

Speckle-Based Relative Wavelength Measurements – A Cost-Effective Alternative

Niklas Borchers*, Sebastian Böhm*, Ulrich Vogl*, Carsten Glasenapp*, Tobias Haist**, Stephan Reichelt**

* Corporate Research and Technology, Carl Zeiss AG

** Institute of Applied Optics (ITO), University of Stuttgart

mailto:niklas.borchers@zeiss.com

Highly accurate relative wavelength changes can be determined from speckle shifts using a simple setup that illuminates a rough surface and records the speckle pattern at a high angle. The standard deviation of the measured wavelength residuals compared to a commercial Fizeau-type wavemeter was reduced by introducing a multi-ROI evaluation scheme from 65 fm to 35 fm over a tuning range of 0.3 nm. The speckle-shift-based wavelength sensor could therefore replace conventional wavemeters in certain use cases.

1 Introduction

Highly accurate relative wavelength measurements and tracking are important in various laser metrology fields such as interferometric distance measurements, optical coherence tomography, or digital holography. Currently, high-resolution use cases commonly rely on interferometric wavemeters, such as those commercialized by HighFinesse. These devices are robust and accurate over a wide measurement range, but they are expensive. Speckle-shift-based wavelength measurements can provide a much cheaper alternative for use cases with a limited wavelength range, such as laser stabilization, where high relative precision is more important than absolute accuracy.

Various speckle-based measurement schemes have been proposed, for example using an integrating sphere or a multimode fiber [1, 2]. Both methods evaluate the speckle decorrelation to determine wavelength changes, which requires calibration over the full measurement range. They are sensitive to temperature changes, but corrections are difficult due to the chaotic speckle generation principle. Alternatively, the method used in this work uses speckle generated by shining laser light onto a rough surface and observing the speckle under an angle [3]. This approach uses a simple, compact setup and the observed shifts are deterministically connected to measurable (geometric) features, enabling e.g. a deterministic temperature correction.

2 Setup

The schematic setup is shown in Figure 1. The laser ($\lambda = 785$ nm), controlled by a laser driver and stabilized using a thermoelectric cooler (TEC) controller, is coupled into a single-mode (SM) fiber. On the device itself, the light is coupled out of the bare fiber connector and directed onto a gold-coated ground glass plate acting as the diffuser. A part of

the resulting objective speckle pattern is captured by a bare image sensor (2048 px $\times$ 1536 px, 3.45 μ m pixel pitch) mounted on the same base plate.

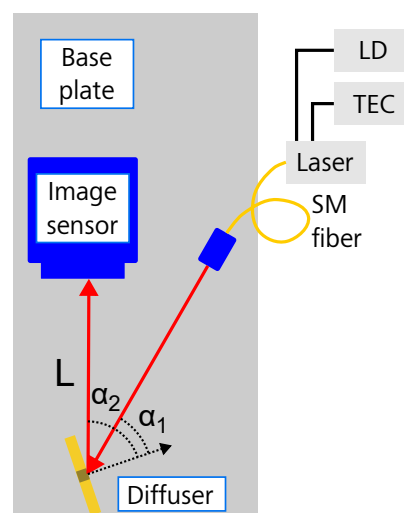


Fig. 1 Schematic representation of the sensor setup.

A change in the wavelength changes the phase relationship between the rays from the different surface elements of the diffuser in the image sensor plane. This change in the phase moves the positions in space at which constructive and destructive interference occurs and thus also the speckles. For small wavelength changes, the speckle shift is linear in wavelength and directly connected to the geometry as $\Delta p_x = \frac{\Delta \lambda}{\lambda_0} \frac{(\sin \alpha_1 + \sin \alpha_2) L}{\cos \alpha_2}$. The diffuser to image sensor distance is $L = 9$ cm, the angle between the diffuser normal and the laser beam is $\alpha_1 = 45^\circ$, and the angle between the diffuser normal and the image sensor normal is $\alpha_2 = 75^\circ$. Since the geometry is fixed during the experiment, all geometric factors can be combined into a single parameter A , as $\Delta p_x = A \Delta \lambda$. To provide the ground truth a HighFinesse (HF) WS7-60 with a resolution of 2 MHz (4 fm at 785 nm) is used.

3 Experiment

First, the system is calibrated for the current sensor geometry and operating wavelength. A series of speckle images at different wavelengths, selected by changing the laser drive current, along with the reference wavemeter readouts, is captured. Then, the speckle shifts relative to the reference images captured at the reference wavelengths are calculated using a cross-correlation algorithm on the Hanning-windowed images. The full measurement range is split into six sections to prevent shift detection degradation due to speckle decorrelation, caused by the changing wavelength. The gearing factor A is then fitted using a linear function on the wavelength recorded by the HF wavemeter and the corresponding speckle shifts. The first evaluation strategy uses only the central $512\text{ px} \times 512\text{ px}$ region of interest (ROI) marked in Figure 2 by the dashed square.

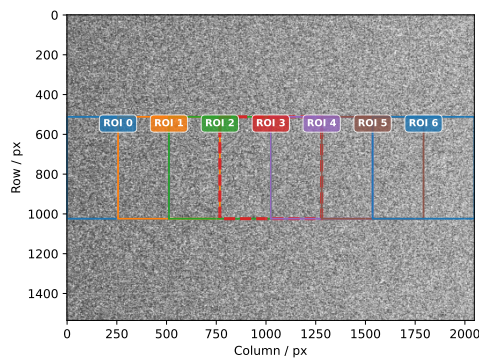


Fig. 2 Distribution of the ROIs on the speckle image, the central ROI is marked by the dashed line.

During the measurement run, the speckle shift relative to the reference image with the lowest shift is selected. Using the gearing factor A the measured wavelength for that ROI is calculated as $\lambda_S = \lambda_{ref} + A\Delta p_x$. For the multi-ROI evaluation, the same procedure is applied to each ROI individually, and the average of all ROIs is used as the wavelength estimate for that image.

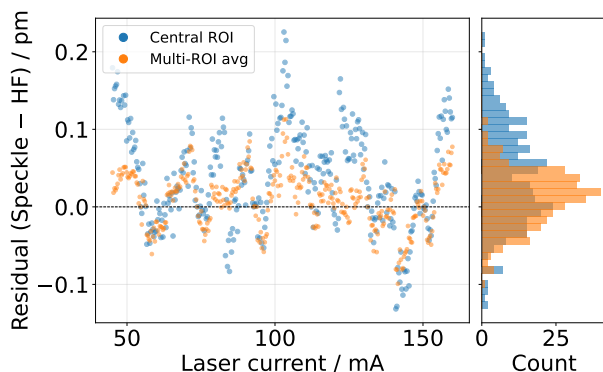


Fig. 3 Comparison of wavelength residual with respect to the HF wavemeter using a single ROI versus multiple ROIs.

The resulting residuals between the wavelengths measured by the speckle shift sensor and the HF reference wavemeter are shown in Figure 3. Both evaluation schemes produce good results, with the multi-ROI evaluation improving the standard deviation of the residuals from 65 fm to 35 fm and the mean residual from 38 fm to 9 fm using 338 measurement points.

4 Discussion

With a simple setup consisting of a single-mode fiber, a rough diffuser, a standard camera and a compact base plate, a femtometer-level resolution is achieved using a desktop PC for evaluation. Compared to commercial interferometric wavemeters, the total system cost is greatly reduced while still achieving competitive resolution over limited wavelength ranges, which is often sufficient for practical applications. The speckle system requires an initial post-assembly calibration using an external reference for each operating wavelength to obtain absolute values. The approach is unsuitable for broadband sources, which reduce speckle contrast and are incompatible with the sensor's single-wavelength output. The available tuning range is limited by the range of the available reference images in combination with the speckle decorrelation.

5 Outlook and Conclusion

In summary, a compact and low-cost speckle-shift-based wavelength sensor that achieves a residual standard deviation of 35 fm over a tuning range of 0.3 nm using a simple optical setup and multi-ROI evaluation was demonstrated. Future work will focus on implementing deterministic temperature correction based on the geometric model, extending the usable wavelength range, and integrating the sensor into stabilized laser systems and other laboratory setups where drift monitoring is more important than metrological traceability.

References

- [1] M. Facchin, K. Dholakia, and G. D. Bruce, "Wavelength sensitivity of the speckle patterns produced by an integrating sphere," *Journal of Physics: Photonics* **3**(3), 035005 (2021).
- [2] B. Redding and H. Cao, "Using a multimode fiber as a high-resolution, low-loss spectrometer," *Optics Letters* **37**(16) (2012).
- [3] M. T. Jamal, M. L. Jakobsen, S. G. Hanson, A. K. Hansen, and O. B. Jensen, "Speckle-displacement-based wavemeter for mode-hop and side-mode detection," *Applied Optics* **61**(4), 989 (2022).