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Wavelength-Division-Multiplexing in Fiber-Optic Micro-Probe Array for Ultrasonic Field Measurements

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SUMMARY For measuring high frequency ultrasonic fields which are often spatially distributed and transient, an array probe with small element sensors is highly required. In this paper, we propose a fiber-optic micro-probe array which is based on wavelength-division-multiplexing technique. The element sensor consists of a micro optical cavity of $100\,\mu$m long made at the end of optical fiber. Optical path length of the cavity is changed by the applied acoustic field, and the modulation of output light intensity is monitored at another end of the fiber for the information of the acoustic field. Array of sensor elements and a light source as well as a photo detector are connected together by an optical star coupler. The Fabry-Perot resonance wavelength of each sensor element is designed different one another, and the outputs from the sensors are discriminated by sweeping the wavelength of light source with the use of a tunable semiconductor laser. In this paper, the performance of the micro-probe array is discussed experimentally.
key words: *fiber-optic probe, array, wavelength-division-multiplexing* (WDM)*, Mega-hertz ultrasonic field, optical cavity, Fabry-Perot resonator*

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 μm) 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. Moreover, an arrayed sensor is desirable since practical acoustic fields are usually transient. Sound intensity measurements [1], which require multipoint sensing, will provide useful information also in high frequency ultrasonic fields.

Several small fiber-optic hydrophones have been proposed [2], [3] for the measurement of ultrasonic pulse or shock wave, which are based on the light intensity modulation by sound pressure. In spite of their high spatial resolution, the sensitivity is so low that their application is limited to very strong acoustic fields. On the other hand, ultrasonic probes using an Fiber Bragg Grating (FBG) have been proposed recently [4], [5], which has a potential to build an array by wavelength-division-multiplexing (WDM). However, 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 use of a small *Fabry-Perot* sensor at fiber end by using polymer film [6]. We have proposed, independently to this work, the fabrication technique of a small cavity at the fiber end using resin [7]. The sensing characteristics were analyzed in detailed by the authors [8]. This probe has a moderate sensitivity and a three-dimensionally confined sensing part. Optical path length of the cavity is changed by the applied acoustic field, and the modulation of output light intensity monitored at the other end of the fiber provides the information for the acoustic field.

This paper presents a method to integrate the sensor elements to an array probe. The sensor elements and a light source as well as a photo detector are connected together by an optical star coupler. The *Fabry-Perot* resonance wavelength of each sensing cavity is designed different one another, and the outputs from the sensors are discriminated by sweeping the wavelength of injected light with the use of a tunable laser diode. Three-element array has been fabricated in this paper, and its performance was discussed experimentally.

2. Construction of the Element Probe

Figure 1 shows the configuration of the element sensor. A small dielectric cylinder with refractive index of n is attached on the fiber end through a half mirror of reflectance R. 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 fiber's cladding.

Optical path length nL of the cavity is changed due

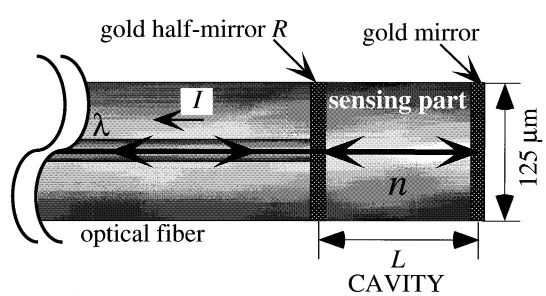

Fig. 1 Configuration of the element sensor.

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to the deformation or the refractivity change by acoustic pressure, and the sound wave can be measured by monitoring the returned light I from another fiber end, if a monochromatic light is used and its wavelength is set at the slope of the cavity resonance. The reflectance of *Fabry-Perot* resonator G_R is written by

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

where, G_R is the normalized reflected light intensity, G_s is the single-pass gain and λ is the light wavelength [9]. The cavity was made with the fabrication technique developed by the authors [7]. The value were chosen as R =0.8, G_s =0.9 and L =100 μm in the design. To confirm the cavity operation, the reflectivity of the cavity was measured as a function of the wavelength λ. An external cavity tunable LD (*Environmental Optical Sensors, Inc.*; 2010) was employed as a light source. Figure 2 shows the experimental and calculated results. By fitting the measured data by Eq. (1), R, G_s and L can be estimated to be 0.78, 0.93 and 94.2 μm, respectively. *Finesse* was about 103. The errors from the design for R, G_s and L were <3%, <3% and <10%, respectively.

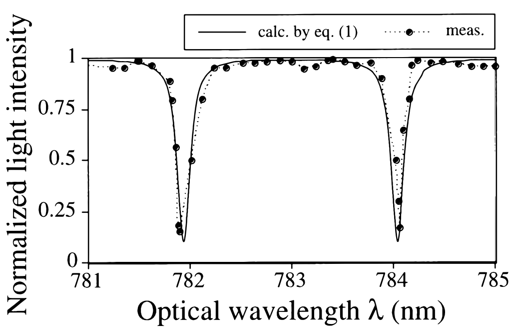

Fig. 2 Reflectivity of the cavity as a function of wavelength.

3. Integration to an Array

Figure 3(a) shows the total construction of the proposed micro-probe array made for trial in this study. Three probes are integrated in this trial. A tunable LD mentioned before is employed as a light source and the light is divided into four ports by an optical star coupler. The back reflected lights from all the sensor elements are combined by the star coupler and received by a photo detector. The 4th port is connected by an optical spectrum analyzer (OSA) to monitor the wavelength and light intensity of the incident light. Every resonance wavelength of each sensor is designed different one another as shown in Fig. 3(b) for WDM detection by changing cavity length. Here, let the optimum operation wavelength of each sensor be λ_1, λ_2 and λ_3. If the light source is tuned at λ_1, probe 1 is activated while probe 2 and probe 3 are not sensitive to acoustic field, and the current of PD gives the output signal of probe 1. If the wavelength is moved to λ_2, the acoustic field applied to probe 2 is detected. This is the principle for discriminating signals from the sensor elements by WDM technique. The resonance dip of one sensor should be separated from that of other sensors to have a good signal discrimination without crosstalk. Thus, the number of sensor element is limited, since *Fabry-Perot* resonator responds at many periodic wavelength.

Here, let us discuss briefly on this limitation before experimental results. The usable number N of element sensor is determined by the free spectrum range (FSR) of the *Fabry-Perot* response and the sensitive width $\Delta\lambda_w$ of the resonance dips. Here, $\Delta\lambda_w$ is defined as wavelength with $G_R \geqq$90% where the slope of resonance curve is large. $\Delta\lambda_w$ is about three times larger than the full width at half maximum ($FWHM$), and N is almost equal to the $Finesse/3$. According to these discussions, maximum element number $N \leqq 8$ for R=0.9, G_s=0.7, n=1.55, around L=100 μm, $\lambda = 784 - 786$ nm, for example. However, practical N will be smaller than

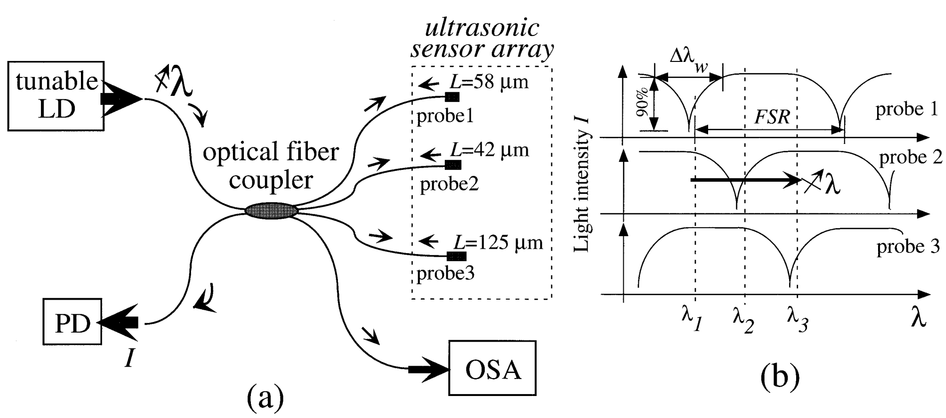

Fig. 3 (a) Construction of the proposed micro-probe array, and (b) concept of WDM detection.

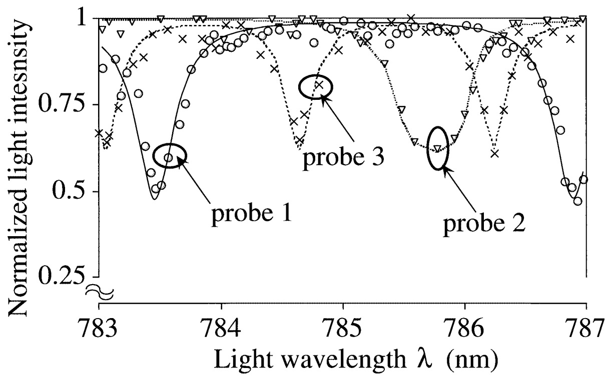

Fig. 4 Reflectivity of the three sensor elements as functions of wavelength. The curves are calculated by Eq. (1) and the symbols are measured data.

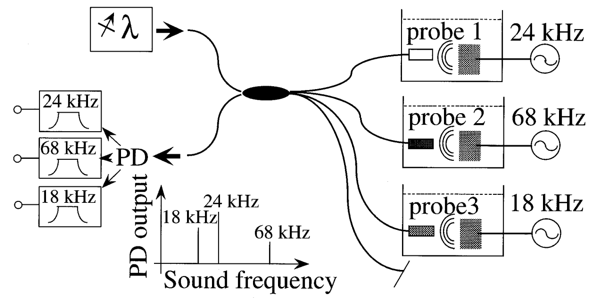

Fig. 5 Experimental setup for the measurement of pressure sensitivity of three sensors.

this number due to the fabrication error.

4. Experiments

The cavity length L of the three sensor elements were fabricated at 58, 42 and 125 μm, respectively, so that their resonance wavelength does not overlap each other during a certain region. It has been theoretically discussed that the pressure sensitivities of probes 1–3 are not different much for these cavity length [8]. The wavelength characteristics of each element sensor were measured separately by using the setup of Fig. 3(a) where only the probe under test was connected to the one port of the star coupler, and other two ports were immersed into matching fluid without sensor element. Then, the results will contain the property of optical components such as the star coupler and optical connectors. An external cavity tunable laser diode (*Environmental Optical Sensors Inc.*; 2010) was employed as a light source. The light wavelength was swept manually by rotating the micrometer attached to the external cavity. This system needs a few seconds for the single sweep over the band of 5 nm. The curves and the symbols in Fig. 4 show the reflectivity G_R of the three sensor elements simulated by Eq. (1) and measured data, respectively. It is observed from the results that there are several possible operation wavelength to activate only one sensor.

Next, we examined the signal separation property as a function of the operation wavelength by using the setup shown in Fig. 5. Probe 1, probe 2 and probe 3 were exposed to different three acoustic fields driven at 24 kHz, 68 kHz and 18 kHz, respectively, which were acoustically isolated one another and had no interaction. The electrical output of the PD is a mixture of these three acoustic signals in general for arbitrary optical wavelength. If the wavelength is tuned at a specific position, two of three signals are suppressed effectively and only the desired signal is extracted. In the experiment, to measure the signal strength of every component independently, we employed three electrical band-pass filters tuned at 24 kHz, 68 kHz and 18 kHz. The measurement can be performed by a spectrum analyzer instead of the filter bank system used in this experiment. Figure 6 shows the components of 24 kHz, 68 kHz and 18 kHz in the PD output versus the optical wavelength λ, where, the plots and the curves are measured value and theoretical one calculated by the gradient of *Fabry-Perot* response in Fig. 4. Here, let us note that the modulation of light intensity becomes in phase or out of phase with the acoustic field depending on the sign of the gradient of *Fabry-Perot* resonance curve. Then, the change in the sign of sensitivity was observed when the wavelength went over the resonance peak. There exist several optimum operation wavelengths which give high sensitivity, and they are summarized in Table 1, the usefull set of operation wavelengths is 786.63 nm for probe 1, 785.86 nm for probe 2 and 786.24 nm for probe 3, which realizes a good signal discrimination. However, there are differ-

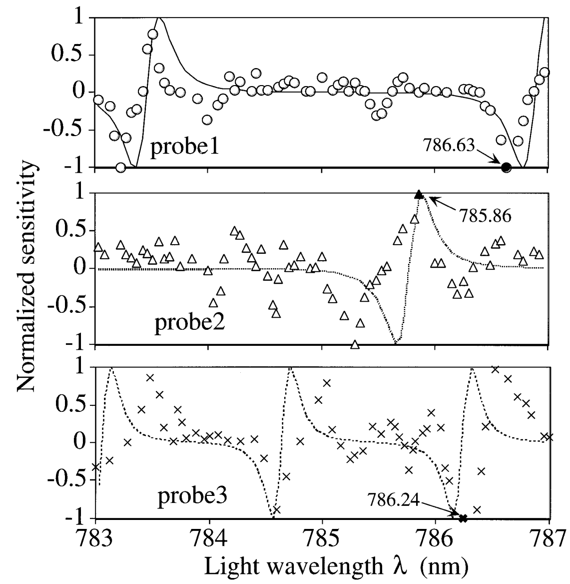

Fig. 6 Pressure sensitivity of the three element sensors as functions of wavelength λ. The curves are calculated value and the symbols are measured data.

Table 1 The resonance wavelength λ_r and the wavelength with high acoustic sensitivity of the probes 1–3.

	probe 1		probe 2	probe 3		
resonance wavelength λ_r (nm)	783.46	786.92	785.77	783.06	784.64	786.24
wavelength with high sensitivity (nm); measured (theory)	783.22(783.37)	786.63(786.78)	785.29(785.66)		784.60(784.60)	786.24(786.12)
	783.51(783.56)		785.86(785.87)	783.48(783.12)	785.04(784.68)	786.52(786.36)

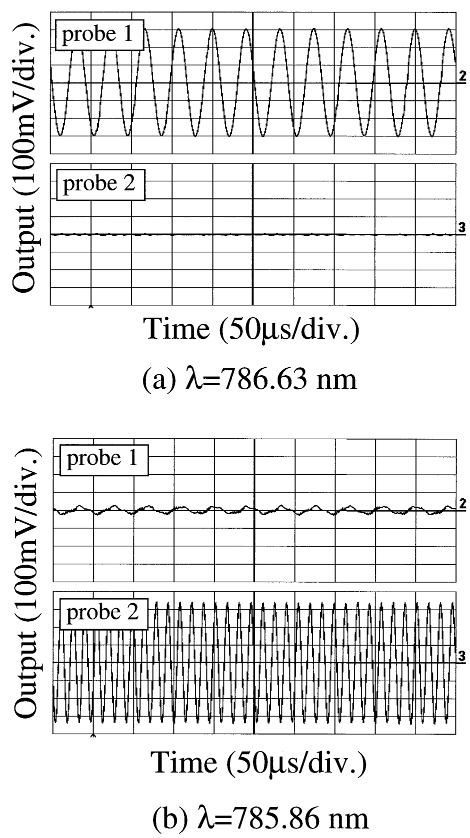

Fig. 7 Output signals of the proposed micro-probe array.

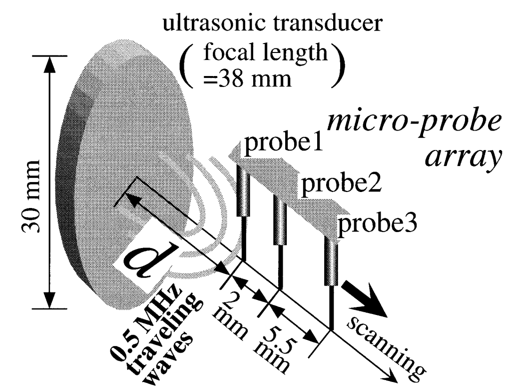

Fig. 8 Experimental setup for a measurement of traveling wave.

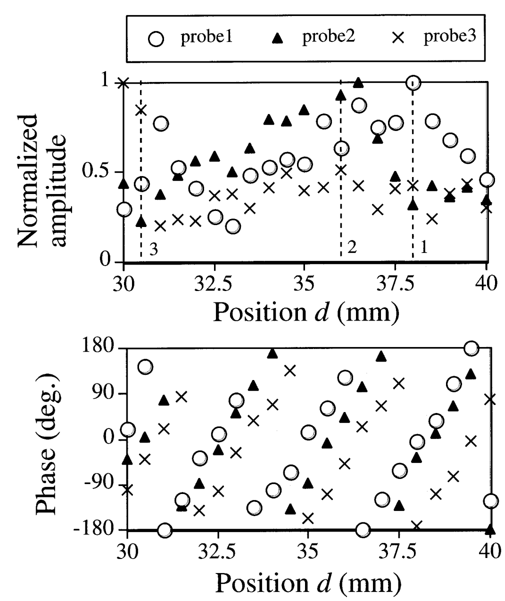

Fig. 9 Amplitude and phase of traveling wave measured by the proposed probe array.

ences between the measured wavelength with high sensitivity and the theoretical one. These may be aroused by an environmental fluctuation during the experiment such as temperature variation around the sensor elements or vibration of the optical system. Figure 7 shows the output signal wave forms of probes 1 and 2 after the electric filters when operation wavelength was set at 786.63 and 785.86 nm. The crosstalks between sensor elements were about −40 and −20 dB, respectively. These crosstalks are due to unexpected ripples in the *Fabry-Perot* resonance. Undesired reflections at fiber ends, connectors and couplers may cause these ripples.

Next, we measured traveling waves of ultrasound at 0.5 MHz in water. The diameter of ultrasonic transducer was 30 mm, and the focal length was 38 mm. The distance d from the radiator to probe 1 was 30–40 mm. As shown in Fig. 8, we set the three points array in line along the direction of traveling wave, and we scanned in the same direction. The intervals between two sensor elements were 2.0 and 5.5 mm, and the wavelength of ultrasound was 3 mm. The operation wavelengths of probes 1, 2 and 3 were 786.63, 785.86 and 786.24 nm, respectively. Both the amplitude and phase distributions were successfully measured by the three probes as shown in Fig. 9, where the position shift in the scanning direction corresponded correctly to the spacing between the sensor elements.

5. Conclusion

Fiber optic micro-probe array for megahertz ultrasonic fields was proposed and made for trial. Three-point measurements and traveling wave measurements were demonstrated. The signal was successfully separated by WDM technique. To increase the number of element sensor, we need to develop another configuration such as a Bragg reflector to have a single wavelength response. Undesired ripples of the cavity response should be suppressed to reduce crosstalk. For measuring transient phenomena by this system, we need to employ the same number of light sources with different wavelength and an optical wavelength filter at the output, instead of a slow scanning single light source.

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