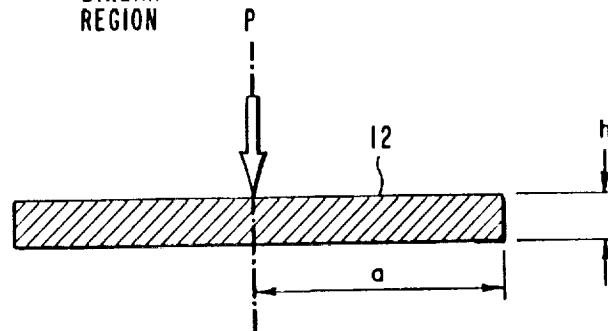


FIG. 5

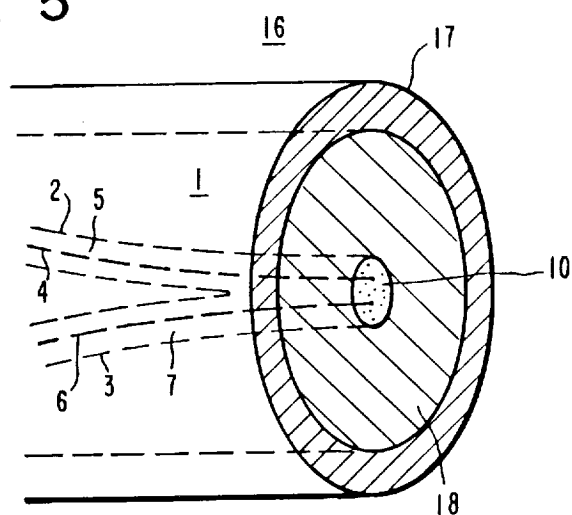


FIG. 6

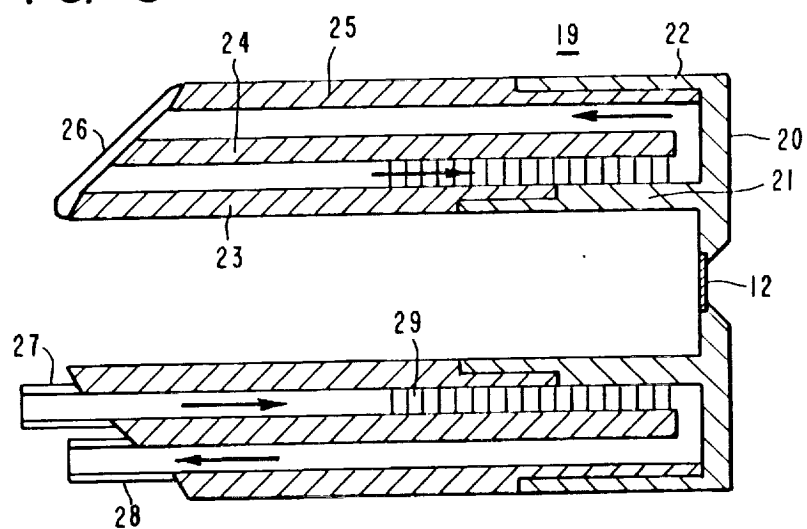


FIG. 7

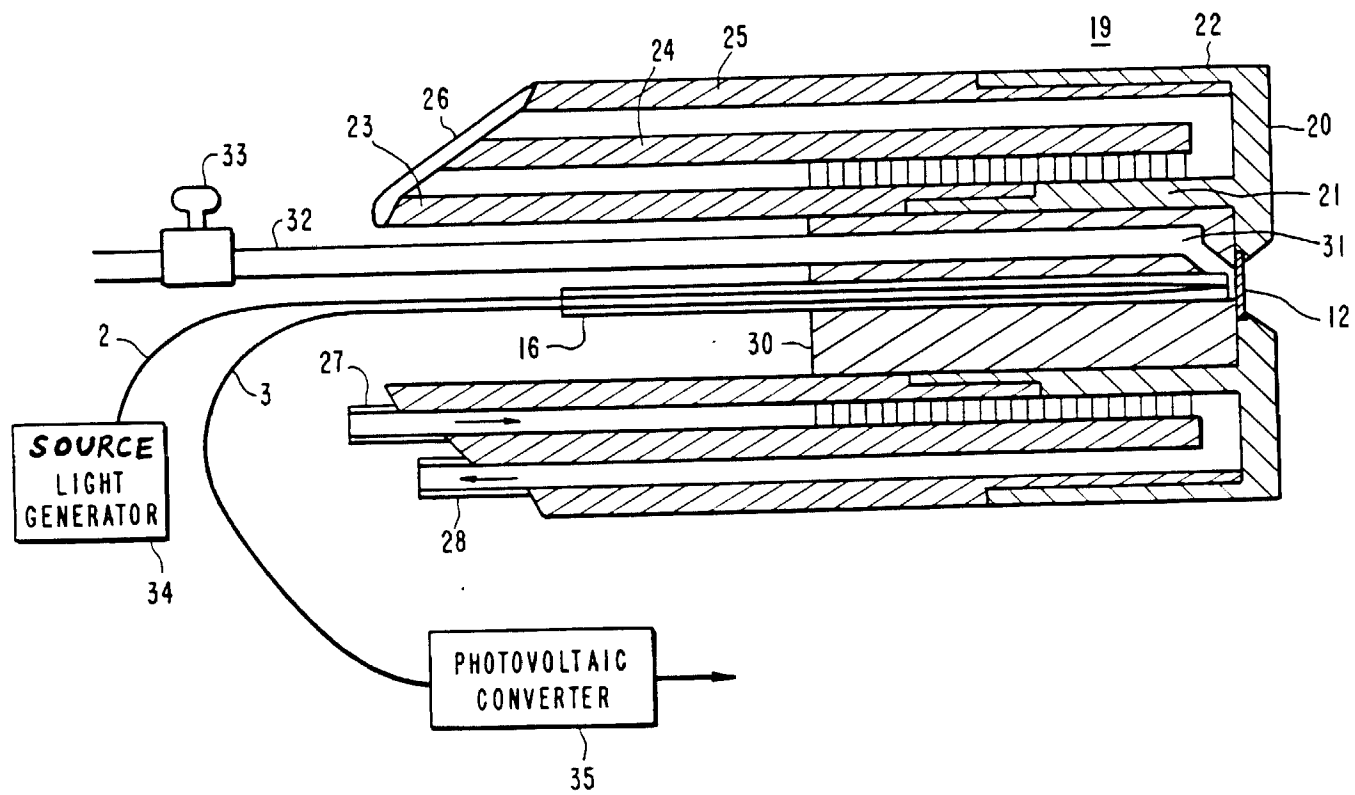


FIG. 8

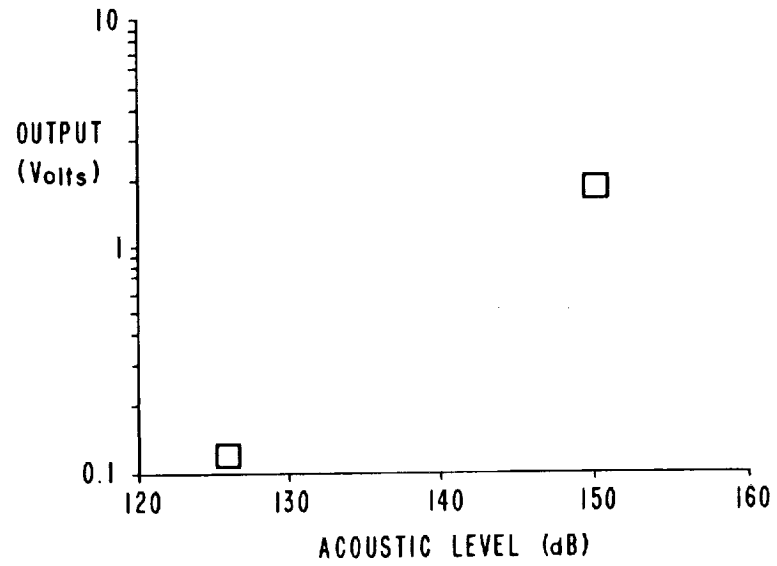


FIG. 9

