Optical micro-electro-mechanical-system pressure sensor based on light intensity modulation

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An optical micro-electro-mechanical-system pressure sensor based on light intensity modulation is described. The idea is to use light for signal transmission to replace electrical signal, which isolates the sensor from electrical signals, so that it is quite suitable in flammable and combustible areas such as petrochemical and oil well. The sensor is composed of silicon diaphragm and optical system. The silicon diaphragm is fabricated from bulk micromachining technology and Si_3N_4 film is deposited on diaphragm for reflecting light. In the optical cable, one fibre conducts source light to the diaphragm and the other fibres conduct the reflected light back to photoelectric detection circuit. When pressure is applied on the sensor, the diaphragm will deform causing the intensity shift of reflected light. Photoelectric detection circuit converts the intensity of reflected light to voltage. The voltage is proportional to reflected light intensity and, in turn, to the deformation of silicon diaphragm, so that pressure can be measured. Deformation of silicon diaphragm is acquired by finite element method. Sensor's optical features are also analysed. Sensor prototype has been fabricated and encapsulated. The measurement range is 0–20 MPa and experimental sensitivity is −7.2 mV/MPa.

1. Introduction: Pressure measurements in modern industry are required in a variety of applications, such as turbine engines, aerospace, and chemical engineering [1, 2]. Especially, in some flammable environment, like gas and oil exploitation and transportation, the widely used semiconductor micropressure sensors have several major drawbacks [3, 4]. Electrical signals make the sensor be easy for causing fire and explosion. Optical micro-electro-mechanical-system (MEMS) combines microsensing structure with optics. Different from most microsemiconductor sensors, optical MEMS sensors use light for signal transformation, so they are suitable in flammable and combustible areas.

In the past decades, a number of microfibre-optic pressure sensors have been developed. Since MEMS technology minimises the sensor size and is suitable to fabricate microsensing element massively and accurately, optical MEMS devices have drawn great attention and have found wide applications [5, 6]. In optical MEMS sensors, two components are necessary: optical fibre and microsensing structure. Optical fibre is employed for transmitting light, which can guarantee that sensor's signal can be transmitted with a long distance with little signal attenuation. Microsensing structure changes optical coupling of input and output lights, which converts measured to the shift of optical parameter. Two different configurations of optical pressure sensors are widely developed: hollow cylinder-based pressure sensors and diaphragm-based configurations [7]. In these sensors, Fabry–Perot interferometry theory is widely used, which has very good testing accuracy and requires precise and complex instrument for processing optical signal. It is quite suitable for very precise pressure testing and low pressure application [8]. However, in oil and gas exploitation and transportation area, it needs high pressure and low cost pressure testing without electrical signal, so the optical sensors based on interferometry theory may be not quite suitable.

Therefore, we proposed a new configuration of optical pressure sensor utilising light intensity detection method, which owns the advantage of high pressure testing, simple structure and it is especially suitable for oil and gas area. We make full use of silicon diaphragm and optical fibre to design a novel high-pressure optical MEMS sensor with electrical signal far away from the flammable objects for safety. The idea is to use light for signal transmission to replace the traditional electrical signal, and light intensity is measured for sensing pressure to guarantee that the proposed sensor and testing system are effective with relatively simple structures and low cost. Si_3N_4 film is coated on silicon diaphragm for reflecting light as it has the property of good surface smoothness, mature fabrication process and stability, and it also works as a protective layer at the fabrication of silicon diaphragm.

2. Description and modelling of the sensor: The operating principle of the optical MEMS pressure sensor is shown in Fig. 1. Position of input and output optical fibres is fixed. The pressure moves the position of silicon diaphragm from ① to ②, the distance (d) between fibre end and reflector varies from d to d', so the light intensity reflected into output optical fibre changes. Intensity of output light is transformed to voltage by a photoelectrical detection circuit. The voltage is proportional to light intensity and, in turn, to the position of reflector. Therefore, if it is pressure that changes the location of reflector, the pressure can be measured.

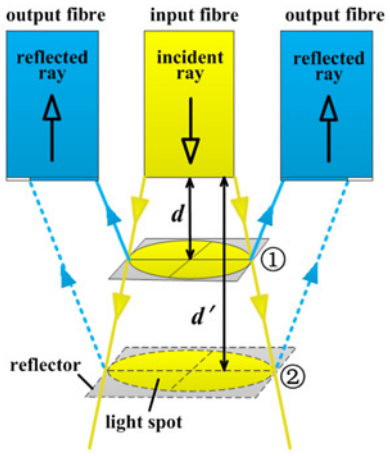


Fig. 1 *Operating principle of the optical MEMS pressure sensor*

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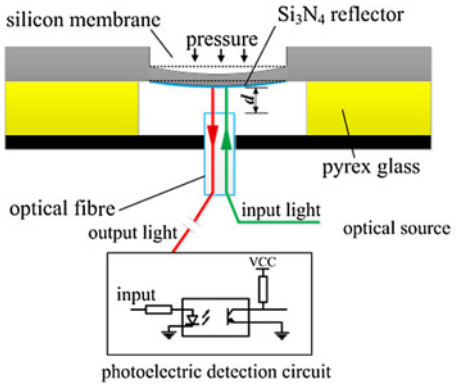


Fig. 2 *Schematic diagram of the proposed optical pressure sensor*

Fig. 2 presents the schematic structure of proposed optical MEMS pressure sensor. The sensor includes three parts: silicon diaphragm, optical fibre transmission and photoelectric detection system. Silicon diaphragm is developed for sensing pressure and Si_3N_4 film is deposited on diaphragm to reflect light for its good surface smoothness. When pressure is applied on the sensor, the diaphragm will deform. The deformation changes the distance (d) between silicon diaphragm and optical fibre, which leads to the intensity shift of light reflected into output optical fibre. A 'Y-style' optical fibre, which includes input and output optical fibres in one cable, transmits the source light to the silicon diaphragm, meanwhile, transmits the reflected light back to the photoelectric detection circuit through the output optical fibre. The photoelectric detection circuit converts the intensity shift of output light to voltage signal, so that the pressure can be measured.

Uniqueness of the proposed optical MEMS pressure sensor is that it has the advantages of both silicon MEMS sensors and optical sensors and suitable for high pressure measurement. The mature fabrication process of silicon can produce diaphragm structure massively and precisely. Optical fibre can transmit light signal for a long distance without signal attenuation, which isolates electricity signal from flammable and combustible areas.

2.1. Design of optical measurement system: Intensity of reflected light should be analysed as it has a great influence on sensor's accuracy. First, we gave the intensity distribution of source light. Then, analysed the modulation of input and output lights to calculate the intensity of light reflected into output optical fibre. Finally, according to the calculation results, we chose the proper optical fibre and optimised the distance between optical fibre and silicon diaphragm.

The intensity distribution with the distance (d) and radius of light spot at fibre end can be expressed as follows [9]

$$I(r, d) = \frac{\Phi_0}{\pi \xi^2(d)} \exp\left(-\frac{r^2}{\xi^2(d)}\right) \tag{1}$$

In (1), $\xi(d)$ can be expressed as

$$\xi(d) = \sigma\left(r + r^{1/2} \cdot d^{3/2} \cdot \tan\theta\right) \tag{2}$$

θ can be calculated by the following equation

$$\sin\theta = \frac{NA}{n_0} \tag{3}$$

In (1)–(3), $I(r, d)$ is the light intensity; r is the radius of light field; d is the distance between optical field and fibre end; Φ_0 is the luminous flux; $\xi(d)$ is the equivalent radius of reflecting light in distance d; σ is an influence factor of refractive index of optical fibre; θ is the maximum output angle of light; and n_0 is the refractive index of the medium.

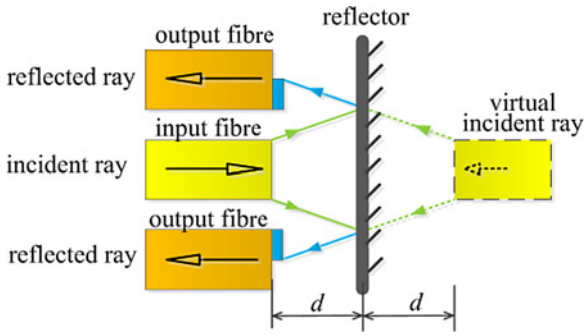


Fig. 3 *Light path in the sensor*

Light path in the proposed sensor can be found in Fig. 3. Light intensity reflected into output optical fibre is equal to the intensity that virtual incident ray irradiates into output optical fibre directly with a double distance ($2d$).

Optical power of source light can be calculated by integral of light intensity times the area of optical spot. The intensity distribution of source light is shown in (1), so light power can be obtained by the following equation

$$P_v(d) = \int_{st} I(r, 2\mathrm{d})\mathrm{d}s \tag{4}$$

Substituting (1) into (4), we can get the power of reflected light (i.e. the power of virtual source light)

$$P_v(d) = 2\pi \frac{\Phi_0}{\pi} \int_0^{\xi(2d)} \frac{1}{\xi^2(2d)} \exp\left[\frac{-r^2}{\xi^2(2d)}\right] r \cdot \mathrm{d}r \tag{5}$$

For the reflected light into the output optical fibre, the power can be calculated dividing into three different cases as shown in Fig. 4 according to the position of reflected light spot and output optical fibre. The three cases correspond to three typical distances between optical fibre and reflective film, i.e. the 'd' shown in Figs. 1–3.

For these three cases, the power of reflected light into output optical fibre can be calculated by the integration of reflected light power times coincide area. The results are expressed in (6)–(8).

(a) First case: $p - r_{of} > \xi(2d)$, no reflected light enters into output optical fibre. The optical fibre for transmitting reflected light has no coincidence with the source light spot. For this circumstance,

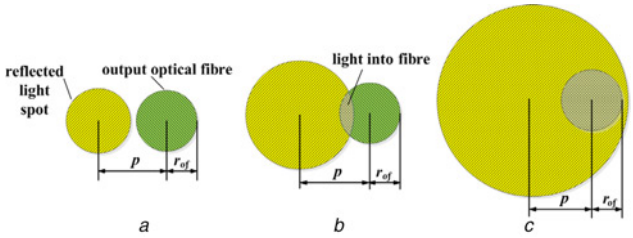


Fig. 4 *Three typical positions between reflected light spot and output optical fibre*
a Non coincide
b Partly coincide
c Full coincide

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no light is output

$$P_o(d) = 0 \tag{6}$$

(b) Second case: $p - r_{of} < \xi(2d) < p + r_{of}$, the optical fibre for transmitting reflected light has partial coincidence with source light spot. Part of reflected light is into optical fibre for output

$$P_o(d) = \frac{\Phi_0}{\pi} \int_{p-r_{of}}^{\xi(2d)} \frac{1}{\xi^2(2d)} \exp\left(\frac{-r^2}{\xi^2(2d)}\right) 2\sqrt{1-a(r)^2} r dr \tag{7}$$

(c) Third case: $\xi(2d) > p + r_{of}$, full of reflected light enters into optical fibre. The optical fibre for transmitting reflected light is fully coincided with the source light spot

$$P_o(d) = \frac{\Phi_0}{\pi} \int_{p-r_{of}}^{p+r_{of}} \frac{1}{\xi^2(2d)} \exp\left(\frac{-r^2}{\xi^2(2d)}\right) 2\sqrt{1-a(r)^2} r dr \tag{8}$$

In (6)–(8), p is the distance of two optical fibres, r_{of} is the radius of optical fibre. $a(r)$ can be obtained by

$$a(r) = \frac{p^2 + r^2 - {r_{of}}^2}{2pr} \tag{9}$$

According to (5)–(8), the value of $P_o(d)/P_v(d)$ (i.e. modulation function) can be calculated. The varying of calculated result with the distance (d) between silicon diaphragm and optical fibre end is shown in Fig. 5*b*. Cross section of optical fibre is shown in Fig. 5*a*. Its numerical aperture, radius and distance between fibres are 0.37, 100 and 200 μm, respectively. The central fibre is for inputting light and the other six fibres are for outputting light.

Fig. 5 demonstrates that nonlinearity and sensitivity are better in the distance of 100–450 μm, so according to the analysis the best distance between optical fibre end and silicon diaphragm is 100–450 μm. In Section 3, the packaging of the sensor must guarantee the distance. To make sure the distance in linear range (100–450 μm), we used the distance calibration instrument and photoelectric detection circuit to obtain the corresponding relations between distance (d) and voltage. In the package of the sensor, as shown in Fig. 9, we adjusted the fine thread to let the sensor's output voltage to be equal to the voltage of distance 100 μm, so we can guarantee that the distance is approximately 100 μm.

2.2. Design of the silicon diaphragm: The silicon diaphragm is a cube with dimensions of 2 mm × 2 mm × 0.3 mm (length, width and thickness). Its deformation is obtained through finite-element (FE) method when 20 MPa pressure is applied on the sensor.

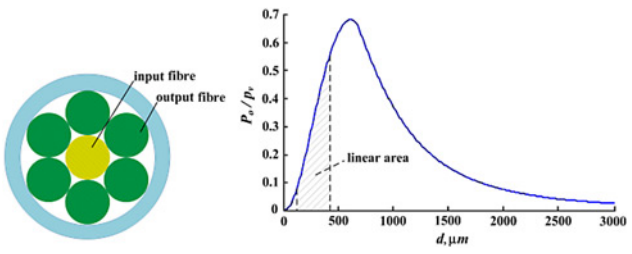


Fig. 5 *Nonlinearity and sensitivity are better in the distance of 100–450 μm*
a Fibre distribution
b Modulation function curves

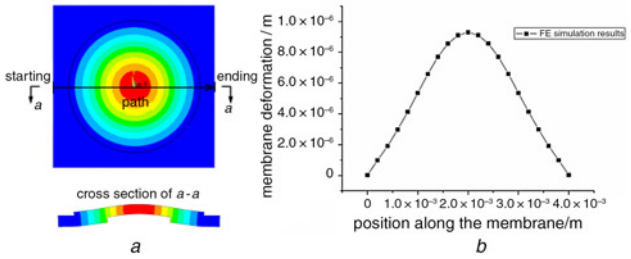


Fig. 6 *Deformation of silicon diaphragm along the defined path*

Fig. 6 presents the FE results and the deformation of diaphragm along the path line through diaphragm centre. From Fig. 6, it can be found that the diaphragm centre owns the largest deformation that is about 10 μm. According to FE results, we can obtain that for the maximal pressure, the sensor still works in linear range.

Silicon diaphragm is fabricated by bulk micromachining technology on 4 in. ⟨100⟩ plane wafer with 450 μm thickness. On the silicon diaphragm, Si_3N_4 layer is deposited by low pressure chemical vapour deposition (LPCVD) process and works as the reflector for its good surface smoothness. At the same time, Si_3N_4 layer protects the not etched area in the anisotropic wet etching of silicon. There is SiO_2 layer between Si_3N_4 and silicon. The detailed fabrication process of silicon diaphragm is shown in Fig. 7, which includes six steps. (i) SiO_2 layer (300 nm) is oxidised and Si_3N_4 layer (150 nm) is deposited by LPCVD on the double polished surfaces of silicon, successively, and these two layers are patterned on one side of silicon wafer. (ii) SiO_2/Si_3N_4 layer is etched by inductively coupled plasma (ICP) to expose silicon needed to be etched. (iii) Silicon is etched with a depth of 150 μm by anisotropic KOH etchant. (iv) The other side of silicon wafer is patterned. (v) SiO_2/Si_3N_4 layer is etched by ICP to obtain the Si_3N_4 reflector. (vi) Finally, photoresist is washed and Pyrex glass is bonded. Finally, fabricated silicon diaphragm is shown in Fig. 7 too.

2.3. Photoelectric detection circuit: Photoelectric detection circuit converts the intensity of reflected light to voltage signal. It mainly includes three parts: power supply, photovoltaic conversion and signal filtering. The diagram of photoelectric detection circuit is shown in Fig. 8.

3. Packaging and experiment: The proposed optical MEMS sensor is simply packaged as shown in Fig. 9. Distance between silicon diaphragm and optical fibre is adjusted to the calculated value (100–450 μm) by fine thread. In the sensor, no electrical signal exists because optical fibre transfers optical signal for a long distance for being converted to voltage signal by

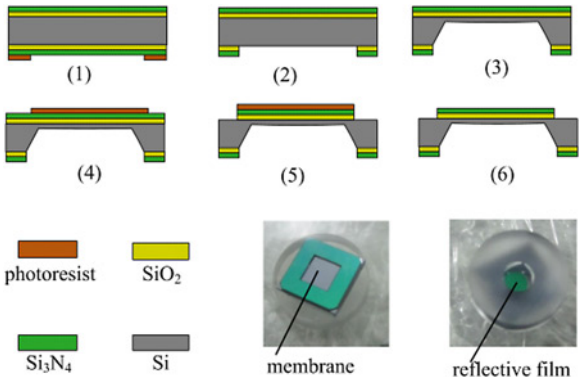


Fig. 7 *Schematic of silicon diaphragm fabrication process*

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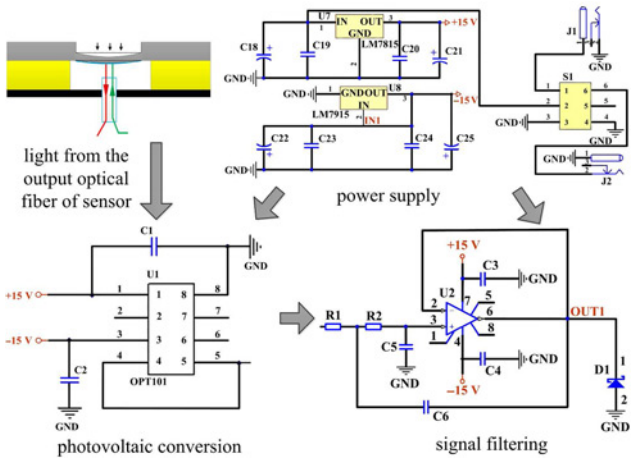


Fig. 8 *Photoelectric detection circuit*

photoelectric detection circuit, which means that the proposed sensor can be used in many flammable and explosive industries.

The sensor prototype is characterised primarily and experimental process is shown in Fig. 10. Piston gauge applies pressure to the optical MEMS sensor. The photoelectrical detection circuit converts light signal to voltage that is acquired and processed by computer.

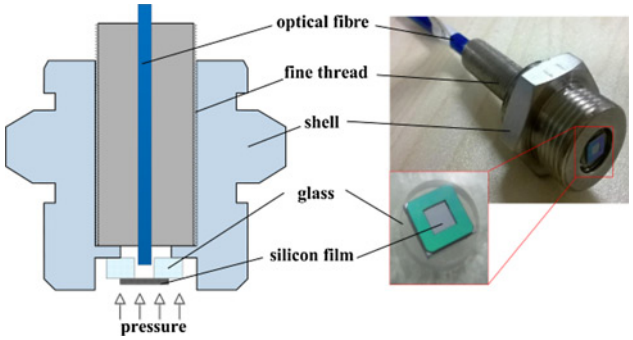


Fig. 9 *Simply packaged sensor*

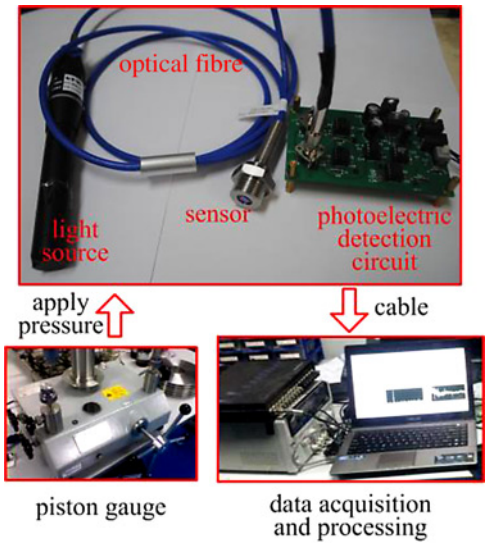


Fig. 10 *Experimental process*

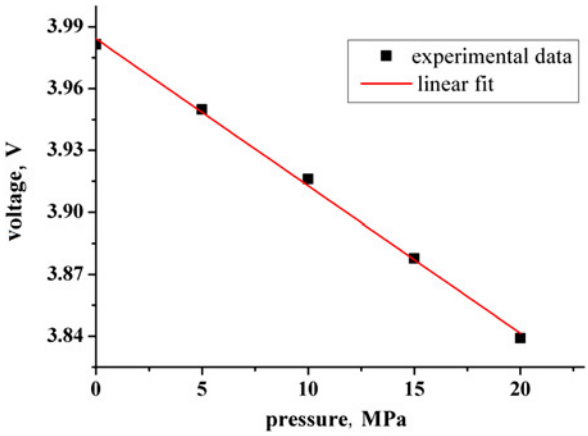


Fig. 11 *Linearity of the optical MEMS pressure sensor*

Experimental results are shown in Figs. 11–13 that demonstrate the linearity, hysteresis and repeatability, respectively. According to the experimental data, the sensitivity, linearity, hysteresis and repeatability are −7.14 mV/MPa, 1.94%FS, 0.58%FS and 1.98%FS, respectively. The results demonstrate the feasibility of the novel configuration of the proposed optical MEMS pressure sensor.

We also compared the proposed optical sensor with other reported optical pressure sensors, and the results are shown in Table 1. The comparison shows that the optical pressure sensor described in this work owns the largest pressure testing range and has a medium sensitivity, so it can be used for high pressure testing such as oil and gas exploitation and transportation.

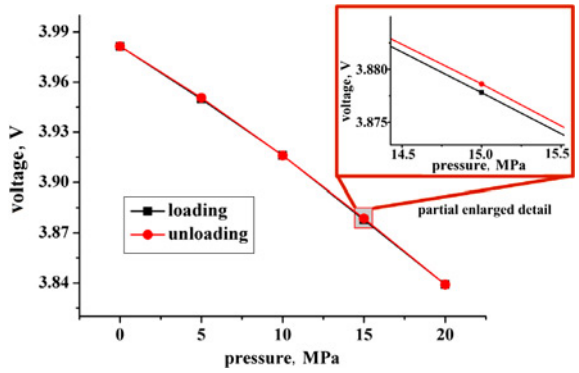


Fig. 12 *Hysteresis of the optical MEMS pressure sensor*

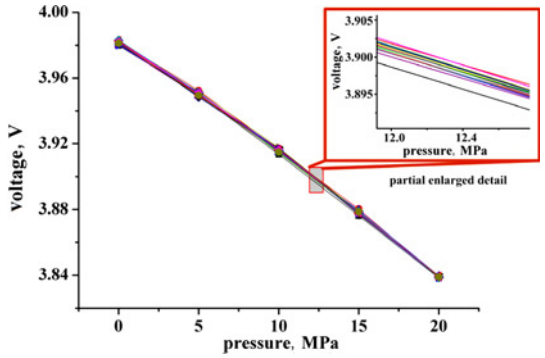


Fig. 13 *Repeatability of the optical MEMS pressure sensor*

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Table 1 Comparison with other optical pressure sensors

	Testing range	Theory	Sensitivity
our work	0–20 MPa	light intensity detection	7.14 mV/MPa
[10]	0–80 psi (0–550 kPa)	Fabry–Perot interferometry	0.11 mV/psi
[11]	none	Fabry–Perot interferometry	2.2 nm/psi
[12]	none	Fabry–Perot interferometry	28.6 mV/Pa
[7]	0–200 psi (0–1.38 MPa)	Fabry–Perot interferometry	2.93 nm/psi
[8]	0–50 kPa	Fabry–Perot interferometry	70.5 nm/kPa
[13]	0–600 kPa	Fabry–Perot interferometry	1.6 rad/bar

4. Conclusion and discussion: In this Letter, a novel configuration of optical MEMS pressure sensor based on light intensity modulation is described. We use silicon diaphragm and optical fibre to design a high pressure sensor with electrical signal far away from flammable objects for safety. The proposed sensor and testing system are effective with relatively simple structure. The experiment demonstrates the feasibility of sensor design. The sensitivity, linearity, hysteresis and repeatability are −7.14 mV/MPa, 1.94%FS, 0.58%FS and 1.98%FS, respectively.

According to FE analysis results, the optimal distance between optical fibre and reflective film is 100–450 μm. Nevertheless, the deformation displacement for the proposed silicon diaphragm is only 10 μm, so we just used less than 3% of linear area. Therefore, there is great potentiality for improving sensor sensitivity with thinner and larger silicon diaphragm.

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