High-precision laser ranging for industrial metrology with dual-color electro-optic frequency combs

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We use electro-optic frequency combs with different center wavelengths to measure distances with 2 µm standard deviation at an acquisition time of 9 µs. The measurement is insensitive to temperature fluctuations in the optical fiber installation. In combination with a coordinate measurement machine, this enables precise digitization of technical objects in an industrial environment.

1 Introduction

Precise and fast non-contact distance measurements are important in many industrial applications. One key requirement is the insensitivity of the measurement to environmental influences such as temperature fluctuations. Measurement schemes using two frequency combs offer potentially fast and precise measurements [1,2], but rely on femtosecond lasers for comb generation, which require considerable technical effort for stable operation in an industrial environment.

In this work, we generate frequency combs from continuous-wave (cw) lasers by using electro-optic Mach-Zehnder modulators (MZM) [3]. This leads to a tunable and stable line spacing defined precisely by the modulation frequency and the possibility to choose one or more center wavelengths by choice of the wavelengths of the cw lasers. Dual-color frequency combs are generated and exploited for distance measurements with simultaneous calibration measurements to cancel environmental influences. We demonstrate distance measurements with acquisition times of 9 µs and a standard deviation of 2 µm. Reliable measurement results with micrometer precision are maintained while the optical fiber leading to the sensor is heated by over 25 K. Technical objects are digitized by mounting the sensor on a coordinate measurement machine (CMM)

2 Measurement principle & setup

The setup is shown in Fig. 1. Dual-color frequency combs are generated from cw lasers with wavelengths of 1550 nm and 1300 nm by electro-optic modulation in MZM. Line spacing and center frequency of the local oscillator (LO) combs (green) is detuned with respect to the signal combs (blue) by use of a different modulation frequency and acousto-optical modulators (AOM). These detuned LO lines are used for heterodyne detection of the signal comb lines. The interference of both comb pairs on the balanced detectors (BD) leads to a multitude of sinusoidal beat signals, containing the phase information of the comb lines.

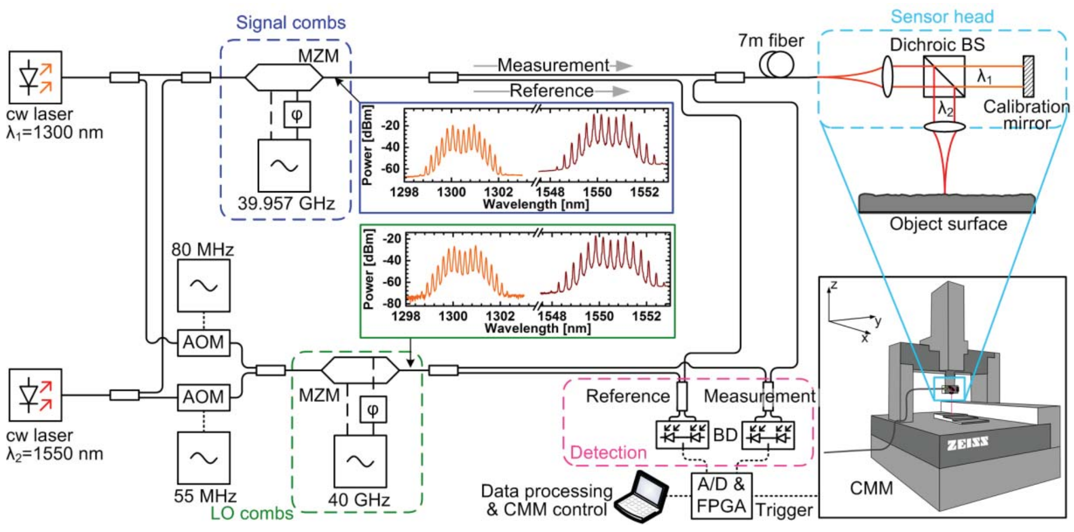

Fig. 1 Experimental setup. AOM: Acousto-optical modulator, MZM: Mach-Zehnder modulator, LO: Local oscillator, BD: Balanced detector, CMM: Coordinate measurement machine, BS: Beam splitter, A/D: analog-to-digital conversion.

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For each measurement, the beat signals are recorded for a duration of 9 µs and processed on an FPGA. This would allow for a measurement rate of more than 100 kHz, even though the current implementation of the system is limited to 3.3 kHz due to the processing speed in the FPGA. From the different phase shifts accumulated by each line by propagation over the optical path, the length differences between measurement and LO path can be calculated [4]. The dichroic beam splitter (BS) in the sensor head splits the signal comb pair: The comb at 1300 nm propagates over a fixed distance to a calibration mirror, while the comb at 1550 nm propagates to the object surface. The measurement at 1300 nm is used to quantify fluctuations of the optical path length inside the fibers, which is essential for precise measurements. For surface scans, the sensor head is mounted on a CMM.

3 Experimental demonstrations

To characterize the system and the long-term precision in a non-acclimatized environment, we consider the Allan deviation σ_{Allan} for different averaging times, Fig. 2. For the compensated measurement, σ_{Allan} of the resulting distance D_{comp} is smaller than 500 nm (100 nm) for 3 ms (30 s) measurement time, while in the uncompensated measurement additional uncertainty of ~1 µm is observed within 300 s as a consequence of mechanical and thermal fiber drift. The precision for measurements with 9 µs acquisition time (3.3 kHz real-time measurement rate) amounts to 2 µm.

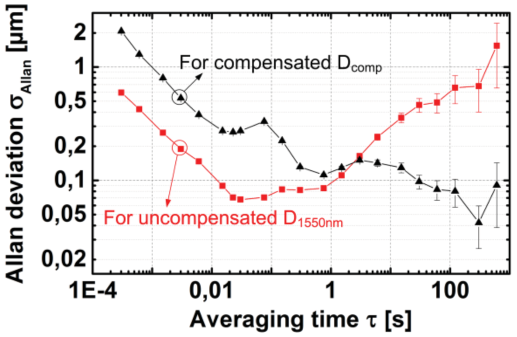

Fig. 2 Allan deviations calculated from repeated measurements over a fixed distance. Red: Uncompensated measurement. Black: Temperature-drift-compensated measurement.

The robustness of the compensation scheme is demonstrated by heating a 0.5 m long section of the fiber leading to the sensor head while measuring a fixed distance, see Fig. 3. The influence on the optical path length is clearly seen in the distances measured with the individual FC at 1300 nm (blue) and 1550 nm (red), while the compensated distance values (difference of the two measurements, black) do not exhibit any measurable temperature-induced variation.

To demonstrate the viability of the sensor for the characterization of technical objects, we measure the surface profile of a bullet casing by using the CMM to scan the fiber-coupled passive sensor head over the object while measuring distances, see Fig. 4. The object is densely digitized with 0.6×10^6 points recorded within 3 min.

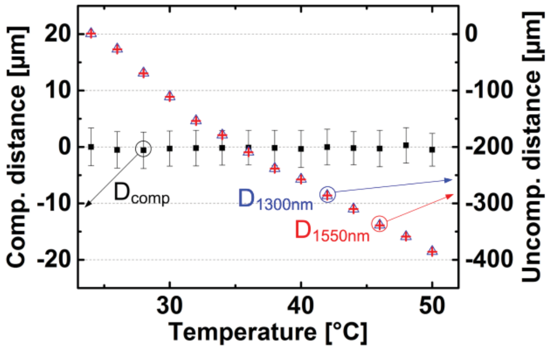

Fig. 3 Measurements over a fixed distance while heating the fiber. Blue triangles: Measurement at 1300 nm. Red crosses: Measurement at 1550 nm. Black squares: Compensated measurement with error bars indicating ± one standard deviation.

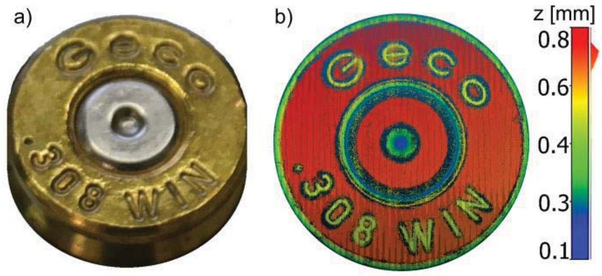

Fig. 4 (a) Photo of the backside of an used bullet casing. (b) Color-coded surface profile with 0.6×10^6 points as results of a scanning measurement.

4 Summary

We demonstrate fast, precise and robust distance measurements using dual-color frequency combs generated by electro-optic modulation. The measurement head comprises only passive optical elements and is connected by a single optical fiber. Mechanical and thermal drifts of the fiber are compensated by measurement at 1550 nm and 1300 nm, permitting micrometer standard deviation for microseconds acquisition times to be maintained despite environmental influences. This enables precise surface digitization of technical objects in an industrial environment.

References

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