

Ultrafast Dual-Comb Distance Metrology Using Dissipative Kerr Solitons

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Abstract: We demonstrate ultra-fast high-precision distance measurements using a pair of dissipative Kerr-soliton frequency combs. We achieve sub- μm accuracy for static targets and measurement rates of 10 MHz that allow sampling of air-gun bullets on the fly.

1. Introduction

Fast and precise optical distance measurement (ODM) techniques are key for many industrial and scientific applications [1]. Among the various techniques, concepts based on frequency combs (FC) and synthetic wavelength interferometry (SWI) are particularly attractive: The precisely defined spacing of comb lines leads to high measurement accuracy independently of the absolute optical wavelength, and the large dynamic range of multi-heterodyne detection ensures robustness with respect to varying sample reflectivity [2-4]. The performance of such systems strongly depends on the underlying frequency comb. By modulation of a narrowband continuous-wave (CW) carrier, combs with approximately ten lines and a free spectral range (FSR) of 40 GHz were generated in previous experiments, enabling accuracies of 2 μm and acquisition times (AT) of approximately 9 μs [5]. Higher accuracies would require frequency comb sources with more optical lines such as mode-locked femtosecond lasers. Such devices, however, are bulky and expensive and cannot be integrated into robust low-cost chip-scale systems. In addition, the large number of densely spaced optical lines would limit the measurement speed.

In this paper, we demonstrate that dissipative Kerr-soliton (DKS) combs generated in high-Q Kerr-nonlinear SiN microresonators [6,7] can overcome these limitations. DKS combs feature hundreds of lines with an FSR of the order of 100 GHz at near-infrared telecommunication wavelengths [6,7]. Such devices have previously been used for high-speed data transmission [8] and spectroscopy [9]. Here we exploit the unique features of DKS combs for ultra-fast high-precision ODM using the SWI concept. The extraordinarily large optical bandwidth allows for high-est measurement accuracy with standard deviations of 480 nm obtained for a static target. Moreover, due to the large FSR, the number of RF tones in the photocurrent can be kept small, allowing for ultra-short acquisition times down to 103 ns. This is, to the best of our knowledge, the fastest SWI measurement reported to date [5]. We demonstrate the viability of the concept by high-resolution on-the-fly sampling of air rifle projectiles at a speed of ~ 150 m/s.

2. Dual-comb distance measurement setup and high-precision measurement to static targets

The distance measurement system is based on a SWI scheme, using multi-heterodyne detection of two independently generated FC with FSR of $\text{FSR}_{\text{FC1}} = 95.646$ GHz and $\text{FSR}_{\text{FC2}} = 95.549$ GHz. The combs are generated by parametric frequency conversion [6,7] in Kerr-nonlinear high-Q SiN microresonators (SiN-MR), Fig. 1(a), which are pumped by CW external-cavity lasers (ECL). Erbium-doped fiber amplifiers (EDFA) are used to adjust the pump power and optical filters (OF) suppress amplified spontaneous emission, Fig. 1(b). The wavelength of the laser is tuned over a cavity resonance from the effectively blue detuned regime ($\lambda_p < \lambda_{\text{cr}}$) to the effectively red detuned regime ($\lambda_p > \lambda_{\text{cr}}$) [5-7]. After the SiN MR, remaining pump light is suppressed by other OF before the combs are amplified and split. One part of the first FC is sent to the measurement target, and the backscattered light is superimposed with the signal from the second FC on a first balanced photodetector (BD1). The other parts of FC1 and FC2 are superimposed on a second detector (BD2), serving as a reference. The beat signals on both BD are recorded using a 32 GHz real-time oscilloscope. Using digital signal processing, phase differences $\Delta\phi$ between neighboring lines of FC1 are extracted from the individual RF beat tones in the photocurrent, Fig. 1(d), and the distance is evalu-

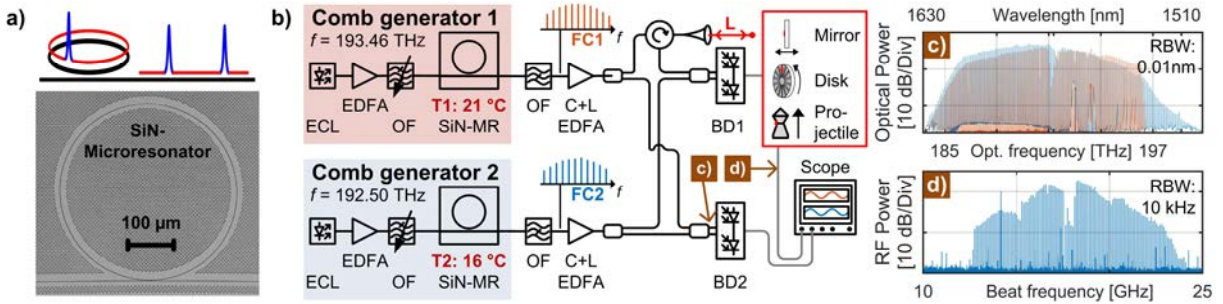


Fig. 1: Experimental setup. (a) Soliton Kerr comb generation in high-Q microresonators. Our experiment relies on single-soliton comb states which consist of only one ultra-short pulse circulating around the cavity. This leads to a broadband comb spectrum with a smooth envelope (b) Distance measurement setup. (c) Optical spectrum of FC after amplification. (d) Radio-frequency (RF) spectrum of the photocurrent signal.

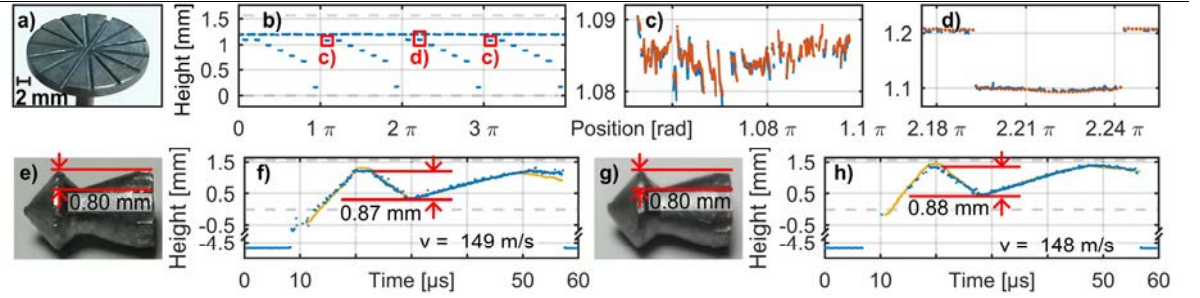


Fig. 2: (a) Photograph of disk used for high-speed measurement. (b) Measured height profile of a rotating disk (493 Hz, ~ 17 m/s) over two roundtrips. (c) Zoomed-in height profile measured at the same position on two consecutive roundtrips. (d) Comparison of measurement (blue) and reference data (orange) obtained with an optical coordinate-measuring machine. (e, g) Fired projectiles with calliper measurements. (f, h) Corresponding evaluated surface profiles: Measured distance (blue) to the flying projectile and to a mirror behind the projectile trajectory. A reference profile extracted from OCT B-scans (in-house fiber based SS-OCT setup, axial resolution $11 \mu\text{m}$) is also shown (yellow). Deviations to calliper measurements are presumably caused by a tilt between the projectile axis and the trajectory.

ated by a linear fit according to the relation $L = \Delta\phi \cdot c / (4\pi \cdot \text{FSR}_{\text{FC1}})$, see [2] for details. We use the fit error to quantify the quality of a distance measurement, which allows for automatic removal of bad data points. The unambiguity range (UR) is dictated by the FSR of FC1 and amounts to 1.567 mm . The FSR difference $\Delta\text{FSR} \approx 97 \text{ MHz}$ defines the spectral spacing of the RF beat signals in the baseband and dictates the minimum possible acquisition time $T = 1/\Delta\text{FSR} = 10.3 \text{ ns}$. For given phase uncertainties, the distance measurement accuracy is inversely proportional to the overall optical bandwidth of the FC such that the scheme can benefit greatly from Kerr comb sources. At the same time, the extraordinarily large FSR of Kerr combs allow to span the optical bandwidth with a manageable number of spectral lines, leading to manageable number of RF tones with large spacing in the photocurrent signal. The measurement speed is dictated by the minimum observation time needed to separate these RF tones by a Fourier transform. Hence, large line spacing is essential to speed up the measurement while maintaining high accuracy. Of course, larger FSR leads to a reduced UR, but this can be overcome by combining the SWI scheme with a less precise time-of-flight (TOF) ODM system [1,3]. The performance of our ODM system is characterized by measuring the distance to a mirror for 18 different positions covering the full UR. Taking 272 consecutive measurements at an AT of 103 ns , a short-term standard deviation of 480 nm is achieved. In this context, “short-term” refers to measurements taken within short time spans of less than $30 \mu\text{s}$ such that thermal drift of the fibers does not play a role.

4. High-speed measurement on rotating discs and flying air-gun projectiles

To demonstrate the speed of our ODM system, we measure the height profile of a rotating disk having grooves of different depths between 0.1 and 0.9 mm , Fig. 2(a). The rotation frequency amounts to 493 Hz , leading to a speed of the sampling point on the disk surface of 17 m/s . The AT is set to 10.3 ns , leading to a spacing of the measurement points on the disk of approximately 170 nm . The diameter of the measurement spot on the disk is approximately $20 \mu\text{m}$, i.e., the surface profile is heavily oversampled. Two consecutive round-trips of the slotted disk are analysed, Fig. 2(b). An overlay of the measured height profile between both round-trips indicates that the system can reproducibly detect μm -scale surface features, Fig. 2(c). In addition, we find good agreement of the height profile with a reference measurement from a commercial coordinate-measuring machine (Werth VideoCheck HA), Fig. 2(d).

In a final step, we measure the height profile of projectiles fired from an air rifle with velocities of approximately 150 m/s , Fig. 2 (e, g). A reference mirror placed behind the projectile trajectory leads to a constant reference signal. The AT is increased to 103 ns for better sensitivity of the measurement. For comparison, each projectile is characterized by optical coherence tomography, Fig. 2 (f, h). The results are in good agreement with evaluated surface profiles obtained from the on-the-fly measurement. In addition, we compare the measured distance between the outer circumference of the projectiles and the waist to a caliper reference measurement, Fig. 2 (e, g). The results show a systematic deviation, which we attribute to a tilt of the projectile axis with respect to the trajectory of movement.

5. Summary

We demonstrate for the first time the use of dissipative Kerr soliton combs for optical distance measurements. We achieve a short-term standard deviation of 480 nm , obtained from a static target at an acquisition time of 103 ns . We furthermore show the viability of our approach by highly accurate sampling of flying airgun projectiles, moving at approximately 150 m/s . DKS comb sources show vast potential for integration into chip-scale ODM systems.

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Empfohlene Zitierung:

Ganin, D.; Trocha, P.; Pfeiffer, M.; Karpov, M.; Kordts, A.; Krockenberger, J.; Marin, P.; Wolf, S.; Randel, S.; Freude, W.; Kippenberg, T. J.; Koos, C.

Ultrafast Dual-comb distance Metrology using dissipative Kerr solitons

2017. CLEO : Science and Innovations 2017, San Jose, California United, States, 14-19 May 2017, The Optical Society of America (OSA).

doi: 10.554/IR/1000071238

Zitierung der Originalveröffentlichung:

Ganin, D.; Trocha, P.; Pfeiffer, M.; Karpov, M.; Kordts, A.; Krockenberger, J.; Marin, P.; Wolf, S.; Randel, S.; Freude, W.; Kippenberg, T. J.; Koos, C.

Ultrafast Dual-comb distance Metrology using dissipative Kerr solitons

2017. CLEO : Science and Innovations 2017, San Jose, California United, States, 14-19 May 2017, Art. Nr. STh4L.6, The Optical Society of America (OSA).

doi:10.1364/CLEO_SI.2017.STh4L.6

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