Nanometric precision metrology based on hybrid spectrally-resolved and homodyne interferometry via a single soliton microcomb

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Abstract: We present ultra-precision distance measurement based on spectral interferometer via single soliton microcomb generated in Si_3N_4 microresonator. We demonstrate 3-nm repeatability over a 23-mm non-ambiguity range via homodyne interferometry, over 1000s long-term stability.

OCIS codes: (140.3945) Microcavities; (280.3640) Lidar; (320.7090) Ultrafast lasers

Introduction

Laser interferometry has served as a pivotal role for precision metrology and dimensional length measurement[1]. In the last two decades, Optical frequency combs have led optical distance metrology[2,3] with various method including synthetic wavelength interferometer (SWI)[4], spectral resolved interferometer (SRI)[5,6], multi-wavelength interferometry (MWI)[7], cross correlation time-of-flight (TOF) [8], and dual-comb interferometry[9]. Recently, Frequency comb generated in Kerr-nonlinear microcavity has unleashed the potential of frequency comb in chip-scale[10-14]. In this paper, we present spectrally-resolved laser ranging via a single soliton frequency microcomb, with precision length metrology at the few nanometers scale. Single soliton was deterministically and stably generated in a planar waveguide Si_3N_4 microcavity by counter propagating dual-pumping technique. We measured time delay between two pulses for determination of distance in frequency domain by principle of spectral resolved interferometer. Due to large pulse repetition rate, an interference spectrum was directly resolved in commercial optical spectrum analyzer without mode filtering part. With the combined soliton and homodyne interferometry architecture, we achieve a 3-nm repeatability over a 23-mm non-ambiguity range.

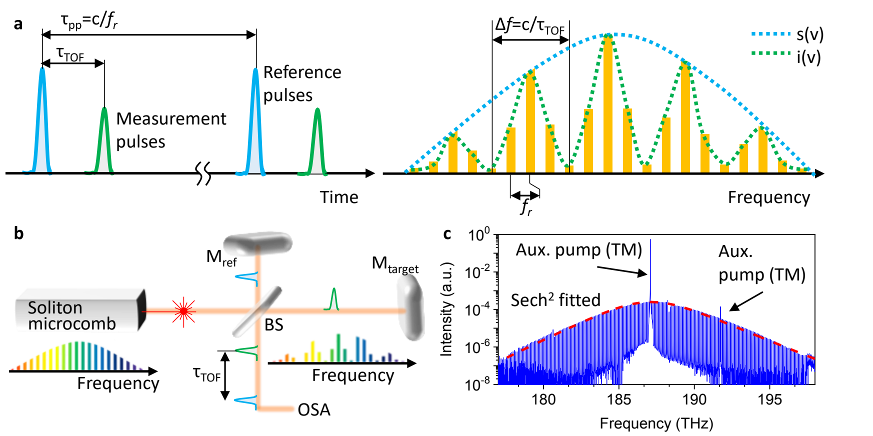

Figure 1. (a) Principle of spectral resolved interferometer for distance measurement **(b)** Experimental set up of soliton microcomb based spectral interferometer for precise distance measurement. Inset is an example spectrum of soliton microcomb used in this study. M_{ref}: reference mirror, M_{target}: target mirror, and BS: beam splitter, OSA: optical spectrum analyzer. **(c)** Optical spectrum of single soliton microcomb.

Experiment and Result

Fig. 1 (a) shows a measurement principle of spectral resolved interferometer for distance measurement. The pulse train with pulse interval of τ_{pp} forms even spaced frequency comb structure with frequency mode interval of $f_r=c/\tau_{pp}$. If the pulse with same optical spectrum ($s(\nu)$) has time delay of τ_{TOF}, the original pulse and time delayed pulse (or measurement pulse) generate interference pattern ($i(\nu)$) in frequency domain and its period is c/τ_{TOF}. Since the period of interference pattern has linear relation with time delay between two pulses, the time delay of τ_{TOF} can be analyzed from frequency-domain data without high speed time-domain rf devices. Fig. 1(b) illustrates the experimental setup of soliton microcomb based spectral resolved interferometry for ultra-precision distance measurement. The soliton microcomb with pulse repetition rate of 88.5 GHz has a hyperbolic secant-square shape centered at 1595 nm with 40 nm bandwidth as shown in Fig. 1. (c). The soliton microcomb was amplified and filtered by C-band (1530-1565 nm) erbium doped fiber amplifier up to average power of 10 mW. The amplified and filtered output was centered at 1561.4 nm (192 THz) with 16 nm (2THz) bandwidth. An interferometer part was based on the Michelson type interferometer and target non-polarizing type beam splitter with 50:50 dividing ratio was used to split and recombine a reference pulse and measurement pulse. The recombined reference pulse and measurement pulse made interference pattern in frequency domain. The interference pattern was monitored by optical spectrum analyzer with 0.05 nm resolution and it was Fourier-transformed to reconstruct time domain signal for measuring time delay between the reference pulse and measurement pulse[5]. Figure 2(a) shows how we extend the non-ambiguity range from hundreds of micrometers to 23-mm by introducing coarse measurement from ASE spectrum-based SRI. Figure 2(b) shows an example resulting spectral interference pattern in the blue plot. Since the microcomb has a large 88.5-GHz repetition-rate, the comb tooth-resolved interferogram can be directly read out with OSA. As shown in Fig. 2(c) and 2(d) up to 1,000-seconds, the measured distance from microcomb SRI is nearly constant without notable long-term drifts and has a standard deviation (1σ) of 81.6-nm. In contrast, the ASE spectrum-based SRI shows large fluctuations in the distance measurement due to its incoherence, but aids to extend the measurement range via non-commensurate periods in the time-domain. With the aid of homodyne interferometry via optical carrier frequency, the distance metrology precision is further improved to the nanometric level, which has a standard deviation (1σ) of 10.4-nm during the 1,000-seconds integration, and down to 3.6-nm during 900 to 1000 seconds range.

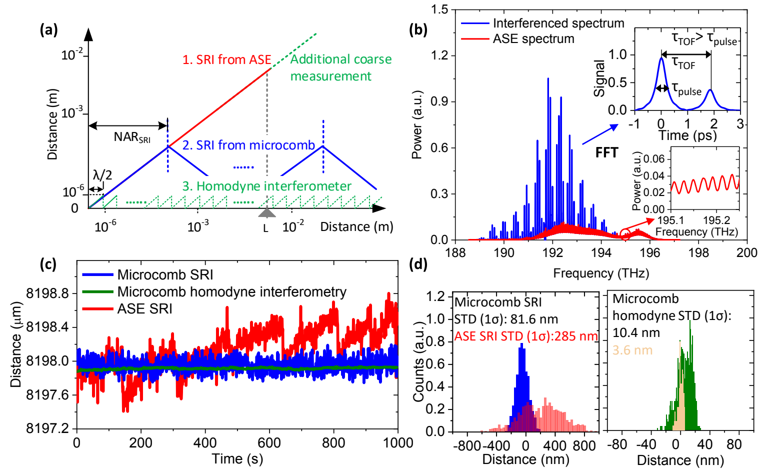

Figure 2. (a) Schematic illustration of non-ambiguity range extension. **(b)** Measured high-coherence spectral interferogram (blue) from the reference and measurement pulses. Red line: amplified spontaneous emission (ASE) noise induced by the EDFA. **(c)** Long-term distance metrology sampled over 1,000-seconds. **(d)** Left figure: histogram distribution of microcomb spectral interferometry and ASE spectral interferometry, with 1σ standard deviation of 81.6-nm (blue) and 285-nm (red) at 1,000-seconds measurement. Right: histogram distribution of homodyne interferometry, with 1σ standard deviation of 10.4-nm at 1,000-seconds measurement (green color). The 3.6-nm standard deviation is an example obtained from 900 to 1,000-seconds (yellow color).

Result

We present precise distance measurement by soliton microcomb based spectral resolved interferometry. We stably generated single soliton in silicon nitride microcavity by the counter propagating dual pumping technique. Our proposed soliton microcomb hybrid spectrally-resolved and homodyne interferometry method demonstrated nanometric level of precision distance metrology over a 23-mm non-ambiguity range. We believe that our proposed method can be integrated in fully integrated chip-scale circuits and brings breakthrough on precision distance metrology near future.

References

[1] R. Felder, *Metrologia* **42**, 323-325 (2005).
[2] S. A. Diddams, *et al, Phys. Rev. Lett.* **84**, 5102-5105 (2000).
[3] Y.-S. Jang, *et al, Nanomanufaturing and Metrology*. **1**, 131-147 (2018).
[4] K. Minoshima, *et al, Appl. Opt*. **69**, 5512-5517 (2000).
[5] S. A. van den Berg, *et al, Phys. Rev. Lett* **108**, 183901 (2012).
[6] K.-N. Joo, *et al, Opt. Express* **14**, 5954-5960 (2006).
[7] Y.-S. Jang, *et al., Sci. Rep*. **6**, 31770 (2016).
[8] J. Lee, *et al, Nat. Photon*. **4**, 716-720 (2010).
[9] I. Coddinton, *et al, Nat. Photon*. **3**, 3351-356 (2009).
[10] B. Stern, *et al, Nature* **562**, 401-405 (2018).
[11] M.-G. Suh, *et al, Science* **359**, 884-887 (2018).
[12] B. C. Yao, *et al, Nature* **558**, 410-414 (2018).
[13] J. Yang, *et al. Comm. Phys*. **3**, 27 (2020).
[14] Y. Li, *et al. Light Sci. Appl*. **9**, 52 (2020).
[15] J. Liu, *et al. Nat. Photonics* **14**, 486–491 (2020).