A MICRO LASER DOPPLER VELOCIMETER DESIGNED FOR A WAFER-LEVEL PACKAGING PROCESS

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ABSTRACT

We develop a micro laser Doppler velocimeter (μ-LDV), designed for fabrication via a wafer-level packaging process for small size and mass production. This sensor is only 1/10,000th the volume of typical commercial LDVs. We successfully performed velocity measurement of moving solid plates and a flowing liquid with suspended particles by FFT analyzing signals obtained by our proposed μ-LDV. It can measure the velocity of any material that by itself or by constituent particles—bubbles, cells, emulsion phases, etc.—can scatter irradiated light: examples include solids like aluminum and cardboard or fluids like water, oil, and air.

KEYWORDS

Laser Doppler Velocimeter, Velocity Measurement, Optical MEMS, Wafer-Level Packaging.

INTRODUCTION

Miniaturization of sensors is increasingly important, because it decreases their weight, space, and cost, and allows them to be embedded at high density onto devices such as not only robots, smart phones, wearable devices, but also medical equipment, pipes in heavy industrial plants, and so on. Some small velocity sensors that have been developed in previous research include micro optical encoders and ultrasonic velocimeters [1-4]. Optical linear encoders measure the velocity of an object using reflected light from a grating scale attached to the object. However, this means they cannot measure the flow of liquids. Moreover, while the sensor can achieve high measurement accuracy, careful and accurate positioning of the grating scale is critical to its success. While ultrasonic velocimeters, in contrast, can measure flow velocity, their measurement results are affected by sonic speeds of fluids and materials between the sensor and the measurement objects. Generally, gel or cream is needed to fill the air space between the sensor and measurement objects for impedance matching in order to propagate ultrasonic waves.

On the other hand, laser Doppler velocimeters (LDV) are sensors that can measure the velocity of various objects without physical contact, by emitting two laser beams from its laser diode (LD) and detecting the reflected light. Any transparent material can be inserted between sensor and measurement objects. Owing to the high directionality of lasers, these devices' spatial resolution can even be on the micro-meter order. LDVs are widely used to measure the velocities of both solids and liquids, including metals, paper, and fluids in fields ranging from industrial production to medicine [5] [6] [7]. However, the sizes of commercially available LDVs are somewhat large, ranging from several to tens of square centimeters.

In this study, we present an extremely miniaturized LDV fabricated through MEMS processes: a micro laser Doppler velocimeter (μ-LDV). Its efficient design enables the μ-LDV to be fabricated via wafer-level packaging (WLP). Using it, we measured velocities of moving solid plates and a flowing liquid with suspended particles.

DESIGN AND PRINCIPLE

Figure 1 depicts our proposed μ-LDV. The size of the sensor is 2.8 × 2.8 mm × 1.0 mm thick. It consists of two layers: 1) a micro-machined Si optical bench incorporating a bonded laser diode (LD), Au micromirrors, and electrodes including through hole vias (Fig. 2(a)); and 2) a glass substrate incorporating a bonded photo diode (PD), electrical interconnection, and refractive microlenses on its backside (Fig. 2(b)). The Si substrate has a cavity fabricated using an anisotropic silicon etching technique [8] to form free space and slanted surfaces for the micromirrors. The electrodes, micromirrors, and layer-bonding pattern are formed by depositing gold onto the Si surface, which includes (111) facets. Refractive microlenses are fabricated by inductively coupled plasma etching with a gray-scale-patterned photoresist structure [9, 10]. Electrodes from PDs are connected through contact points on the top surface of the Si layer, and all electrodes can be connected from the backside of the Si layer by the through hole via. Bonding of the Si layer and glass layer is achieved by Au-Au surface activated bonding with an Au pattern on both layers, which also work to seal the device. This method allows bonding in low-temperature conditions, which is effective for preventing thermal damage to the LD and PD, and for precise alignment [11, 12]. Those diodes and layers are aligned using a flip chip bonder, specifically by matching alignment marks [13]. This design not only aids miniaturization, but also mass fabrication using wafer-level packaging.

Figure 3 shows a schematic of the A-A′ section of the μ-LDV. Two laser beams are simultaneously emitted by the LD, reflected by the Au mirrors, collimated by the lenses within a radius of 0.35 mm, and then become incident where

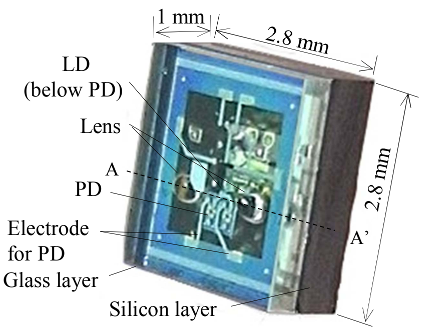
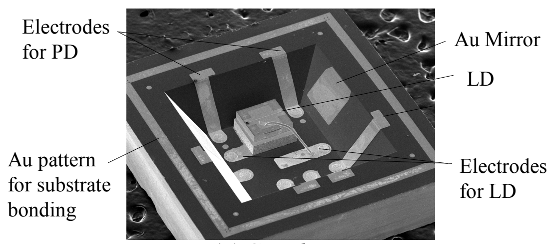
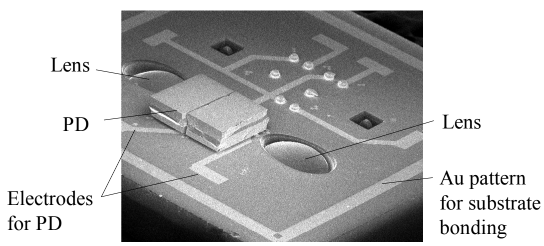


Figure 1: Picture of the µ-LDV.



(a) Si substrate



(b) Glass substrate (view from backside)

Figure 2: SEM images of the components of the µ-LDV: (a) the Si substrate and (b) the glass substrate.

they contact the moving object. The frequencies of the two scattered laser beams are Doppler-shifted and interfere with each other. The PD thus receives a heterodyne signal called a beat frequency, $\boldsymbol{f_d}$ [7]:

$$\boldsymbol{f_d} = 2\frac{V}{\lambda}\boldsymbol{cos\theta}, \quad (1)$$

where V is the velocity of the scattering material, θ is the angle between the laser beam axis and the material's direction of movement, and λ is the laser wavelength.

EXPERIMENTS AND RESULTS

Experimental setup

We measured velocities of solid and liquid flow using the sensor we developed. Figure 4 shows the experimental setup for measurement of a) liquid flow and b) solid plate velocity. Output voltage from the PD was amplified and then transformed into a power spectrum using a Fast Fourier Transform (FFT) analyzer to obtain the beat frequency at each velocity. The frequency range of FFT analysis was 0 to 20 kHz, with 25 Hz resolution. Colloidal silica slurry (COMPOL 120, Fujimi Inc., Japan) was used as the

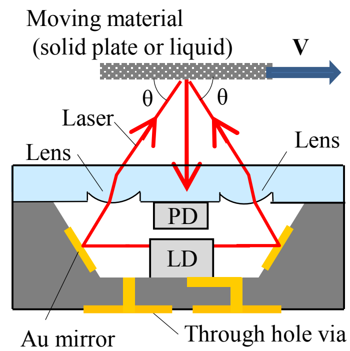


Figure 3: Schematic of the A-A' section of the µ- LDV.

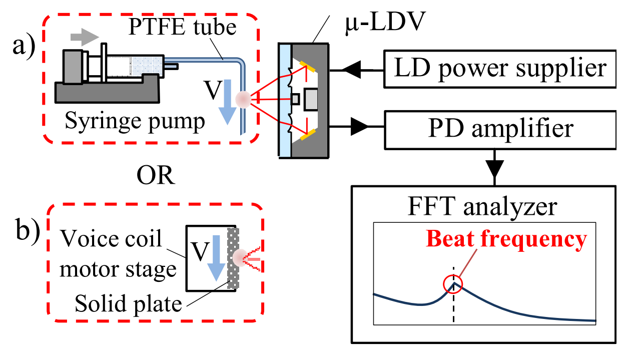


Figure 4: Experimental system for velocity measurement of a) liquid flow and b) a solid plate.

liquid sample because it includes regularly distributed fine particles that can scatter the laser beams. Liquid was transferred through a polytetrafluoroethylene (PTFE) tube (0.5-mm inner diameter) by a syringe pump at constant flow. The PTFE tube was set parallel along the A-A' section line shown in Fig. 1. For the solid velocity measurements, an aluminum plate and a piece of cardboard were used as the solid samples in order to compare differences in measurement quality due to surface flatness, roughness, and reflectivity. Solid plates were moved parallel along the A-A' section line using a voice coil motor stage.

Results of solid velocity measurements

Figure 5 shows the experimental power spectra for the velocities from the aluminum and cardboard specimens. The velocity was varied from 2 to 12 mm/s. The frequency at the power spectrum peak, shown as a blue dot, represents the beat frequency. The velocity can be calculated from the beat frequency with Eq. 1. The beat frequency at each velocity was defined as the frequency at maximum power, excluding frequencies below 1 kHz (high power at lower frequencies is unavoidable, since the DC component of the output voltage is significantly higher than beating component of the output voltage). Beat frequency was shifted as velocity rose. Although the powers from aluminum and cardboard differ by approximately 20 dBVrms, the beat frequencies at each of the measured velocities are close. Those beat frequencies

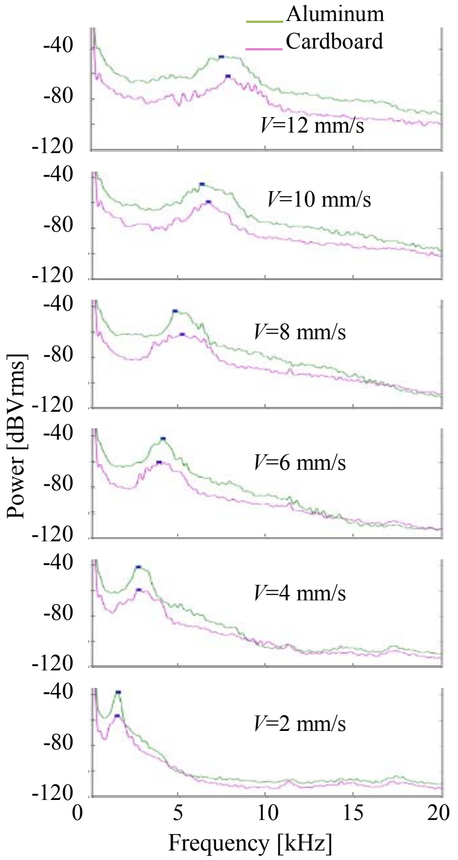


Figure 5: Power spectra for velocities of the aluminum and cardboard specimens.

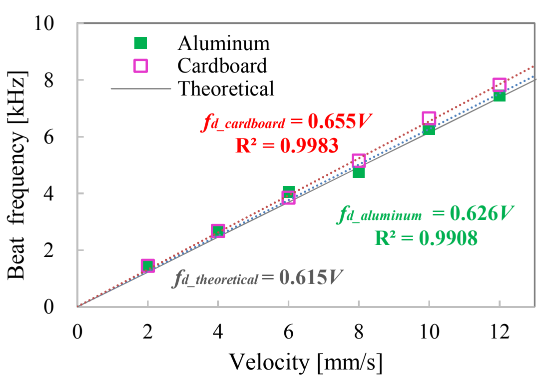


Figure 6: Beat frequencies at each of the tested velocities for the aluminum and cardboard specimens, with respective theoretical beat frequencies calculated from Eq. 1.

are plotted with the theoretical line on Fig. 6. The experimental results for beat frequency are directly proportional to velocity and largely trace along the theoretical line. The error between the theoretical and experimental constants of proportionality were 6.5 % for cardboard and 1.8 % for aluminum. We believe that the former's larger relative difference was caused by the wavy surface and low reflectivity of cardboard.

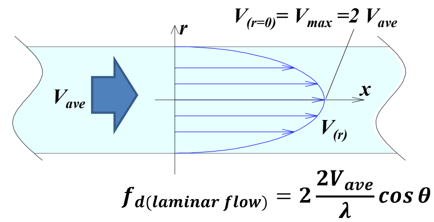


Figure 7: Schematic of Poiseuille flow and the relation between its average velocity V_{ave} and maximum velocity V_{max}.

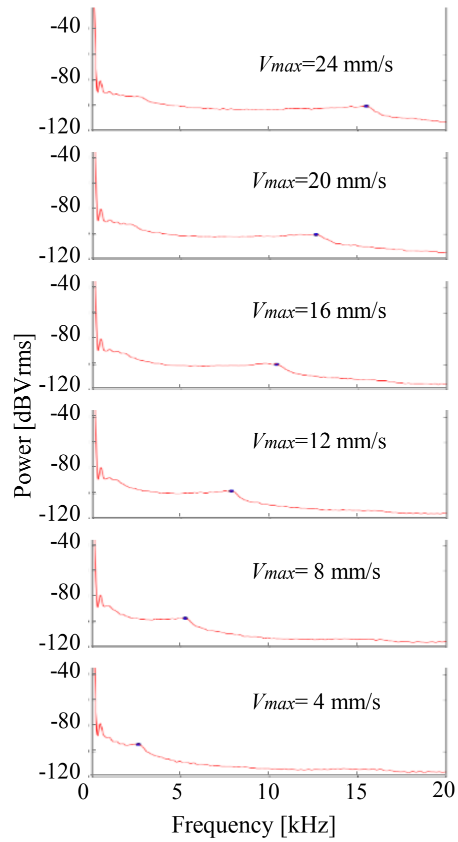


Figure 8: Power spectra for maximum velocities of liquid flow.

Results of liquid flow velocity measurement

The average flow velocity was varied from 2 to 12 mm/s. Here, the flow condition can be safely assumed to be Poiseuille flow, because the Reynolds number at average flow velocity 12 mm/s is 3.4, negligibly small compared with typical critical Reynolds numbers of 2,000 to 4,000. Then, we can assume the maximum flow velocity is twice the average flow velocity, ranging from 4 to 24 mm/s (Fig. 7). The intersection point of the laser beams emitted by theμ-LDV is aligned to be at the center of the flow. Figure 8 shows the experimental power spectra for liquid flow. The frequency at each power spectrum peak, shown as a blue dot, represents beat frequency. Since powers at lower frequencies are higher than at the peak, we defined the criteria for beat

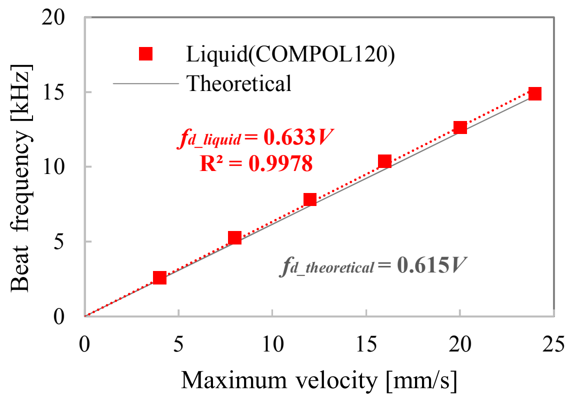


Figure 9: Beat frequencies at each of the tested maximum flow velocities, with respective theoretical beat frequencies calculated from Eq. 1.

frequency differently than for the solids. Specifically, a frequency was defined as a candidate peak if the power at that frequency was higher than any other powers at frequencies range of ±100 Hz from that frequency by certain threshold value. The candidate peak with the highest frequency among candidate peaks was defined as the beat frequency for that velocity. All thus measured and defined beat frequencies are plotted in Fig. 9. The experimental results for beat frequency are directly proportional to velocity and almost the same as the theoretical line. The constant of proportionality is almost the same as both the theoretical value and the experimental value for solids. The error between the theoretical and experimental constants of proportionality was 2.9 %. Something to consider is that the radius of the laser beams emitted from our sensor are 0.35 mm, which is large for a tube radius of 0.5 mm. This is because the flow in the intersection area of laser beams has a velocity distribution, then PD detects scattered light from particles that do not reach maximum flow velocity, and they behave as noise for the measurement of maximum flow velocity. Error can be further reduced by narrowing the beam radius to increase the sharpness of the power spectra.

CONCLUSION

We developed an extremely miniaturized laser Doppler velocimeter called the μ-LDV. The miniaturization of the sensor was achieved by employing multi-function layers: a glass layer as a sensor cap, collimation lenses, electrode substrate, and bench for the PD, and a Si layer as a bench for the LD, electrode substrate, and mirror base. This design allows the sensor to be fabricated by wafer-level packaging process, making it suitable for mass production. We successfully performed velocity measurements of solids and a liquid with the proposed sensor. Thanks to its small size and light weight, the μ-LDV can be embedded onto spaces less than a centimeter wide, high-speed stages, and pipe walls. These advantages can further extend the practical scope over which LDV technology can be applied.

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