Fast high-precision distance measurements with electro-optic frequency combs

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Using electro-optic frequency combs in a fiber-based setup, we measure distances with 8.3 µs acquisition time and standard deviations of <4 µm for an optical power range of 37 dB. We demonstrate measurements to a rough steel surface. Main system components are integrated on a silicon photonic chip with sub-mm² footprint, enabling fast distance measurements with errors below 5 µm.

1 Introduction

Precise non-contact distance sensors are of great importance for many scientific and industrial applications. To enable measurements of rough surfaces of technical precision parts, a highly sensitive detection scheme is needed. Further requirements for such sensors are high measurement speed as well as compact size. Measurement schemes based on two frequency combs [1, 2] offer the potential for fast and precise measurements, but rely mainly on femtosecond lasers, making miniaturization difficult. The frequency combs used in this work are generated electro-optically from cw lasers and omit a tunable and stable line spacing of tens of gigahertz, distributing the optical power over relatively few lines while covering a considerable spectral range. Furthermore, the comb generation principle lends itself to dense integration on silicon [3], making highly miniaturized sensors possible.

In this paper, we demonstrate fast distance measurements with acquisition times of 8 µs using electro-optically generated combs in a fiber-based setup. The measurement standard deviation is in the range of 0.3-4 µm for a drop in optical power of up to 37 dB, allowing measurements of a milled steel surface. Furthermore, an integrated interferometric system on silicon with a sub-mm² footprint is presented.

2 Comb generation and measurement principle

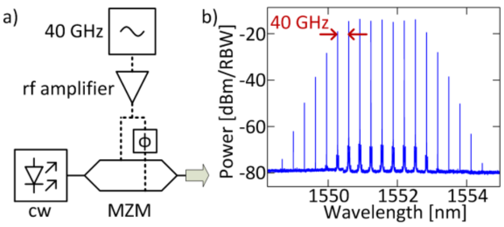

Fig. 1 *a) Comb generation. A cw laser (cw) is modulated by sinusoidal driving signals using two phase modulators in Mach-Zehnder configuration (MZM). b) Generated optical spectrum.*

The setup used for frequency comb generation is shown in Fig. 1. A cw laser is fiber-coupled to a dual-drive lithium-niobate Mach-Zehnder modulator (MZM). Carefully adjusted sinusoidal driving signals generate higher order sidebands by phase modulation in both arms of the MZM [4]. The interferometric combination of both sideband spectra leads to a spectrally flat comb with a line spacing determined by the driving frequency.

The distance measurement scheme is based on synthetic-wavelength interferometry [5]. The setup is depicted in Fig. 2. One comb (red) is split and propagates over a reference path and a free-space measurement path with a focusing lens to balanced photodetectors. There it is superimposed with another comb (blue), slightly shifted in frequency with detuned line spacing, serving as local oscillator (LO) for heterodyne detection. The frequency offsets between the comb lines generate electrical beat signals (Inset Fig. 2) containing the phase information of the optical lines. From the different phase shifts accumulated by each line by propagation over the free-space path the distance can be calculated.

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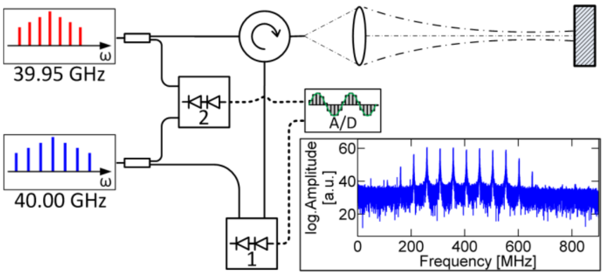

Fig. 2 *Fiber-based setup. One frequency comb (red) propagates over the free-space measurement distance. A second, detuned frequency comb is used as local oscillator, generating multiple electrical beat signals (inset) on the photodiodes, containing the phase information of the comb lines.*

3 Experimental demonstrations

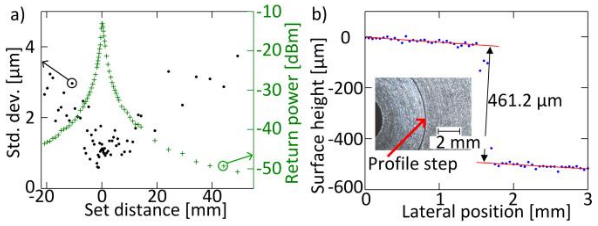

Fig. 3 *a) Standard deviation (black) of subsequent measurements vs. mirror position. Moving out of focus leads to a drop in power returned to the fiber (green). b) Measured values for a step profile of a technical steel surface(Inset: Microscopic image).*

The results obtained with the fiber-based setup are depicted in Fig. 3. Fig. 3a) shows the standard deviation (black) for repeated distance measurements to a mirror over different mirror positions. Due to the focusing lens, the optical power (green) drops by up to 37 dB when moving the mirror out of focus. The standard deviation amounts to 0.3-4 µm for the measured power range and an acquisition time of 8.3 µs per measurement value. To demonstrate the viability for measurements on rough surfaces, a step profile in a milled steel part was measured. The measured step height of 461.2 µm using our scheme agrees well with a tactile reference measurement of 464.4 µm.

4 Silicon photonic interferometer chip

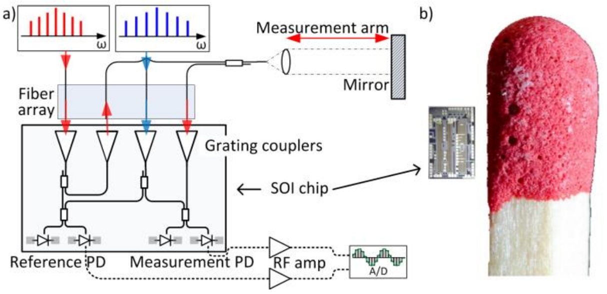

Fig. 4 *a) Chip-based setup. External frequency combs are coupled to an integrated interferometric setup including photodiodes (PD) via fiber array and grating couplers. b) Silicon photonic chip and match head for size comparison. Less than 1 mm² on-chip area are used for the depicted setup.*

Photonic integration on silicon offers the chance to design highly miniaturized sensors using mature CMOS processes offered by foundry services. The interferometric system with photodetectors needed for the presented measurement scheme was realized on a photonic integrated circuit (PIC), relying entirely on the standard device portfolio offered by the foundry, see Fig. 4 [6]. It comprises passive components such as beam splitters and waveguides as well as active components such as phase shifters and photodetectors. In this first proof-of-principle, the PIC is fed by externally generated frequency combs using a fiber array and grating couplers for fiber-chip coupling. With acquisition times of 14 µs, measurements of mirror positions are possible with standard deviations of less than 5 µm, see Fig. 5.

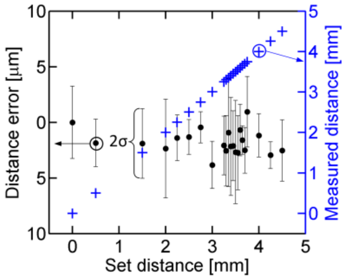

Fig. 5 *Unwrapped measured distance vs. set distance for different mirror positions (blue), deviations from set distances and standard deviation of repeated measurements (black), using the chip-based setup.*

5 Summary

We demonstrated fast and sensitive distance measurements using electro-optically generated frequency combs. Standard deviations in the µm-range are maintained for an optical power dynamic range of 37 dB, enabling measurements to a rough steel surface of a milled part. An integrated silicon PIC with sub-mm² footprint is presented, capable of distance measurements with 14 µs acquisition time and 5 µm standard deviation using synthetic-wavelength interferometry with externally generated frequency combs.

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