

# Fabrication and Performance of a Fiber Optic Micro-Probe for Megahertz Ultrasonic Field Measurements

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## Summary

For measuring high-frequency and intense ultrasonic fields, a miniature sensor with a durable structure has a great demand recently. The authors propose a new fabrication method of the small acoustic sensor which is composed of a micro optical cavity of 100  $\mu\text{m}$  long at the end of an optical fiber. The deformation or the refractivity change of the cavity by sound wave is measured by monitoring the reflected light intensity at another end of the fiber. In this report, the fabrication technique of the sensing part is first described. Then, we examine the basic properties for measuring ultrasound in water. It is shown experimentally that megahertz ultrasonic field can be measured successfully by the prototype micro probe with a good spatial resolution.

Keywords: *ultrasonic field, fiber optic probe, optical cavity, spatial resolution*

## 1. Introduction

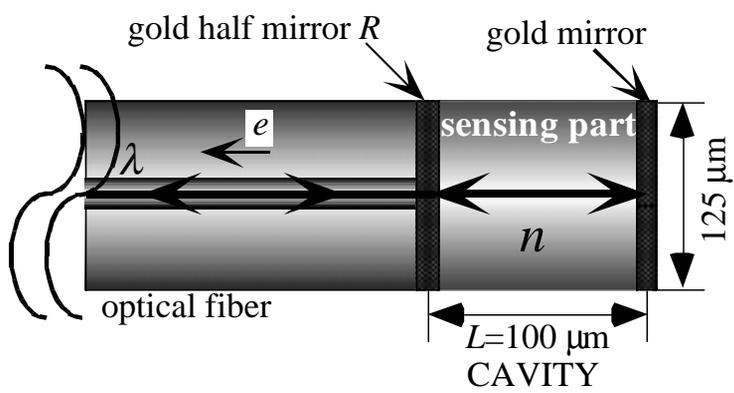
A miniature ultrasonic probe has a great demand recently due to the rapid developments of high frequency ultrasonic engineering. Sensors should be smaller than the wavelength of ultrasound to be measured (less than several hundred  $\mu\text{m}$ ) for high spatial resolution and prevention of interference to the ultrasonic field. It should also be durable against both intense sound pressure and high level electromagnetic noise. For example, in medical diagnostics and surgeries, ultrasonic pulses operating at over several MHz and acoustic pressure of kPa-MPa are used. Recently, much higher frequency over 10 MHz is coming into practical use for higher resolution. However, we have practical difficulties in miniaturizing the conventional piezo-hydrophones to a hundred  $\mu\text{m}$  size since the feeding wire or the electrode sometimes has problem in strength, and the high electrical impedance may become a difficulty in remote measurement. An optical fiber sensor has possibility to overcome all of these problems. Optical fiber hydrophones using an interferometric technique<sup>(1),(2)</sup> have been developed for twenty years. However, they have been mainly aimed at low frequency region up to 10 kHz for ocean acoustics. On the other hand, several small fiber optic hydrophones have been proposed<sup>(3),(4)</sup> for the measurement of ultrasonic pulse or shock wave, which are based on the light intensity modulation by sound pressure. These small hydrophones consist of only a cut fiber end or a curved fiber immersed in acoustic field. The optical refractivity change of media due to the sound pressure is detected as a function of the reflective index at the fiber end<sup>(3)</sup> or the

bending loss of fiber<sup>(4)</sup>. In spite of their high spatial resolution, their very low sensitivities due to the small change of refractive index limit their application to very strong acoustic fields. On the other hand, ultrasonic probes using an Fiber Bragg Grating (FBG) have been proposed recently<sup>(5),(6)</sup>. These papers reported the detection of ultrasound by FBG, where the sound pressure was measured as a shift of the center wavelength of the FBG. The grating length of an FBG needs to be no less than a few millimeters, and the spatial resolution in the axial direction is limited.

Beard and Mills reported a new approach to make a small Fabry-Perot sensor at fiber end by using polymer film<sup>(7)</sup>. We have proposed, independently to this work, a fiber-optic probe with a moderate sensitivity and a three-dimensionally confined sensing part by introducing a micro cavity at the end of fiber<sup>(8)</sup>. Optical pass length of the cavity is changed by the applied acoustic field, and the modulation of output light monitored at the other end of the fiber gives the information for the acoustic field. This principle provide us a sensitive sensing because the phase modulation is detected by the cavity instead of the intensity modulation in Refs. (3) and (4). This paper describes the fabrication technique of the small polymer cavity on the fiber end, as well as the performances for acoustic field measurements.

## 2. Construction and principle

Figure 1 shows the configuration of the proposed probe. A



**Fig. 1** Construction of the proposed probe.  $n$ , refractive index of the cavity;  $L$ , length of the cavity;  $R$ , reflectivity of the half mirror;  $e$ , back reflect light intensity;  $\lambda$ , wavelength of the incident light.

small dielectric cylinder with refractive index of  $n$  is attached on the fiber end through a half mirror. Another end of the cylinder is terminated with a full reflection mirror. The length of the cavity  $L$  is almost as large as the diameter of the fiber's cladding. Optical path  $nL$  of the cavity is changed due to the deformation or the refractivity change by acoustic pressure, and the sound wave can be measured by monitoring the reflected light intensity  $e$  from the fiber end, if a monochromatic light is used and its wavelength is at the slope of the cavity resonance.

### 3. Fabrication method

The procedure for the fabrication of the cavity is described as follows by referring Fig. 2: (1) A gold half mirror is formed at the end surface of a fiber by vacuum evaporation. Transmittance is controlled by the deposition time. Then, another fiber, which is a 'dummy', is placed facing with the coated fiber; (2) Polyester resin of  $n = 1.55$  is injected between the fibers. We feed a guiding light into the fiber and monitor the output light from the dummy fiber for the alignment of the fibers; (3) After the resin hardened, the dummy fiber is removed and the gold coating is formed over the cavity. The photograph of a prototype is shown in Fig. 3. The final coating was made thick in order to protect the sensitive part.

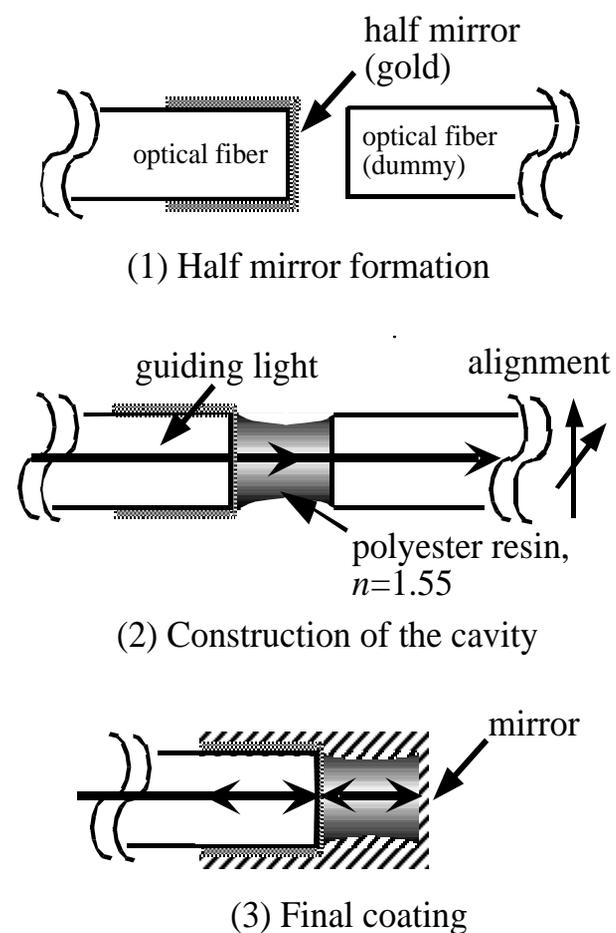
### 4. Sensitivity estimation

First, the wavelength dependence of the fabricated cavity was measured to discuss the pressure sensitivity. Here, we used a single-mode fiber (for  $\lambda = 1.3 \mu\text{m}$ ) with  $10 \mu\text{m}$  core and  $125 \mu\text{m}$  cladding. The length of the cavity was designed to be  $100 \mu\text{m}$ . Here, the cavity length was measured under a microscope by comparing with the diameter of cladding. As shown in Fig. 4, the returned light intensity was picked up by a half mirror and monitored by a pin photo diode.

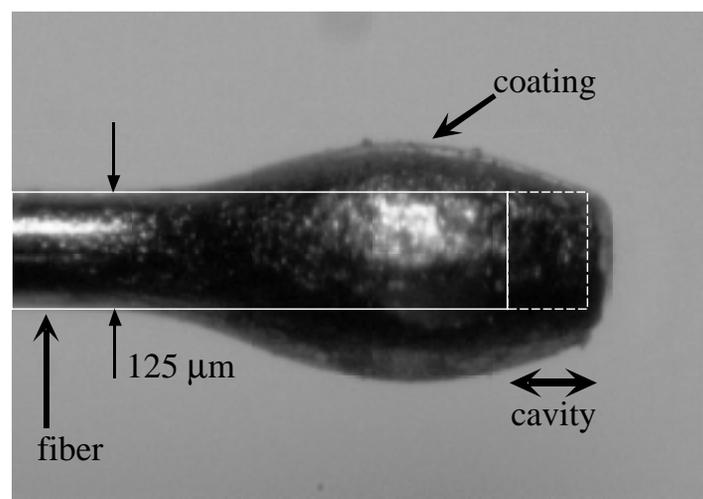
An external cavity diode laser (*Environmental Optical Sensors, Inc.*; 2010) was used as the light source for sweeping the wavelength of injected light from  $781 \text{ nm}$  to  $787 \text{ nm}$ . The returned light intensity  $I_0$  was measured as a DC voltage, and plotted in Fig. 5. It can be confirmed from the figure that the fabricated cavity worked as expected. The reflectance of Fabry-Perot resonator is written<sup>(9)</sup> by

$$G_R = \frac{(\sqrt{R} - G_s)^2 + 4\sqrt{R} G_s \sin^2(2\pi nL/\lambda)}{(1 - \sqrt{R} G_s)^2 + 4\sqrt{R} G_s \sin^2(2\pi nL/\lambda)}. \quad (1)$$

To fit the measured data, the cavity length  $L$ , the single pass gain  $G_s$  and the reflectivity of the mirror  $R$  were chosen to be  $94.2 \mu\text{m}$ ,  $0.92$



**Fig. 2** Fabrication of the cavity.



**Fig. 3** Photograph of the sensing part of the prototype probe.

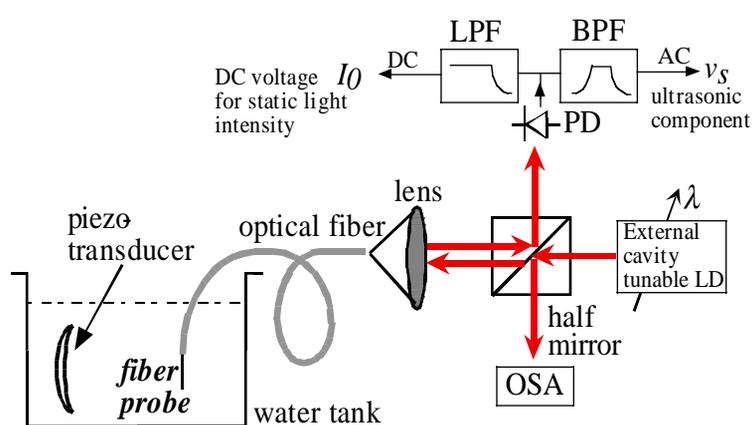
and 0.8, respectively. From this result, the sensitivity of the reflectivity to the change of optical path  $\Delta G_R/\Delta(nL)$  is derived to  $50 \mu\text{m}^{-1}$  at  $\lambda=784.3 \text{ nm}$ . On the other hands, the change in optical path  $\Delta(nL)$  with respect to acoustic pressure  $\Delta p$  is written by the next equation<sup>(10)</sup>:

$$\frac{\Delta(nL)}{\Delta p} = n \frac{\Delta L}{\Delta p} + L \frac{\Delta n}{\Delta p} = nL \left( \frac{1}{L} \frac{\Delta L}{\Delta p} + \frac{1}{n} \frac{\Delta n}{\Delta p} \right). \quad (2)$$

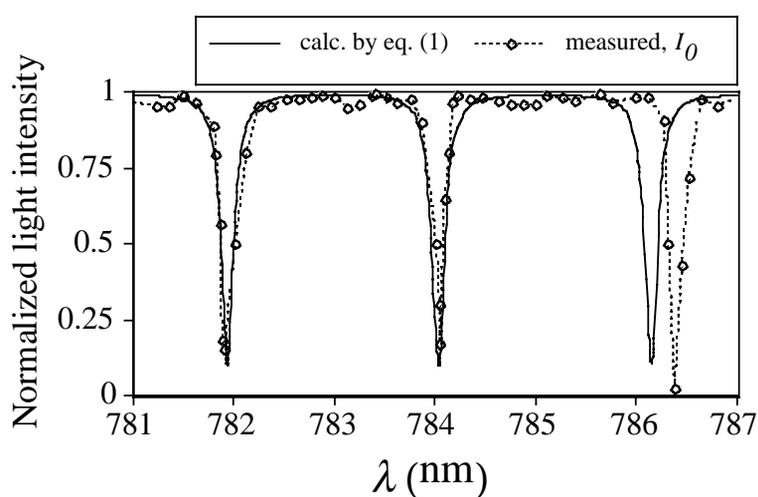
The second term, which is the change of refractivity, can be ignored since the first term, which is the change of the geometrical length, is much bigger than the second term for a short polymer cavity of  $L=100 \mu\text{m}$ . The elastic constant of polyester resin is  $1/L(\Delta L/\Delta p)=2.5 \times 10^{-4} (\text{MPa}^{-1})$ <sup>(11)</sup>. Then, the final result is

$$\frac{\Delta G_R}{\Delta p} = \frac{\Delta G_R}{\Delta(nL)} \frac{\Delta(nL)}{\Delta p} = 1.9 (\text{MPa}^{-1}). \quad (3)$$

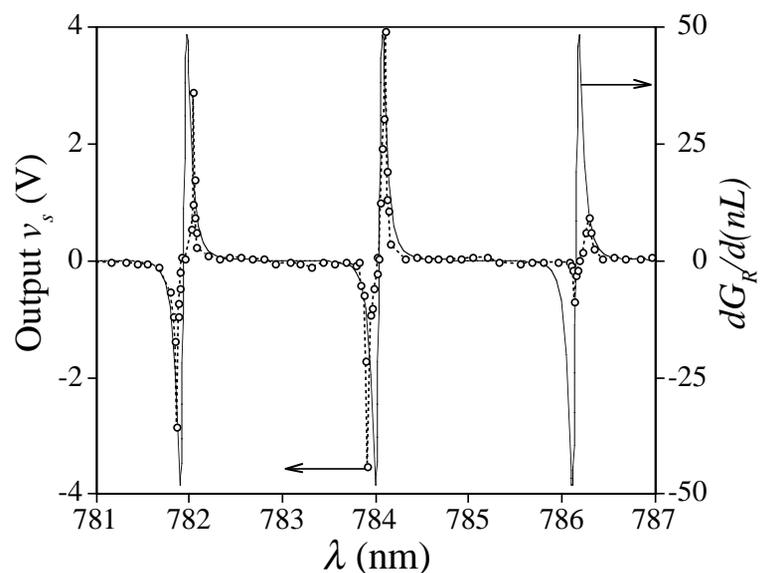
This value for the reflectivity modulation type reported in ref. (3) is  $\Delta G_R/\Delta p=2.0 \times 10^{-3} (\text{MPa}^{-1})$ , which is directly proportional to the refractivity change, and is very small. The sensitivity of the proposed



**Fig. 4** Experimental setup for ultrasonic field measurements by the proposed probe. LPF, low pass filter; BPF, band pass filter; OSA, optical spectrum analyzer.



**Fig. 5** Reflectance of the cavity as a function of wavelength.



**Fig. 6** Sensitivity to sound pressure as a function of wavelength. The measured data are plotted by --o-- while the solid curve shows the derivative of eq. (1) with respect to  $nL$ .

prototype probe is large due to the steep slope of the Fabry-Perot curve  $\Delta G_R/\Delta(nL)$  in eq. (3) and Fig. 5, and is estimated to be about 60 dB higher than this value of reflectivity modulation type.

## 5. Measurements of acoustic field and properties

### 5.1 Confirmation of the principle

First, we measured light intensity  $I_0$  and ultrasonic component  $v_s$  simultaneously with applying 68 kHz ultrasonic field on the sensing part for various optical wavelength as shown in Fig. 4.  $I_0$  and  $v_s$  were extracted from the PD output by electric filters. The ultrasonic component  $v_s$  is plotted as a function of light wavelength in Fig. 6 as well as the gradient of theoretical Fabry-Perot curve. As is expected, the proposed sensor has the sensitivity to the acoustic fields if the optical wavelength is tuned at the slope of the cavity resonances, and it is proportional to  $dG_R/d(nL)$ . The sensitivity to sound pressure becomes zero just at the bottom of the resonance curve in Fig. 5. Here, let us note that the temperature variation during the experiment might shift the resonance wavelength around 786.5 nm.

### 5.2 Sensitivity

Then, we employed a concave piezoelectric transducer of 100 mm in diameter and 150 mm in focal length to demonstrate the performance of the prototype. It was driven by a burst wave with the center frequency of 0.5 MHz. The fiber probe was traversed across the focal point of the piezoelectric transducer. In this experiment, a He-Ne laser at 632.8 nm was used. The drift of the cavity resonance was not compensated, and the operation point was not necessarily

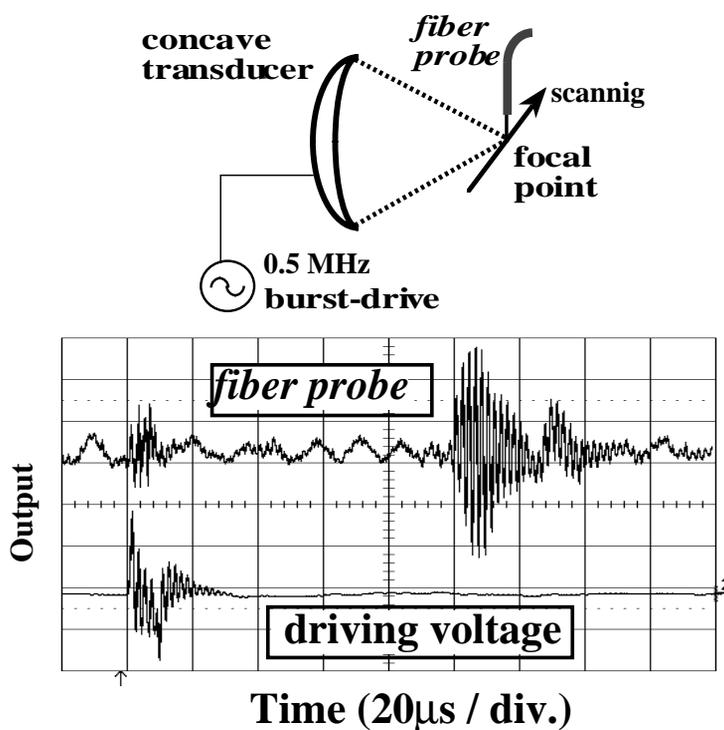


Fig. 7 Signal received by the proposed probe.

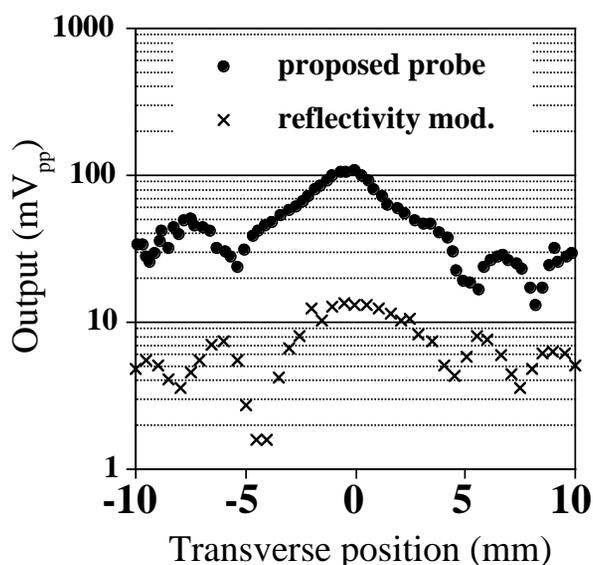


Fig. 8 A focused acoustic field measured by the proposed probe ( $f=0.5$  MHz).

optimum in this experiment. A fiber optic hydrophone of intensity modulation type reported in ref. (3) was also used for comparison. Figure 7 shows the signal received by the proposed fiber probe and the driving voltage of the transducer. An electromagnetically induced signal and a system noise at lower frequency are included in the result due to a poor experimental condition. However, it is easy to discriminate the acoustically received signal from the electromagnetically induced one, since the time delay ( $=100$  ms) corresponds to the time-of-flight of the acoustic wave in water.

Figure 8 shows that we could measure the ultrasonic beam profile precisely with the sensitivity of about 10 times higher than the previously proposed intensity modulation type<sup>(3)</sup>. The absolute sensitivity of the proposed probe was about 37.3 dB less than the

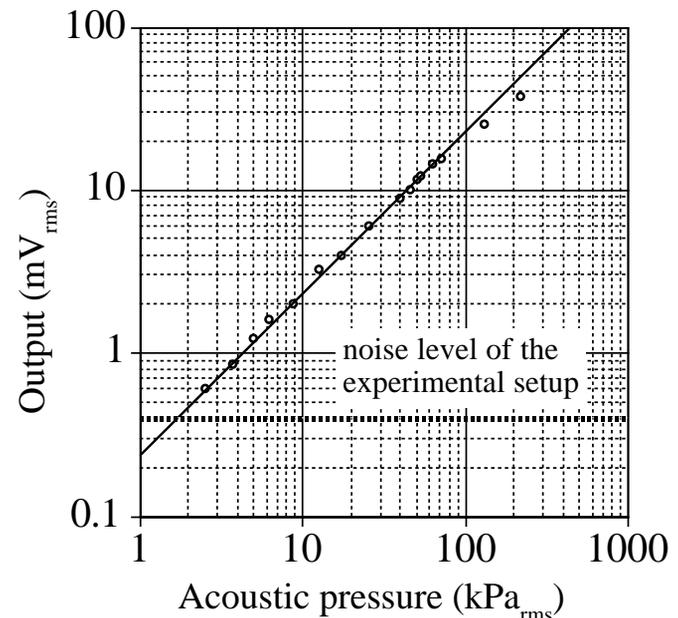


Fig. 9 Linearity.

maximum value expected theoretically in Sec. 4. This difference can be attributed to that the operation point was out of the center of the slope in wavelength characteristics due to the environmental disturbance. We confirmed by another experiment that the sensitivity optimized by the tunable LD was 6 dB lower than the theoretical value. We also consider that the effect of the pressure to the real cavity deformation was different from the simple model used in Sec. 4.

### 5.3 Linearity

The maximum measurable pressure is limited by the linear region of the optical resonance curve of Fig. 5. The maximum change of pass-length within the linear region is  $0.025$   $\mu\text{m}$  in the prototype. This corresponds to the pressure of  $0.38$  MPa. On the other hand, the minimum detectable pressure is determined by the noise in the

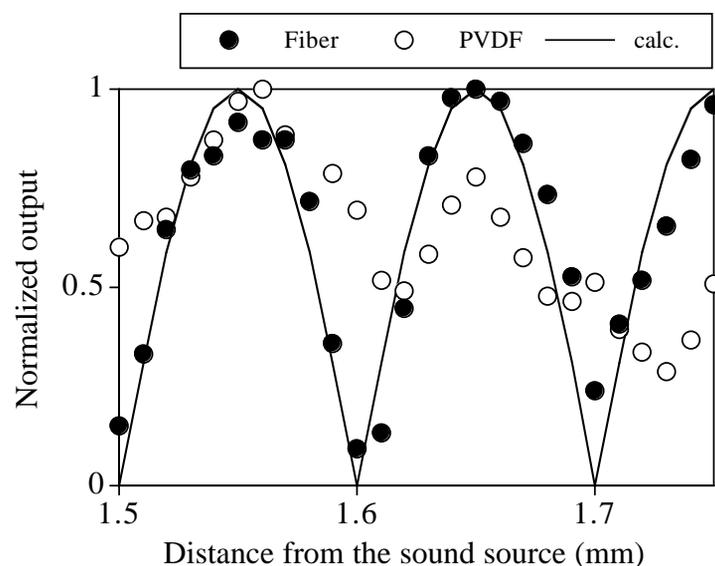


Fig. 10 Measurement of standing wave:  $f=7.5$  MHz and  $\lambda_s=0.2$  mm.

detector. The noise equivalent power (NEP) of the used detector (S1223; Hamamatsu Photonics corp.) is  $8.9 \times 10^{-15} \text{ W}/\sqrt{\text{Hz}}$ . If the bandwidth is 10 MHz and the static light power at the detector's window is  $80 \mu\text{W}$ , the minimum detectable pressure is estimated to be about 1.9 kPa for the prototype.

We measured linearity of the proposed probe by using the focused burst acoustic field at 0.5 MHz. A PVDF hydrophone was employed for reference. The measured result is shown in Fig. 9. Distortion begins at about 100 kPa. This was lower than the estimated value, since the operation point was not tuned at the center in the prototype. The overall noise of the experimental setup was higher than the NEP since the noise figure of the post amplifier was not so low. Then, the minimum detectable limit was about 2 kPa.

#### 5.4 Spatial resolution

We measured a standing wave ultrasound field at 7.5 MHz (wavelength of ultrasound  $\lambda_s = 0.2 \text{ mm}$ ) to examine the spatial resolution. The conventional PVDF hydrophone (0.5 mm in diameter, MH28-5; The Danish Institute of Biomedical Engineering) was employed for comparison. The results are shown in Fig. 10. It should be noted that the diameter of PVDF hydrophone is two times as large as the whole width of the horizontal scale. The higher contrast between the node and the antinode is obtained by the proposed probe, though standing wave field is sensitive to the size of sensor inserted.

## 6. Conclusion

A fiber optic acoustic probe of  $125 \mu\text{m}$  in diameter was made by introducing a micro cavity at the fiber end, and megahertz ultrasonic fields were measured. It was shown experimentally that the sensitive part of the probe was confined only in the micro cavity at the fiber end, and the sensitivity was higher than the simple intensity modulation type. Sensitivity of the prototype was lower than the simple calculation even when the optical wavelength was adjusted. We need much accurate analysis for better sensitivity estimation. A smaller cavity will provide improvements in characteristics. It is also noted that a help of electronic circuit technology such as a modulation of a semiconductor laser should be used to stabilize the output for practical use.

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## References

- (1) J. A. Bucaro and H. D. Dardy, *Fiber-optic hydrophone*, J. Acoust. Soc. Am., 62, pp. 1302-1304, 1977.
- (2) J. H. Cole, R. L. Johnson and P. B. Bhuta, *Fiber optic detection of sound*, J. Acoust. Soc. Am., vol. 62, pp. 1136-1138, 1977.
- (3) J. Stardenraus and W. Eisenmenger, *Fiber-optic probe hydrophone for ultrasonic and shock-wave measurements in water*, Ultrasonics, vol. 31, pp. 267-273, no. 4, 1993.
- (4) K. Nakamura, Y. Uno and K. Iga, *Sound Field Measurements by a Sharply Bent Optical Fiber*, J. Acoust. Soc. Jpn., (E)17, pp. 45-47, Jan. 1996.
- (5) N. Takahashi, A. Hirose and S. Takahashi, *Underwater acoustic sensor with Fiber Bragg Grating*, Optical Review, vol. 4, no. 6, Dec. 1997.
- (6) NE Fisher, SF O'Neill and et al., *Response of in-fiber Bragg Gratings to focused ultrasonic fields*, Proc. of International Conference on 12th Optical Fiber Sensors, OWC12, pp. 190-193, Oct. 1997.
- (7) P. C. Beard and T. N. Mill, *Miniature optical fibre ultrasonic hydrophone using a Fabry-Perot polymer film interferometer*, Electronics Letters, vol. 33, no. 9, Apr. 1997.
- (8) Yasuto Uno and Kentaro Nakamura, *Measurements of High-Frequency Ultrasonic Field by a Fiber Optic Micro-probe*, Proc. of International Conference on 12th Optical Fiber Sensors, OTuD6, pp. 87-90, Oct. 1997.
- (9) T. Mukai and Y. Yamamoto, *Gain, Frequency Bandwidth, and Saturation Output Power of AlGaAs DH Laser Amplifiers*, IEEE J. Quantum Electron., QE-17, pp. 1028-1034, June 1981.
- (10) Peter Shajenko, James P. Flatley and Mark B. Moffett, *On fiber-optic hydrophone sensitivity*, J. Acoust. Soc. Am., 64(5), pp. 1286-1288, Nov. 1978.
- (11) J. Saneyoshi, K. Kikuchi and O. Noumoto, *Cho-onpa Gijyutsu Binran* (in Japanese), Nikkan Industrial Newspaper Publishing Company, ch. IV-5.17-(i), pp. 1356, 1978.

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