Guided-Wave Optical Pressure Sensor Responding only to Changing Pressure

Yoshisumi Endo[a], Masashi Ohkawa[*b], Seishi Sekine[b], and Takashi Sato[b]
[a]Niigata University, Graduate School of Science and Technology, Ohkawa Lab.
8050 Ikarashi 2-no-cho, Niigata 950-2181, Japan
[b]Niigata University, Faculty of Engineering
8050 Ikarashi 2-no-cho, Niigata 950-2181, Japan

ABSTRACT

In this paper, an original guided-wave optical pressure sensor that responds only to rapid pressure change is described. The proposed sensor is based on a conventional guided-wave optical pressure sensor using intermodal interference, with an added semi-closed space with a small hole under the bottom side of the diaphragm. By the addition of this semi-closed space, the sensor, unlike conventional sensors, can withstand high static pressure. When there is a sudden change in ambient pressure, pressure within the semi-closed space cannot quickly adjust due to the small hole that restricts fluid flow. So, pressure difference is induced on the diaphragm for a short while. Thus, the sensor shows a response only to changes in pressure, not to static pressure. We examined the step response of the sensor, that is, the output characteristics for sudden pressure change. The diaphragm dimensions of the fabricated sensor were 14 mm×14 mm×0.22 mm. Also, the volume of the semi-closed space was 14 mm×14 mm×1.8 mm, and the sectional area of the small hole was 93 μm×25 μm. In this experiment, the pressure in a 30 cm×28 cm×30 cm closed box, in which the fabricated sensor was placed, was suddenly increased by 0.78 kPa. Due to the pressure change, the output intensity decreased by approximately 20 % of the initial intensity level. Approximately 1.4 sec after the step-like change in pressure, output intensity returned to the initial level.

Keywords: integrated optics, guided-wave optics, pressure sensor, diaphragm

1. INTRODUCTION

Since the late 1980's, several groups have demonstrated guided-wave optical pressure sensors with micro-machined diaphragms.[1-3] Our group has been also developing glass-based and silicon-based guided-wave optical pressure sensors using intermodal interference between the fundamental TM-like and TE-like modes.[4, 5] In such sensors, maintaining both high sensitivity and withstanding high pressure has generally not been compatible. Therefore, the conventional sensors with high sensitivity cannot be used under high pressure, greatly limiting the sensing range to relatively low pressure cases. However, in some applications, *e.g.* malfunction detection in industrial plants, detection of small pressure fluctuation under high static pressure is desired. So, we propose a new pressure sensor that has a semi-closed space with a small hole under the bottom side of the diaphragm. In static pressure, no pressure difference appears on the diaphragm even in the high ambient pressure since the small hole balances the pressures in the surroundings and in the semi-closed space. When the ambient pressure is suddenly changed, the pressure in the semi-closed space cannot follow the ambient pressure change because the fluid flow is restricted by a small hole. Thus, our original sensor can have high withstanding pressure for static pressure as well as high sensitivity, but unlike the conventional sensors, sensitivity is for sudden pressure change only. In this study, the characteristics of the proposed sensor, *e.g.* duration of the induced pressure difference on the diaphragm, were examined theoretically and experimentally. In theory, it was found that the duration of the induced pressure difference is proportional to the ratio between the volume of the semi-closed space and the sectional area of the small hole, called the V/A ratio in this paper. In the experiment, the duration of the induced pressure difference was 1.4 sec for the fabricated sensor with the V/A ratio of 150 m, while the theoretical duration is 0.046 sec. Although there is a difference between the theoretical and experimental results regarding the duration, the operation of the original sensor was successfully confirmed. The sensor would be useful to detect malfunctions in static-high-pressure pipelines of industrial plants, to detect tidal waves caused by hydraulic pressure changes on the bottom of the sea, etc.

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2. PRINCIPLES OF SENSOR OPERATION

Figure 1 shows a guided-wave optical pressure sensor responding only to changing pressure. The sensor consists of a rectangular diaphragm as a pressure-sensitive structure and a straight single-mode waveguide over the diaphragm. A thick plate with a small hole is attached to the bottom, so that a semi-closed space is formed under the bottom side of the diaphragm. The semi-closed space with the small hole conducts high withstanding pressure for static pressure to the sensor. When the sensor is placed under static pressure, the pressure in the surroundings is equal to that in the semi-closed space because the small hole connects the semi-closed space with the surroundings. Therefore, pressure difference is not yielded onto the diaphragm under normal static pressure. However, when there is a rapid change in the ambient pressure, the pressure in the semi-closed space changes at a slower rate due to the small hole restricting fluid flow. The delay creates a pressure difference on the diaphragm for a short while.

By the induced pressure difference, the diaphragm is distorted. The distortion causes strain, which in turn produces a change in the refractive index of the diaphragm by the elasto-optic effect. The index change yields phase retardation in the lightwave, which propagates in the waveguide on the diaphragm. Since the phase retardation is dependent on the guided modes, *i.e.* the fundamental TM-like and TE-like modes, the phase difference between the two modes is also a function of pressure difference. To detect the phase difference, the sensor is placed in a pair of crossed polarizers.[4,5] The input polarizer is oriented at 45° with respect to the polarization of each guided mode. The light beam through the input polarizer is coupled to the TM-like and TE-like modes at equal intensities. The crossed output polarizer converts the polarization-modulated light into intensity-modulated light. Therefore, the ambient pressure change can be detected by output intensity.

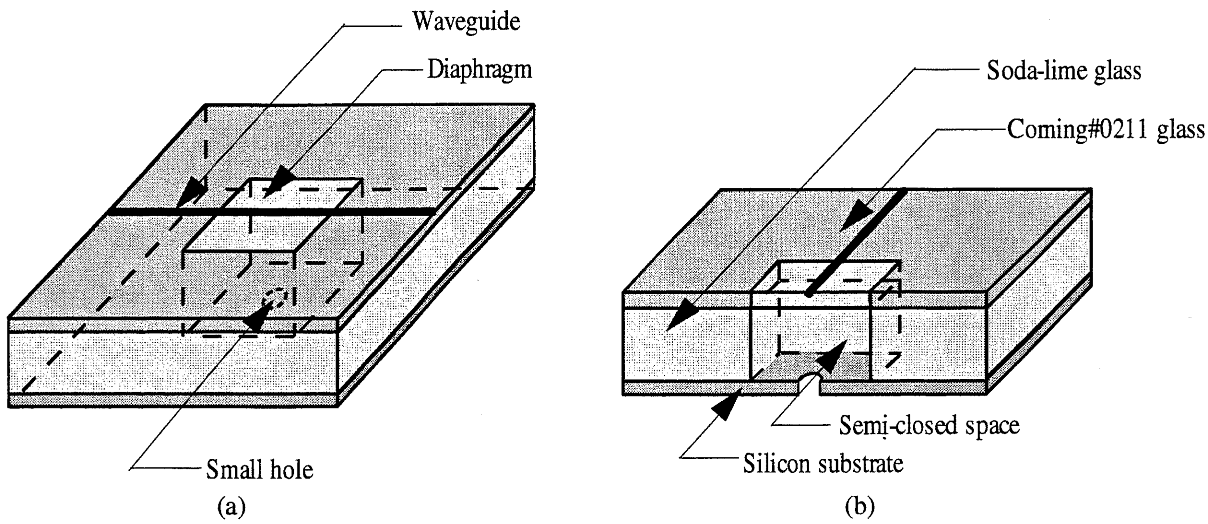

Fig. 1 (a) Schematic drawing of a guided-wave optical pressure sensor using intermodal interference. The sensor shows a response only to sudden pressure change by a semi-closed space with a small hole. (b) The cross-sectional view of the sensor.

3. THEORY

3.1 Theoretical duration of induced pressure difference

In the proposed sensor, the duration of the induced pressure difference is very significant in sensor operation. Figure 2 is a schematic diagram showing how the induced pressure difference $\Delta p(t)$ is derived when there is a sudden change in ambient pressure. Here, V and A denote the volume of the semi-closed space and the sectional area of the small hole, respectively. In an initial state, that is, just after the sudden increase of the ambient pressure from p_0 to p_a, the pressure of the semi-closed space remains p_0, which is written as $p_0 = p_a - \Delta p_0$ using the initial pressure difference Δp_0. After the sudden pressure change, the pressure $p(t)$ in the semi-closed space, written as $p(t) = p_a - \Delta p(t)$, varies since the fluid flows into the semi-closed space through the small hole. At $t = 0$, $p(0) = p_0$ and $\Delta p(0) = \Delta p_0$.

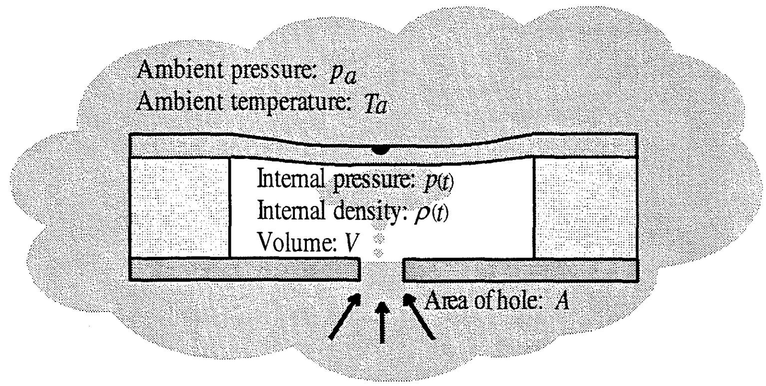

Fig. 2. Schematic diagram mathematically showing how the sensor obtains the induced pressure difference and its duration. In the model, the volume of the semi-closed space is V, and the sectional area of the small hole is A. The pressure and temperature in the surroundings just after the sudden pressure change are p_a and T_a, respectively. The pressure and density in the semi-closed space are $p(t)$ and $\rho(t)$, respectively.

From Bernoulli's theorem for the compressible fluid, the mass flow rate through the small hole is expressed as

$$\dot{m} = \frac{p_a A}{\sqrt{RT_a}} \sqrt{\frac{2\gamma}{\gamma-1}\left\{\left(\frac{p(t)}{p_a}\right)^{\frac{2}{\gamma}} - \left(\frac{p(t)}{p_a}\right)^{\frac{\gamma+1}{\gamma}}\right\}} = \frac{p_a A}{\sqrt{RT_a}} \sqrt{\frac{2\gamma}{\gamma-1}\left\{\left(1-\frac{\Delta p(t)}{p_a}\right)^{\frac{2}{\gamma}} - \left(1-\frac{\Delta p(t)}{p_a}\right)^{\frac{\gamma+1}{\gamma}}\right\}}, \tag{1}$$

where R is the gas constant, and γ is the specific heat. Assuming that the fluid is air, γ is 1.4. If the induced pressure difference $\Delta p(t)$ is assumed to be much less than the ambient pressure p_a, eq. (1) can be approximately rewritten as

$$\dot{m} = \sqrt{\frac{2p_a}{RT_a}} A \sqrt{\Delta p(t)}\,. \tag{2}$$

Under an assumption of the adiabatic change,

$$\frac{p(t)}{p_0} = \left(\frac{\rho(t)}{\rho_0}\right)^{\gamma}, \tag{3}$$

where $\rho(t)$ denotes the density of the fluid in the semi-closed space, and ρ_0 is the initial value of $\rho(t)$ at $t = 0$. From eq. (3) and $\rho(t) = \rho_0 + \Delta\rho(t)$, if $\Delta\rho(t)$ is much less than ρ_0, the pressure difference can be approximately given by

$$\Delta p(t) = \Delta p_0 - \gamma \frac{p_0}{\rho_0} \Delta\rho(t)\,. \tag{4}$$

Equation (4) being substituted into eq. (1), the mass flow rate $\dot{m}$ is expressed as

$$\dot{m} = \sqrt{\frac{2p_a}{RT_a}} A \sqrt{\Delta p_0 - \gamma \frac{p_0}{\rho_0} \Delta\rho(t)}\,. \tag{5}$$

Incidentally, from the law of conservation of mass, mass $\dot{m}dt$ of the fluid coming into the semi-closed space during a short period of dt must equal the increased mass $Vd\rho$ in the semi-closed space as follows.

$$\dot{m}dt = Vd\rho = Vd(\Delta\rho)\,. \tag{6}$$

Eq. (5) being substituted into eq. (6),

$$\sqrt{\frac{2p_a}{RT_a}}\frac{A}{V}dt = \frac{1}{\sqrt{\Delta p_0 - \frac{\gamma p_0}{\rho_0}\Delta\rho}}d(\Delta\rho)\,. \tag{7}$$

Equation (7) is integrated from 0 to t with respect to t in the left side and from 0 to $\Delta\rho$ with respect to $\Delta\rho$ in the right side. After the definite integral,

$$\sqrt{\frac{2p_a}{RT_a}}\frac{A}{V}t = 2\frac{\rho_0}{\gamma p_0}\left(\sqrt{\Delta p_0} - \sqrt{\Delta p(t)}\right). \tag{8}$$

Equation (8) can be rewritten as

$$\sqrt{\Delta p(t)} = \sqrt{\Delta p_0} - \sqrt{\frac{p_a}{2RT_a}}\frac{\gamma p_0}{\rho_0}\frac{A}{V}t\,. \tag{9}$$

When the right side in eq. (9) is positive, the pressure difference is induced on the diaphragm. Therefore, the duration of the induced pressure difference is given by

$$t = \sqrt{\frac{2RT_a}{p_a}}\frac{\rho_0}{\gamma p_0}\frac{V}{A}\sqrt{\Delta p_0}\,. \tag{10}$$

From eq. (10), the duration is found to be proportional to the V/A ratio between the volume of the semi-closed space and the sectional area of the small hole, and proportional to the square root of the initial pressure difference. Within the duration, the pressure difference is expressed as

$$\Delta p(t) = \left(\sqrt{\Delta p_0} - \sqrt{\frac{p_a}{2RT_a}}\frac{\gamma p_0}{\rho_0}\frac{A}{V}t\right)^2. \tag{11}$$

3.2 Numerical calculations

Pressure differences induced after a rapid change in ambient pressure were calculated as functions of time in eq. (11). In the calculations, it was assumed that the volume of the semi-closed space was 14 mm×14 mm×1.8 mm, and the diameter of the small circular hole was 5 μm, 10 μm and 20 μm. Moreover, the ambient pressure was increased by 1 kPa in a stepwise fashion, and the ambient temperature T_a was 300 K. Figure 3 shows the calculated results. From the figure, it was found that the duration of the induced pressure difference shortens as the sectional area of the hole increases.
According to eq. (10), the duration of the induced pressure difference is proportional to the V/A ratio between the volume of the semi-closed space and the sectional area of the small hole. Figure 4 shows the calculated duration versus the V/A ratio. In the figure, the initial pressure difference Δp_0 is taken as a parameter. Although the optimum duration would be dependent on the application, and the V/A ratio can be found from eq. (10) or Fig. 4 once the duration and the initial pressure difference have been determined. Thus, the semi-closed space can be designed from the chosen V/A ratio.

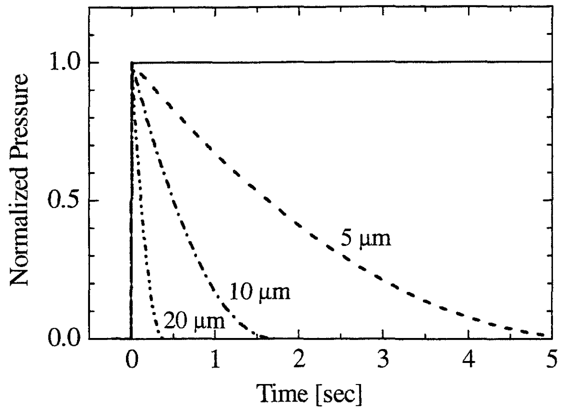

Fig. 3 Normalized pressure difference $\Delta p(t)/\Delta p_0$ induced on the diaphragm as a function of time; diameter of the small hole is taken as a parameter. In the figure, the solid line represents the ambient pressure change.

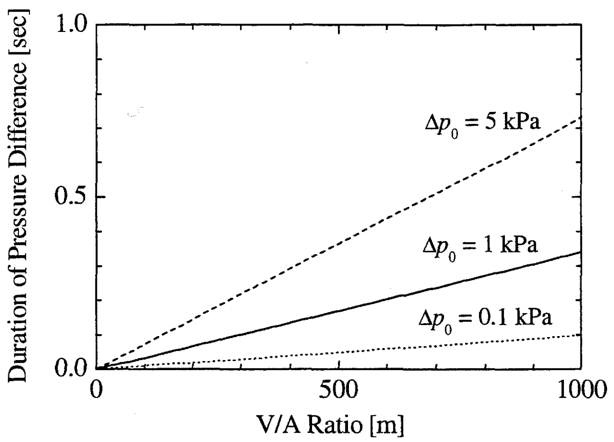

Fig. 4 Duration of the induced pressure difference as a function of the V/A ratio. In the figure, the initial pressure difference is taken as a parameter.

4. EXPERIMENT

4.1 Fabrication

Figure 5 shows the top and cross-sectional views of the fabricated sensor, including the actual dimensions. The sensor, except for the bottom plate, was built using two glasses: a Corning#0211 glass as a diaphragm plate and a soda-lime glass with a 14 mm×14 mm square hole to support the diaphragm plate. First, a thin aluminum film was evaporated on a Corning glass. The aluminum film was removed by using a patterned photoresist mask. Next, the glass was immersed in KNO_3 for two hours at 400°C to form the single-mode channel waveguides. Before the two substrates were joined, the waveguide was adjusted to be parallel to the diaphragm. Then, both substrates were bonded together by UV adhesion.

In this study, a silicon substrate was used as the bottom plate shown in Fig. 5. A silicon dioxide layer was first formed on both sides of the substrate by thermal oxidation. The silicon dioxide layer was selectively removed by an etchant of buffered HF acid using a patterned photoresist as an etching mask. Then, the exposed silicon was anisotropically etched by KOH to produce the small hole. The sectional area of the rectangular hole was 93 μm×25 μm. The thick plate with the small hole was attached to the bottom of the pressure sensor by UV adhesion. The diaphragm dimensions were 14 mm×14 mm×0.22 mm, and the volume of the semi-closed space was 14 mm×14 mm×1.8 mm.

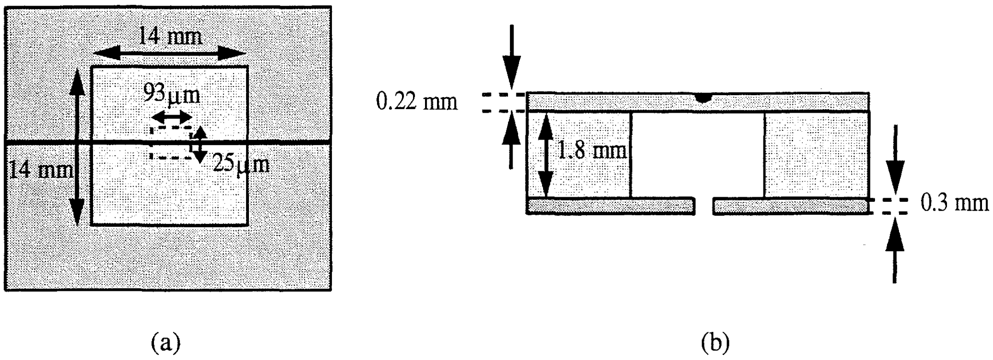

Fig. 5 (a) Top and (b) cross-sectional views of the fabricated sensor and actual dimensions.

4.2 Measurement

4.2.1 Pressure sensitivity of a sensor without a semi-closed space

For a sensor without the semi-closed space, halfwave pressure and phase sensitivity were evaluated.[5] Figure 6 shows the experimental setup to measure output intensity versus applied pressure. In the measurements, a linearly-polarized He-Ne laser at 633nm was used. The polarization of the laser beam was set at 45° with respect to the sensor surface, so an input polarizer was not necessary in this study. The sensor was connected to a syringe by a silicone tube in order to apply pressure to the diaphragm. Pulling and pushing on the plunger of the syringe caused pressure difference, ranging from –40 kPa to 60 kPa, on the diaphragm. A positive value signifies that the pressure on the bottom side of the diaphragm plate is greater than that of the atmosphere. Figure 7 shows normalized output intensity versus the applied pressure for the waveguide nearest the center of the diaphragm. Incidentally, sensitivity is dependent on the waveguide position. Although many waveguides had been formed on the diaphragm, the center position was taken to evaluate sensitivity because of its high sensitivity and the small dependence of sensitivity on the waveguide position. In Fig. 7, the solid line indicates the computer projection of the experimental data. The half period of the output intensity is called the halfwave pressure, and corresponds to a phase difference of π rad. Phase sensitivity is defined as the phase difference between the two guided modes per unit pressure. From Fig. 7, the halfwave pressure is evaluated to be 35.0 kPa, corresponding to phase sensitivities of 89.7 mrad/kPa.

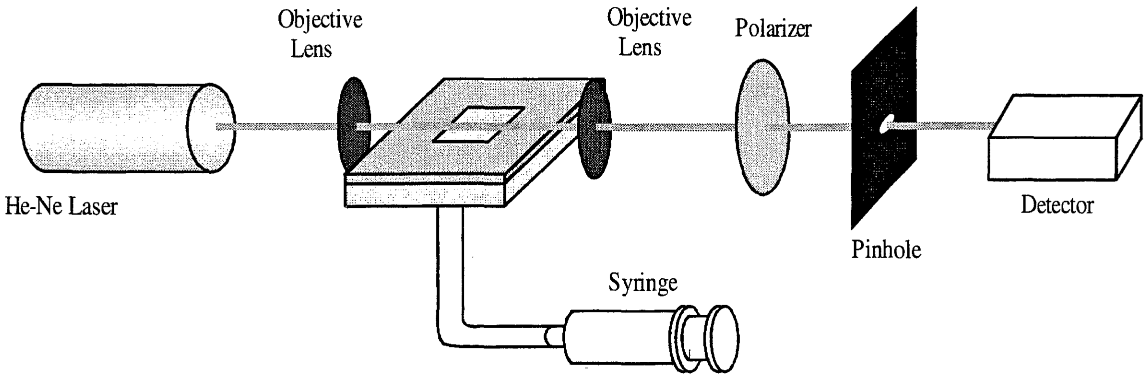

Fig. 6 Experimental setup to measure output intensity as a function of applied pressure.

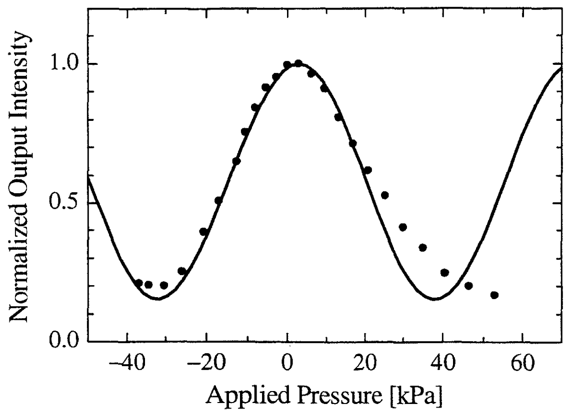

Fig. 7 Normalized output intensity versus applied pressure for the waveguide nearest to the center of the diaphragm.

4.2.2 Step response of a sensor with a semi-closed space

Figure 8 shows the experimental setup to measure output intensity by changing ambient pressure. The fabricated sensor with the semi-closed space was placed in the closed box with a volume of 30 cm×28 cm×30 cm. Although the sensor in this subsection was different from one in the previous subsection, pressure sensitivities of the sensors did not differ as good reproducibility for sensitivity has been confirmed. The closed box was connected to a syringe by a silicon tube. The pressure in the closed box was rapidly changed by 0.78 kPa, by pushing the plunger of the syringe. According to the phase sensitivity described in the previous subsection, the pressure change of 0.78 kPa produces a phase difference of 70 mrad, which would be sufficient to observe a change in output intensity.

Figure 9 shows the experimental results. The pressure in the closed box suddenly increased by 0.78 kPa at the 15 sec mark. Due to the pressure change, the output intensity decreased by approximately 20 % of the initial intensity level. Approximately 1.4 seconds after the step-like change in pressure, the output intensity returned to the initial level. According to the theoretical prediction, the duration of the induced pressure difference should be 0.046 sec. There is a large difference between the theoretical and experimental results. Such a large difference is attributed to pressure drop and fluid friction at the small hole. In addition, we could not confirm whether the change of the output intensity by 20 % was appropriate to the pressure difference of 0.78 kPa since the initial phase difference of the sensor was not known in this measurement.

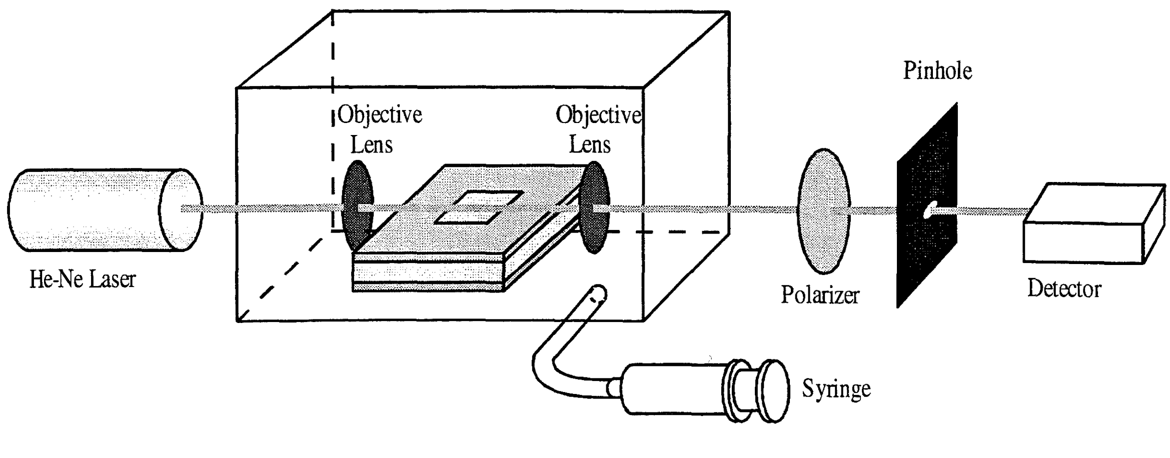

Fig. 8 Experimental setup to measure output intensity as a function of applied pressure. A sensor and two objective lenses were put in a closed box.

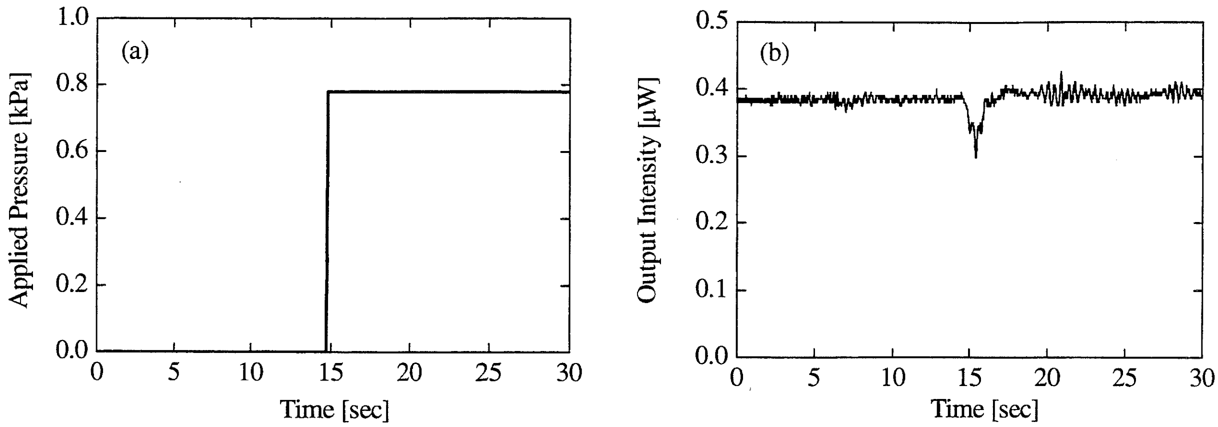

Fig. 9 (a) Ambient pressure change was increased by 0.78 kPa in a stepwise fashion at about 15 sec. (b) Measured output intensity as a function of time.

5. CONCLUSION

We proposed an original guided-wave optical pressure sensor that responds only to sudden pressure change. The sensor has a high withstanding pressure by a semi-closed space with a small hole, unlike the conventional pressure sensors with a diaphragm. The characteristics of the sensor with the 14 mm×14 mm×1.8 mm semi-closed space and the 93 μm×25 μm small hole was examined experimentally. In the experiment, when the ambient pressure of the sensor was rapidly changed by 0.78 kPa, variation in output intensity was observed. Approximately 1.4 sec after the step-like change in pressure, the output intensity returned to the initial level. According to the theoretical prediction, the duration of the induced pressure difference should be 0.046 sec. Although there was a large difference between the theoretical and experimental results, the sensor would still be useful to detect any malfunctions in static-high-pressure pipelines of industrial plants, to detect tidal waves under high hydraulic pressure on the sea floor, etc.

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*Correspondence: E-mail: ohkawa@eng.niigata-u.ac.jp; Telephone & Fax: +81-25-262-6734