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Inventors: Bucholtz et al.
Serial No.

PATENT APPLICATION
Navy Case No 78,952

QUASI-STATIC FIBER PRESSURE SENSOR

BACKGROUND OF THE INVENTION

Field of the Invention

This invention pertains generally to a quasi-static fiber pressure sensor and mor articularly to a quasi-static fiber pressure sensor using self-referenced fiber spectral interferometry.

Description of the Related Art

Precise, real time, remote, self-calibrated measurement of quasi-static pressure is of fundamental significance to the sensing community. Remote optical measurement of pressure-induced plate deflection is often obtained via white light interferometry or dual wavelength illumination, which require a path matching demodulator for coherent addition of the beams reflected from the two sides of the gap. Those techniques suffer from several drawbacks; first, since the system infers the value of the pressure from the difference in gaps between the sensor cavity and the demodulator, one needs to keep the demodulator length free from any drift due to environmental perturbations within the resolution of the instrument. Secondly, the two paths must be either precisely matched to obtain coherent addition, or require a fine precision linear translation stage. Since white light sources do not efficiently couple into optical fibers, one typically uses LEDs or multi-mode lasers.

The problems associated with implementing dual wavelength demodulation are; first, one needs to select two sources with a predetermined wavelength difference that will cover the range of deflections and yield an unambiguous solution. In order to maintain the proper accuracy on pressure, the sources mean wavelengths must be stabilized, requiring active current and temperature laser controllers. Secondly, one needs to ensure that the coherence function of both sources is matched so that only the term corresponding to the difference in cavity lengths contributes to a phase term. Otherwise interference between the other path delayed beams will show as spurious modulation signals. This implies that the spectra of the sources cannot vary with age or feedback, within the required accuracy.

SUMMARY OF THE INVENTION

The object of this invention is to provide a device capable of real-time, high resolution remote measurements of pressure.

Another objective of this invention is to provide a device that can obtain pressure sensing with psi resolution in a kpsig pressure range.

These and other objectives are accomplished by a quasi-static fiber pressure sensor using self-referenced interferometry based on a broadband semiconductor source which probes the pressure plate deflection within a Fabry-Perot cavity where phase is demodulated with a dual grating spectrometer providing real-time, high resolution remote measurement of pressure using optical interrogation of a deflecting pressure plate. This technique yields absolute gap measurement in real time over a wide range of gap lengths with submicron resolution. By tailoring the pressure plate design to cover the range of gaps and deflection that can be resolved . pressure sensing with psi resolution can be obtained in a kpsig pressure range

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a quasi-static fiber pressure sensor using self-reference spectral interferometry.

Figure 2 shows a flow chart of a curve fitting routine.

Figure 3 shows a dependence of a coupler's transmission with wavelength.

Figure 4a shows spectral power distribution of the source reference.

Figure 4b shows spectral power distribution of the sensor signal for a 43 μm gap.

Figure 4c shows ratio of sensor to reference after coupler correction for a 43 μm gap.

Figure 5a shows sensor spectral distribution for a 6 μm gap.

Figure 5b shows sensor spectral distribution for a 114 μm gap.

Figure 5c shows sensor spectral distribution for a 240 μm gap.

Figure 6 shows variation in gap as a function of voltage applied to plate deflector.

Figure 7 shows a spectral interferometer sensor with a fiber optic switch and a single spectrometer.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In a preferred embodiment of the quasi-static fiber pressure sensor using self-reference spectral interferometry **10**, as shown in **Figure 1**, a near Infrared (IR) source **12** , such as a light emitting diode (LED) or super luminescent diode (SLD) emitting a mean wavelength in the 800 - 850 nm range from a pig-tailed fiber. The light-emitting diode (LED) having 200 μW output power made by MRV Technologies of Chatsworth CA. or the SuperLuminescent Diode (SLD) with ≈ 1mW output power made by EG&G Optoelectronics Sunnyvale, CA generates an optical light **22** is guided through a single mode optical fiber **18** of any type compatible with the output frequency of the light source **12** to a 3 dB fiber optic fused coupler **14**, of any type well known to those skilled in the art, where the optical light **22** is divided into two components-- a first light beam **22a** directed to a reference spectrometer **32a** and a second optical light signal **22b** directed to a pressure sensor **16**. The light **22b** is reflected at the fiber/air interface **28** (by Fresnel reflection of about 4%) and at the pressure plate reflector **24** within the pressure sensor **16**. The reflected light beam **23**, resulting from the optical light beam **22b** being reflected from the pressure plate reflector **24** , is phase delayed by the round trip in the sensing gap **26** with respect to the beam **25** reflected at the fiber cleave or interface **28**. The air gap **26** is formed between a cleaved fiber **28** and a reflecting glass plate **24**, positioned approximately 20 to 200 μm from the fiber cleave **28**. A pressure plate **24** is mounted on a translation stage **42** with piezo translation actuator (PZT) **44**.

Light **23** and **25** from both reflections is collected by the fiber **18** and transmitted through the coupler **14** to form the optical light beam **27** in optical fiber **38** and applied to a spectrometer portion **32b** of a dual spectrometer **32**, using standard single mode fibers **18** and **38** and couplers

14 at 830 nm (typically narrow band couplers with ± 10 nm bandpass). Quasi-simultaneous measurement of the source and the sensor spectra can be obtained either by using a dual visible grating spectrometer **32** on a board, such as Ocean Optics S2000, made by Ocean Optics, Inc. of Dunedin, FL, with resolution ≈ 0.3 nm.

Light beam **27** is projected from the optical fiber **38** onto a high dispersion grating **34** (~ 1200 lines/mm) within the sensor portion **32a** of the dual spectrometer **32** and reflected onto an associated charge coupled device (CCD) array detector **36a**. Each pixel on the CCD **36** being responsive to an predetermined wavelength. The optical light **22a** from the light source **12** and passed through the coupler **14** is directed onto a grating (similar to the grating **34**) in the reference portion **32b** of the dual spectrometer **32** and reflected onto an associated CCD **36b**. Collecting lenses are used for improved optical efficiency in gathering light **27** and **28** onto their respective CCD arrays **36a** and **36b** in the spectrometers **32a** and **32b**.

The output distribution at the CCD array detector **36** is uniquely related to the gap **26** length. For a gap **26** of length L between the pressure plate reflector **24** and the fiber cleave **28**, the phase delay seen by the reflected beam is

$$\Phi = 4\pi nL/\lambda \qquad (1)$$

where Φ is the phase delay, λ the wavelength of light and L the optical gap **26**. For an air index = 1.000, the optical gap = physical gap where n = index of refraction at wavelength λ. Assuming that the cavity formed by these two interfaces is a low finesse Fabry-Perot (the reflection from both interfaces is small) and can be approximated to a two-beam interferometer.

When the gap 26 is illuminated with a broadband light 22 of intensity $I_O(\lambda)$, the intensity obtained on each pixel of the CCD array 36a and **36b** is a summation over the band of wavelengths detected, which is defined by the grating **34** dispersion and spectrometer **32** geometry. The intensity at pixel k with center wavelength λ_k of the CCD **36a** the sensor output) is then

$$I(\lambda_k) = I_O(\lambda_k)(1 + \Gamma\cos(4\pi nL/\lambda_k)) \qquad (2)$$

where the fringe contrast Γ is governed by the spectral resolution at the CCD **36a** and the relative **intensities of the two interfering beams ; the reflected beams 23and 25 from the cleaved end of the optical fiber 28 and reflected from the pressure plate 24.**

The output signals 54 and 52 from the sensor portion 36a and reference portion 36b, respectively, of the CCDs 36a and 36b, respectively of dual spectrometer 32 can be readily decoded in an analog/digital (A/D) converter 56a and electronically processed in a data processing section 56b of an electronics module 58 from the spectral pattern exhibited by the spectrometer CCD detector arrays 36a and 36b. Since the fringe contrast is defined by the spectrometer **32** geometry, path matching is not required in order to obtain a high fringe contrast at the CCDs **36a** and **36b**. The outputs **52** and **54** from the arrays **36a** and **36b**, respectively, of N pixels (typically N=1024 or 2048) is then comparable to N interferometric responses from the same gap **26**. Knowledge of the absolute value of the gap **26** and its respective plate **24** deflection is obtained by extraction of the phase over the complete spectrum. The spectrum shows a maximum at wavelengths for which the phase is an even number of π. Therefore, for a gap **26**, L, two consecutive maxima will occur for:

$$\Phi = (M)*2\pi = 4\pi nL/\lambda_m \quad \text{and} \quad \Phi = (M+1)*2\pi = 4\pi nL/\lambda_n \tag{3}$$

and the gap **26** can be estimated from subtraction, as

$$L = \lambda_m \lambda_n/(2n\Delta\lambda) \quad \text{where } \Delta\lambda = \lambda_m - \lambda_n \tag{4}$$

The gap **26** extraction requires the knowledge of the source spectrum $I_O(\lambda)$ and the sensor spectrum $I(\lambda)$.

Referring to **Figure 2**, after subtraction of the CCD dark count **62**, normalization to the CCD **36a** and **36b** response by linearization to the optical power response **64** and "zooming" **66** to highlight pertinent data by retaining only data in a window ≈ ± 50 nm around the source peak emitting wavelength because the CCD **36a** and **36b** gives an echo window which is ≈ 700 - 900 nm, wider than the ≈ 100 nm window which contains intensity above the dark count and that is actually used in the computations. For each pixel on the CCD **36a** and **36b** there is an equivalent wavelength which is registered **68** through wavelength calibration **72** .Wavelength registration **68** also allows for interpolation of pixel assignments when the two CCD arrays **36a** and **36b** exhibit different wavelength calibration curves.

The wavelength calibration **72**, dark count **74** and CCD spectral response **76** are stored in a data bank that is manually input into a memory microchip (not shown). The wavelength calibration data **72** is obtained by obtaining measurements of that portion of the wavelength with a spectroscopic lamp (not shown) such as a Mercury-Argon source. The data for the dark count **74** is obtained by making measurements with the optical light source **12** OFF, these techniques are well known to those skilled in the art. The data for the spectral response **76** is obtained from a calibration of the system using a calibrated irradiance source (not shown), such as a tungsten halogen source, utilizing techniques well known to those skilled in the art.

The input signals of V_0 **52** and V_1 **54** from the CCDs **36a** and **36b** are output as adjusted electrical signals **78** and **82**. Because of the broadband source **12** used, the fiber coupler **14** may exhibit a variation in splitting ratio with wavelength. This will introduce a skewing between the sensor spectrum **82** that has traversed the coupler **14** twice and the reference spectrum **78** that has traversed the coupler **14** only once. This skewing can be eliminated by correcting for the coupler **14** spectral response utilizing a T corrector **84** for the reference spectra **78** and RT corrector **86** for the sensor spectrum **82** . The coupler **14** response can be measured by recording the fiber **45** reflection, while blocking the pressure plate **16** back reflection, and dividing it to that of the reference source spectrum **22a**. By dividing the fiber-reflected spectrum (special case of sensor spectrum **82**) by the source spectrum **78** one obtains the spectral dependence of the coupler transmission, that can be folded into $I_O(\lambda)$ to linearize the output.

The gap **26**, L, is determined by curve fitting **102** the sinusoidal dependence on λ through the formula

$$I_C(\lambda)/I_{OC}(\lambda) = 1 + \Gamma\cos(4\pi nL/\lambda) \tag{5}$$

Simultaneously recording the spectra of the source **22a** (reference) and the gap **26** (signal) from the two fiber outputs **22a** and **27** performs a self-calibration, eliminating potential errors due to source drifts.

One then obtains the ratio of sensor signal to reference source intensities:

$$P(\lambda) = A[1 + \Gamma\cos(4\pi nL/\lambda)] \qquad (6)$$

The ratio of the corrected signal **92**, I_C, to source spectra, I_{OC} **94**, is obtained in a divider circuit **96** which yields the divided optical signal **98**, I_{oc}/I_c.

Curve fitting **102**,P(λ), is obtained by fitting (by estimation)**104** the three parameters of Eq. (6). A (normalizing constant due to the difference in intensity between the reference and sensor beams). Γ (fringe contrast) and L (air gap), with a (least square) iterative process. The first estimate on the parameters is obtained by finding the value and location of the central maxima and minima. From the maximum and minimum intensities, P_{Max} and P_{Min} one can extract

$$A = (P_{Max} + P_{Min})/2$$
$$\Gamma = (P_{Max} - P_{Min})/(P_{Max} + P_{Min}) \qquad (7)$$

From the value of the wavelengths corresponding to two consecutive maxima one can estimate the gap **26** as per Eq. (4) for all maxima. Since those wavelengths correspond to a maximum in the intensity, the phase at those wavelengths should be an even number of 2π, therefore the ratio of the gap **26** to wavelengths must be an integer, decreasing with increasing wavelength, yielding a mean value for the estimated gap **26**.

The estimates **104** are then inserted into the algorithm performing the above curve fit **102**, the iterations yield the final solutions for A, Γ and L and the results logged in with the respective curve fit error. Any slow variation in gap **26** can then be estimated using the previous set of parameters as the start parameters for the convergence.

In a test device, referring again to **Figure 1**, the coupler's **14** transmission was measured according to the above procedure and shows a linear dependence with wavelength around its 3 dB point at 830 nm, see **Figure 3**. The fringe spectra's source spectrum (**Figure 4a**), sensor spectrum (**Figure 4b**), and ratio of the sensor to the source (**Figure 4c**), after linearization by the coupler **14** transmission function, is shown for the test device. Comparison of **Figure 4a** and **Figure 4b** shows the effect of the coupler **14** narrow bandpass in the shift of the peak wavelength. After correction, the ratioed spectra exhibit the expected quasi-sinusoidal dependence on wavelength of Eq. (6).

Gap **26** variations between 5 μm (1 fringe) and 500 μm (87 fringes) can be measured within sub-micron precision. The variation on the sensors **10** spectra with deflection is shown in **Figures 5a - 5c**, for three different gap **26** values. A calibrated piezo-ceramic transducer was used as a translator actuator or plate deflector **48** and the variation in air gap **26** measured as a function of voltage to the transducer **48** is shown in **Figure 6.** This shows the very good agreement between the variation in air gap **26** due to plate deflection obtained by curve fit and calibrated displacement.

Therefore, the pressure plate **24** design can be tailored to cover the required range of gaps **26**. For example, a simple circular plate with clamped edges is known to deflect under a uniform pressure load P by

$$d = 3PE\, r^4(1-\mu^2)/16Et^3 \qquad (10)$$

where E is the modulus of elasticity and μ the Poisson ratio of the plate material, r is the radius of the plate of thickness t. For a given material, r and t can be tailored to cover the pressure range of interest and achieve high range and resolution in a remote , all optical fiber sensor.

Since the optical system measures the phase delay seen by the light traveling through the Fabry-Perot cavity, absolute gaps **26** or variations in gap **26** due to other physical parameters can also be measured using the same sensing techniques. Examples of parameters that can be detected from measurement of the change in gap **26** are strain, temperature (via thermal expansion), magnetic and electric field (via magnetostriction or piezo electricity), chemical reaction, etc.. For example, if a pressure plate **24** exhibits a temperature dependent deflection, such system can be implemented to simultaneously measure the temperature dependence of the plate deflection and compensate for thermal effects on the plate.

Although the algorithm is shown in the case of a two-beam interferometer (assuming a low reflectivity cavity) with cosine dependence on the air gap **26**, L, the same procedure can be used for a more general Fabry-Perot cavity, if multiple reflections are present at the air gap **26**, using the known Fabry-Perot relationship between intensity and air gap.

In another preferred embodiment, referring again to **Figure 7**, a spectral interferometer **20**, utilizing a mechanical fiber optic switch **37**, such as those made by E-Tek Dynamics of San Jose, CA combined with a single grating spectrometer **41**, such as the Ocean Optics S2000m is utilized to obtain a quasi-simultaneous measurement of the source and the sensor spectra. The operation is similar to the described embodiment shown in **Figure 1**. The exception is that the single grating spectrometer **41** with the mechanical fiber optic switch **37** is utilized instead of the dual-grating spectrometer The fiber optic switch **37** takes the optical inputs of the source and sensor optical signals **22a** and **27** and selectively impinges them onto a single grating **35** in the spectrometer **41** where they are reflected onto a single charge coupled device (SCCD) 33. An electromagnetic output **55** from the SCCD **33** is applied to an analog-to- digital converter **56a**, split into its respective source and sensor components, utilizing techniques well known to those skilled in the art and processed through a data processor **56b** in an electronics module **58** similar to that previously described in reference to **Figure 2**.

This invention offers high sensitivity as a result of the selection of a single mode fiber having a small core size (about 5μm), combined with a high resolution spectrometer grating; yielding a high spectral resolution (i.e., better than 0.3 mm). The device is highly efficient due to the selection of a source wavelength at 830 nm combined with a low noise CCD array and is self-referenced, as a simultaneous reading of the reference spectrum eliminates any source drifts. A calibration source integrated into the fiber-optic switch maintains the spectrometer calibration. Curve fitting the normalized spectrum makes use of the complete spectral data and yields a resolution of a fraction of a pixel, yielding a very precise value for the gap, hence the pressure. The device offers a large dynamic range and can extract the value of a gap from a spectrum with about one fringe to 100 fringes, which allows for a large range of pressure-induced deflections, hence pressures. The combined high resolution and high accuracy sensing is obtained in a simple, compact, alignment insensitive package, due to the selection of an all-fiber design.

The device can perform remote detection due to the low-loss waveguiding of the light in a single mode fiber. and the fact that the spectral modulation information it contains is essentially immune from potential environmental disturbances on the lead fiber. The sensing technique can be applied to other measurements of small gaps or moving reflecting surfaces.

Although the invention has been described in relation to an exemplary embodiment thereof, it will be understood by those skilled in the art that still other variations and modifications can be affected in the preferred embodiment without detracting from the scope and spirit of the invention,

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ABSTRACT

This invention is a quasi-static fiber pressure sensor using self-referenced interferometry based on a broadband semiconductor source which probes the pressure plate deflection within a Fabry-Perot cavity where phase is demodulated with a dual grating spectrometer providing real-time, high resolution remote measurement of pressure using optical interrogation of a deflecting pressure plate. This technique yields absolute gap measurement in real time over a wide range of gap lengths with nanometer resolution. By tailoring the pressure plate design to cover the range of gaps and deflection that can be resolved . pressure sensing with psi resolution can be obtained in a kpsig pressure range