GaN laser self-mixing velocimeter for measuring slow flows

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The self-mixing (SM) laser sensing technique allows for a simple, self-aligned, and robust system for measuring velocity. Low-cost blue emitting GaN laser diodes have recently become available owing to the high volume requirements for Blu-ray Disc devices such as high-definition video players and gaming consoles. These GaN lasers have a significantly shorter wavelength (around 405 nm) compared with other semiconductor lasers (generally around 800 nm for SM sensors). Therefore, if used in SM flow sensors, they allow measuring of flow rates that would otherwise be too slow to measure. In this Letter we report what we believe to be the world's first SM flow measurement system based on a blue emitting semiconductor laser, demonstrating the ability to measure flow rates down to 26 μm/s. © 2010 Optical Society of America

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The self-mixing (SM) laser sensing technique offers the possibility of providing a low-cost self-aligned system for measuring velocity [1,2]. Even though the first room-temperature cw blue emitting GaN based laser was demonstrated only in 1996 [3], with the advent of Blu-ray Disc devices, low-cost GaN lasers have become available. These lasers offer shorter wavelength emission than the IR lasers used in most SM systems reported so far. Using a shorter wavelength laser leads to a higher Doppler frequency in the SM flow signal that allows slower flow rates to be measured than is possible with longer wavelength devices. The ability to measure low flow rates makes an SM sensor based on the blue emitting GaN laser superior in microfluidic experiments where bulk flow velocities around 50 μm/s [4] with localized regions in the flow that are much lower. Additionally, the shorter wavelength enables smaller diffraction limited spot sizes to be produced, increasing the available spatial resolution.

The SM flow measurement technique is a low-cost method for mapping flow without requiring the introduction of additional marker particles (although the fluid must scatter some light) and bulky equipment required by other commonly used techniques such as particle-image velocimetry [5]. In this Letter we report for the first time (to our knowledge) an SM flow measurement system based on a blue emitting GaN laser and compare its ability to measure small flow rates with a near-IR laser.

Before SM signals were acquired, the blue laser was characterized. The nominal laser wavelength is 405 nm. The laser used was designed for the disc read assembly of a Sony PlayStation 3 console (PS3).

Light-current and current-voltage (L-I-V) characteristics appear in Fig. 1. This plot can be used to deduce the threshold current, slope efficiency, and junction voltage of the laser. This laser has a substantial level of spontaneous emission below the threshold as indicated by the slope of the L-I curve in this region. Spontaneous emission is likely the main cause of noise observed in the SM experiments with this laser.

The inset in Fig. 1 shows a representative optical spectrum of this laser showing characteristics typical of a Fabry–Perot cavity device.

An important figure of merit in an SM sensor is the signal-to-noise ratio (SNR). Velocity measurements were made to evaluate the SNR performance of the SM laser sensors to be compared. Figure 2 provides a schematic diagram of the experimental setup used to measure the SM velocity signals from the laser. The rotating target consisted of an aluminium disc with a sand-blasted surface attached to a dc servo motor and run at a constant rotational velocity. The angle of inclination of the disc with respect to the laser axis, θ, was 75°.

The SM signal is acquired by an analog-to-digital converter attached to a computer. The signal is converted from the time domain to the frequency domain using the fast Fourier transform (FFT). A Doppler peak is observed, because the light emitted from the laser receives a Doppler shift and mixes with light in the laser cavity, giving rise to a spectral peak at the beat frequency [2]. The motor velocity was set such that the Doppler peak was at approximately 25 kHz.

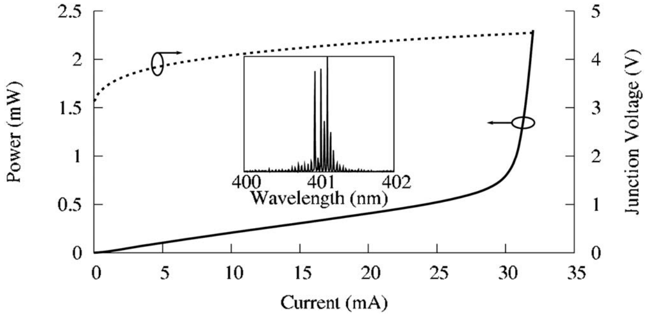

Fig. 1. Laser light-current and current-voltage characteristics (main plot) and the multimode emission spectrum (inset). Note the significant level of spontaneous emission below the lasing threshold.

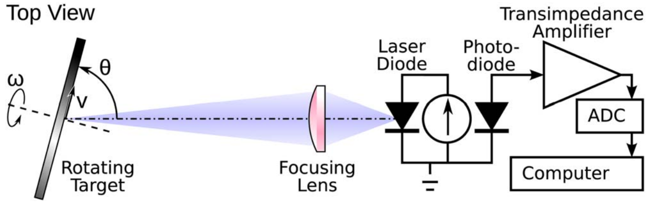

Fig. 2. (Color online) Experimental setup for measuring the SM velocity signal. The laser emission strikes the disc below the center of rotation, and v is the velocity vector at this point. The monitor photodiode variations are amplified and digitized before being processed in software running on a computer.

The SNR of the Doppler velocity sensors was determined by measuring the difference between the Doppler signal peak and the noise floor on each side of the Doppler signal. Figure 3 shows a typical Doppler signal spectrum along with the signal fits used to extract the SNR. The SNR was determined automatically in real time as the laser currents were swept in order to determine an operation point for each laser that provides a good SNR. The results of the SNR measurements for the blue laser and the IR laser used as a comparison are presented in Fig. 4. The two dips in the IR laser SNR curve in Fig. 4 are probably due to mode hopping at these points when modes of similar power were present, as it was noted that the noise floor at these points increases. Similar noise peaks due to mode hopping have been reported by Yamada *et al.* [6]. The more smooth blue laser SNR curve in Fig. 4 is probably due to the presence of many lasing modes leading to less abrupt changes in the SNR. It is also noted that the blue laser has an SNR disadvantage at most bias currents when compared with the IR laser. This is probably due to the high level of spontaneous emission observed in the L-I curve in Fig. 1. The IR laser was operated at 28.0 mA and the blue laser at 31.7 mA in the flow experiments.

Flow measurement were performed in order to confirm the ability of the blue emitting laser to measure slower flow rates than a typical IR laser. The experimental setup used to measure flow is the same as the setup in Fig. 2, except that the rotating disc target is replaced by a glass tube. The axis of the glass tube was positioned at $\theta = 75°$, and the glass tube was supplied with a constant rate of flow from a syringe pump (New Era Pump Systems NE-1002X). The flow consisted of a 9:1 mixture of water and 3.06 μm polystyrene microspheres (Duke Scientific 4203A). The $1/e$ spot size of the blue laser emission at the glass tube was 55 μm.

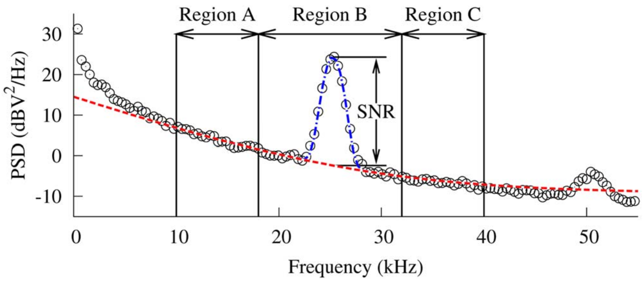

Fig. 3. (Color online) Example Doppler signal spectrum showing how the SNR is determined. The dotted line shows the noise floor determined by fitting an exponential function plus a constant over regions A and C to the measured spectrum (circles). The signal peak is fitted to a combination of a Gaussian function and the obtained noise floor in the region B (chain line). The SNR is the difference between the signal peak level and the noise floor below (in this case, 26.7 dB).

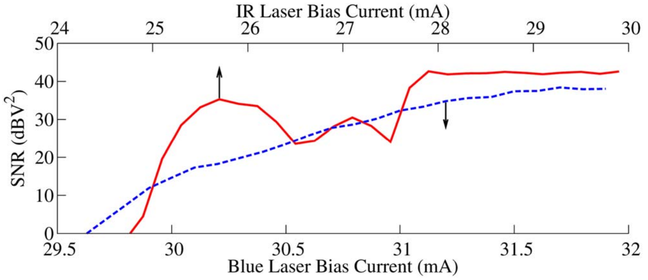

Fig. 4. (Color online) Plots of SNR versus laser bias currents for the blue laser (dashed curve) and IR laser (solid curve) SM signals with the rotating disc target. The IR laser has an SNR advantage of approximately 5 dB over the blue emitting laser.

Because the flow through a circular pipe contains a distribution of flow velocities that decreases from a maximum at the center of the circular cross section, the SM signal contains a distribution of spectral components. In fact, if the velocity profile across the tube is parabolic, the spectrum will be flat up to a maximum frequency [7] (as long as the particle concentration is sufficiently low that multiple scattering events are insignificant). This maximum frequency corresponds to the maximum velocity in the tube. The relationship between the maximum velocity, v_m and the maximum frequency in the spectrum, f_m, is as follows:

$$v_m = \frac{f_m \lambda}{2 \cos \theta}, \tag{1}$$

where λ is the wavelength of the laser.

The maximum flow velocity in the tube was calculated from the syringe pump flow rate and the tube inside diameter (1.81 mm) and by ensuring that the tube was long enough so that a fully developed parabolic flow was present where the maximum velocity is twice the average flow velocity. Once the maximum flow velocity is calculated, the maximum Doppler fre-

Table 1. Calculated and Measured Maximum Frequency Components for Different Flow Velocities for the IR and Blue Lasers[a]

Max. Velocity (μm/s)	IR f_m (Hz) Calc.	IR f_m (Hz) Meas.	Blue f_m (Hz) Calc.	Blue f_m (Hz) Meas.
25.9	17.1	–	33.5	34.4
51.8	34.3	36.0	67.9	67.5
77.7	51.4	49.6	100.3	102.3

[a] The measured values were obtained from the spectra in Fig. 5.

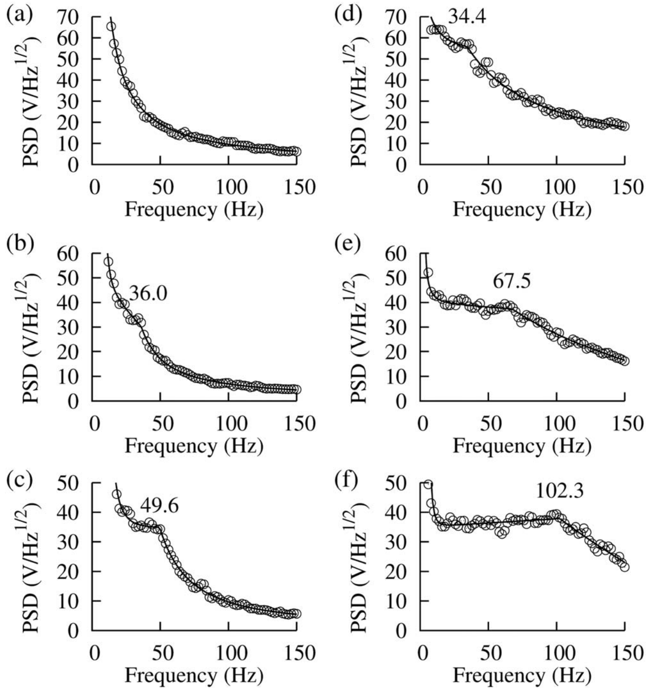

Fig. 5. Averaged SM spectra for the flow experiment. Results (a)–(c) are for the IR laser, and results (d)–(f) are for the blue laser. The corner frequency for each of the signals is indicated. The maximum flow rate for the results in (a) and (d) was 25.9 μm/s, the rate for (b) and (e) was 51.8 μm/s, and the rate for (c) and (f) was 77.7 μm/s.

quency components are calculated from Eq. (1) with $\theta = 75°$ and $\lambda = 783$ nm for the IR laser and $\lambda = 401$ nm for the blue laser. The results of these calculations appear in Table 1.

Spectra obtained for the different flow rates used in the experiment appear in Fig. 5. The spectra were generated from the average of 100 FFTs with 2048 points acquired at 4096 samples per second. The following function was fitted to these spectra in order to extract the maximum frequency component, f_m, corresponding to the maximum flow velocity:

$$\mathrm{PSD}(f) = \begin{cases} \dfrac{a}{f^b} + c + gf + e & \text{if } f < f_m \\ \dfrac{a}{f^b} + c + \dfrac{d}{\left[f - f_m + \left(\dfrac{d}{gf + e} \right)^{1/h} \right]^h} & \text{otherwise} \end{cases},$$

where a, b, c, d, e, g, h, and f_m are fitting parameters; f is the frequency; and PSD(f) is the power spectral density of the acquired SM signal. The fit is performed using a nonlinear least-squares Levenberg–Marquardt algorithm. Fitting allows an accurate estimate of the point, f_m, on the curve where there is a clear change in slope. The maximum frequency component for the signal from the IR laser at 25.9 μm/s in Fig. 5(a) is not observed due to the low-frequency, excess noise of the laser overwhelming the signal. However, the signal from the blue laser at the same velocity in Fig. 5(d) shows a maximum frequency component, giving rise to a shoulder on the spectrum that illustrates the advantage of the shorter wavelength of the blue laser in detecting smaller flow velocities.

It is interesting to note that even though the blue laser has poorer SNR performance than the IR laser and has a very multimodal spectrum, it is still possible to measure lower flow rates than the more well-behaved IR laser used for comparison. Because blue lasers have been available commercially for only a short time, it is expected that as the technology improves the benefit of using the sorter wavelength laser will become even more pronounced and more desirable as a flow sensor.

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References

1. F. F. M. de Mul, M. H. Koelink, A. J. Weijers, J. Greve, J. G. Aarnoudse, R. Graaff, and A. C. M. Dassel, Appl. Opt. **31**, 5844 (1992).
2. S. Shinohara, A. Mochizuki, H. Yoshida, and M. Sumi, Appl. Opt. **25**, 1417 (1986).
3. S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, Appl. Phys. Lett. **69**, 4056 (1996).
4. J. G. Santiago, S. T. Wereley, C. D. Meinhart, D. J. Beebe, and R. J. Adrian, Exp. Fluids **25**, 316 (1998).
5. R. Adrian, Annu. Rev. Fluid Mech. **23**, 261 (1991).
6. M. Yamada, N. Nakaya, and M. Funaki, IEEE J. Quantum Electron. **23**, 1297 (1987).
7. C. Riva, B. Ross, and G. Benedek, Invest. Ophthalmol. Visual Sci. **11**, 936 (1972).