Fluid Flow Speed Measurement System Using Fiber Bragg Grating Temperature Sensor Based on Microwave Heating

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***Abstract*—A fluid flow speed measurement system using a Fiber Bragg Grating (FBG) temperature sensor based on microwave heating is proposed. The technique of this system features contamination-free operation with fluids, due to its adoption of platinum electrodes for non-contact microwave heating and the use of FBG fiber made of fused quartz. The results demonstrate that sensing linearity could be achieved. This capability is in nearly perfect accord with the sensing characteristics of conventional flow sensors using a thermal method.**

Keywords- flow speed measurement; FBG sensor; fiber ring laser; microwave heating; thermal flow meter.

I. INTRODUCTION

Recently, the necessity of new techniques for measuring low fluid flow speeds has been recognized [1]. For example, to maintain acceptable quality control, it is necessary to precisely control extremely low speeds of injecting solutions [1]. Furthermore, each approach to extremely low-speed measurement using conventional techniques, such as Doppler methods and ultrasonics, has its particular difficulties. This is because such means cannot achieve detection of changes in physical parameters due to the extremely low speed. Consequently, thermal techniques have previously been applied for this purpose, and several sensor device configurations have been proposed, developed, and commercialized [2]. This technique is adequate for extremely low-speed measurement, but there remain several unresolved fundamental problems, such as chemical contamination, mixing of debris at the sensing element, and durability. In medical applications, such problems pose the risk of fatal consequences.

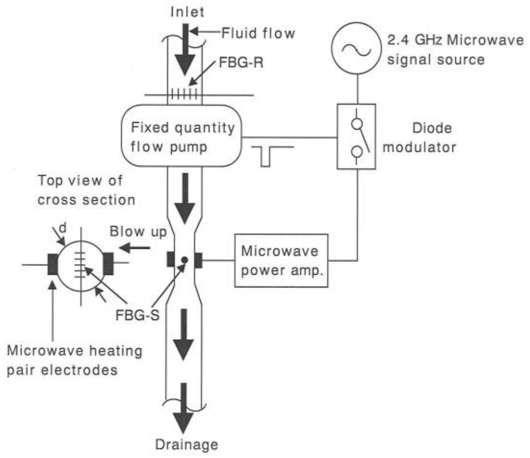
This paper proposes the construction of a fluid flow speed measurement system using a Fiber Bragg Grating (hereinafter referred to as FBG) temperature sensor based on microwave heating. Basically, such systems have extremely complex configurations, and they are very expensive for use in a sensor system. On the other hand, the proposed sensor has distinctive features including contamination-free operation with fluids, due to its adoption of platinum electrodes for non-contact microwave heating and the use of FBG fiber made of fused quartz; moreover, a flow-cell can certainly be made of quartz. Additionally, the mixing of debris at the sensing element into the fluid can be almost entirely eliminated. As the first step, in this article, a sensing principle is described and a system configuration is proposed. Next, experimental data obtained from closed cycle water flow are shown. Finally, the measuring capabilities are briefly discussed.

II. MEASUREMENT SYSTEM CONFIGURATION

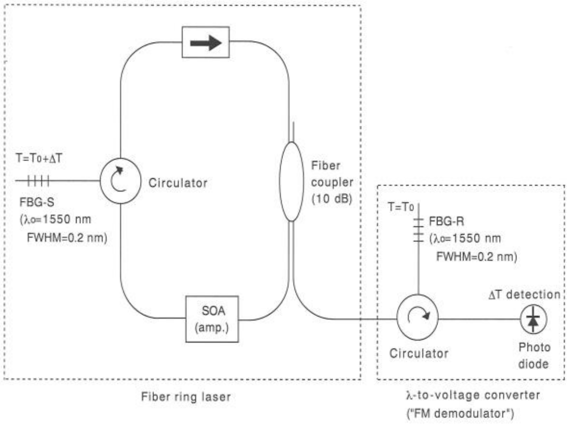
Figures 1 (a) and (b) show the experimental apparatus in a laboratory, prior to designing the prototype sensor, and its fiber optical system composed of a fiber ring laser, respectively. The details of the fluid flow system are described in the next section, while this section mainly addresses the optical system. In the configuration of this apparatus, the following two FBG sensors are assembled to function independently as temperature measurement elements. FBG-R (reference) operates as a steady fluid temperature sensing element, converting the change in wavelength to that in the amplitude of the laser beam, as shown on the right side of Figure 1 (b). FBG-S (sense) functions as a sensing element of the transition temperature change induced by the microwave heating, and this is applied to a wavelength tunable device using a fiber ring laser, as shown on the left side of Figure 1 (b) [3].

The microwave heating electrodes are situated across from each other, enclosed in the fluid flow tube with a diameter of 2 mm, and FBG-S is mounted in the center of the tube's interior. Here, FBG functions adequately for high electromagnetic fields because the optical device is manufactured solely of fused quartz. The microwave with a frequency of 2.45 GHz is fed between the two electrodes after the signal power is boosted to approximately 2 W by a power amplifier. The frequency of 2.45 GHz was chosen due to regulations in Japan's radio law. Here, the combination of FBG-R and FBG-S, each with a reflection wavelength of 1550 nm, has certain advantages, as follows. Even with a steady fluid temperature, the offset temperature changes; however, this change and the wavelength transition induced by it normally cancel each other due to the differential effect achieved by combining these FBGs.

The fiber ring laser shown in Figure 1 (b) contains the Semiconductor Optical Amplifier (SOA; Thorlabs SOA1013S) for compensating the optical loss inside the ring loop, resulting in laser oscillation. The linewidth of this laser is found by adopting a self-delayed heterodyne interferometry method. As a result, a linewidth of a few MHz was obtained. This spectrum is absolutely a straight line without any uncertainty, when considering the spectrum of FBG-R to have a full width at half maximum of 0.2 nm. The laser beam branched by a fiber coupler is reflected by the FBG-R and then fed to a photo diode. The block composed of the circulator, FBG-R, and photo diode is equivalent to a demodulator used for "optical wavelength modulation."



(a) Fluid flow system and configuration of sensing elements.



(b) Fiber ring laser of sensing demodulator.

Figure 1. Experimental apparatus in laboratory (prototype sensor).

III. MEASUREMENT RESULTS AND DISCUSSION

The prepared fixed-quantity flow pump shown in Figure 1 (a) alternates in its operation mode like a "heartbeat" between the charge (suction mode) and discharge (extrusion mode) of fluid in the cylinder. The volume of the cylinder was fixed to 7.5 ml constantly in this pump, using the ability to control the flow speed by adjusting the time of discharge. The microwave heating is toggled to active in extrusion mode and to dormant in suction mode, and a PIN diode modulator is installed for these operations. Figure 2 shows an example of a signal's waveform detected by the photo diode. The signal of the upper wave is driven by the PIN modulator, operating in the above two modes. When the fluid flowed to the flow cell is cut off in suction mode, the FBG-S detects the transition change in temperature, corresponding to the lower wave form drawn. The peak-to-peak vale of the lower wave form indicates the magnitude of temperature change.

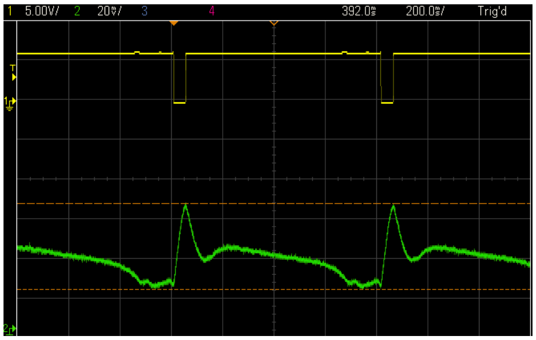


Figure 2. Typical waveform of detected signal (lower).

Figure 3 shows an example of the water flow rate dependence of the detected signal's amplitude. As can be seen in the figure, it was demonstrated that the sensing linearity could be obtained when the flow rate was between approximately 0.2 and 1.5 ml per second. This result corresponds almost perfectly with the sensing characteristics of a conventional flow sensor using a thermal method, i.e., the temperature of the flow medium is negatively proportional to its flow rate. On the other hand, the amplitude of the detected signal decreased dramatically when the flow rate was below 0.2 ml per second. The reason for this is assumed to be as follows. At first, the temperature of the fluid rises sharply due to an exceedingly low flow speed. Next, the recovery time of returning to the temperature prior to heating becomes longer due to the thermal capacity of the fluid after microwave heating is halted. Thus, the alternating of temperatures is suppressed, which certainly decreases the detected signal's amplitude to a low level. It is important to optimally adjust the power of the microwave.

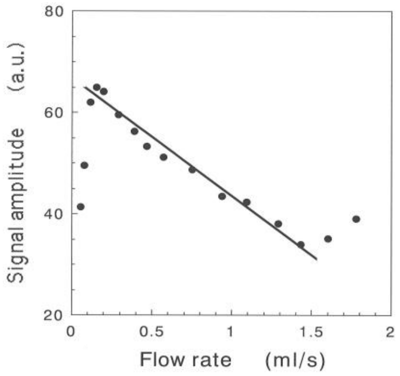


Figure 3. Water flow rate dependence of detected signal's amplitude.

IV. CONCLUSION AND FUTURE WORK

A new fluid flow speed measurement system using a fiber Bragg grating temperature sensor based on microwave heating was proposed. The key feature of this system is the combination of microwave heating and an FBG temperature sensor having a high electromagnetic field. Consequently, the system is free of chemical contamination due to the use of only platinum and fused quartz. Furthermore, results demonstrate that sensing linearity could be achieved. This capability is in nearly perfect

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accord with the sensing characteristics of conventional flow sensors using a thermal method. As future work, we will address the system design and optimization of several parameters, such as microwave power and the mounting positions of FBGs, to expand the dynamic range of measurement. After that, we will compare the sensing characteristics of the proposed method in accord with the conventional flow sensors.

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