Frequency-Comb Based Approaches to Precision Ranging Laser Radar

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1. Introduction

The output of pulsed femtosecond lasers can be controlled to generate optical pulse trains with very precise timing and carrier frequency. In the frequency domain, these sources create a frequency comb of narrow, well-defined lines that can be used for precision optical frequency metrology.[1, 2] This source naturally lends itself as well to precision measurements of range or velocity since there is a direct connection between time/frequency and range through the speed of light. In this paper, we will discuss several implementations of comb-based ranging including a system based on phase-locked dual comb transceivers, free-running dual-comb transceivers, and comb-assisted fm laser radar. We will present data from laboratory distance measurements using the two dual-comb approaches. We will also present data on the calibration of a fast swept laser using a frequency comb at rates of up to 1500 THz/sec or 12,000 nm/sec.

2. Comb-based ranging

Because of its ability to provide an absolute timing/frequency reference in the optical domain, frequency combs have been exploited in a number of different ways for absolute distance measurements. Comb sources have been used to support conventional multiwavelength or swept laser interferometry by providing precise measurements of the laser wavelength.[3-5] Combs sources have also been used directly in a number of different approaches. In a first demonstration, the intermodulation rf beats from a single comb were detected,[6] and recently intermodulation beats in the THz have been used in a dual comb approach.[7] In a number of other approaches, the comb is combined with an unbalanced Michelson interferometer and the relative distance between the two arms and is determined either in time through the pulse cross-correlation or in frequency through dispersive/spectral interferometry.[8-12] The "dead zones" or slow acquisition time associated with the unbalanced interferometer can be avoided by using two coherent frequency combs in a dual-comb interferometer approach. In Ref. 13 we demonstrated such a dual-comb interferometer that combined time-of-flight and interferometric range measurement to achieve absolute distance measurement at high accuracy and rapid update rates.

In the remainder of this paper, we will discuss our recent implementation of the dual-comb interferometer, which avoids some of the complexity of our first demonstration. We will also discuss a different approach that might achieve higher sensitivity and therefore be more appropriate for a diffuse target. Specifically, we consider a comb-assisted fm lidar system where the frequency of a very rapidly swept mems-based ECL is calibrated against a fixed frequency comb.

3. Dual comb approach

In the dual-comb approach, shown in Figure 1, two combs with slightly different repetition rates are used. One comb is reflected from the

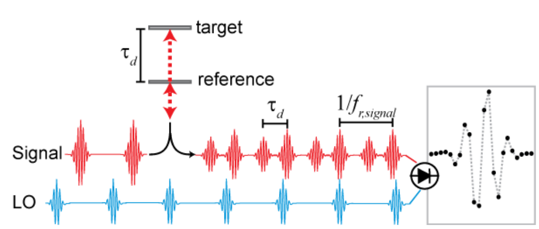

Figure 1: Concept of dual-comb interferometer for ranging measurements. The signal pulse train is reflected from a reference and target plane and heterodyned against a LO comb with a slightly different repetition rate. The detected overlap voltage between the LO and signal pulses is a downsampled measurement of the reflected signal pulse train.

target and its return signal is read out by heterodyning it against the second local oscillator comb. The relative arrival time of the pulse envelopes from the target and reference gives a very accurate time-of-flight measurement between the two. If the time-of-flight measurement is averaged down to below a fraction of a wavelength, then the carrier phase can be used for an interferometric range measurement with nm precision. This handover to an interferometric range measurement was demonstrated in Ref. 13.

The advantage of this dual comb approach is its high precision, wide ambiguity range, rapid update rate, and insensitivity to systematic errors. Unlike the approaches based on an unbalanced Michelson interferometer, there are no mechanical moving parts and there is no need to adjust the reference arm to achieve overlap of the signal and reference pulse (which effectively precludes the use of the unbalanced Michelson approach for coherent LIDAR with rapidly changing ranges). However, in our original implementation, the approach is experimentally complicated, involving a significant number of phase locks and, furthermore, the interferometric range measurement supplied a precision well in excess of that which can be supported in terrestrial applications because of the uncertainty in the index of refraction of air. Therefore, in our more recent system, we have traded off some of the precision for a simpler system by dropping the interferometric range measurement which removes the requirement of optical coherence over long periods of time and, consequently, the requirement of a tight optical phase lock between combs.

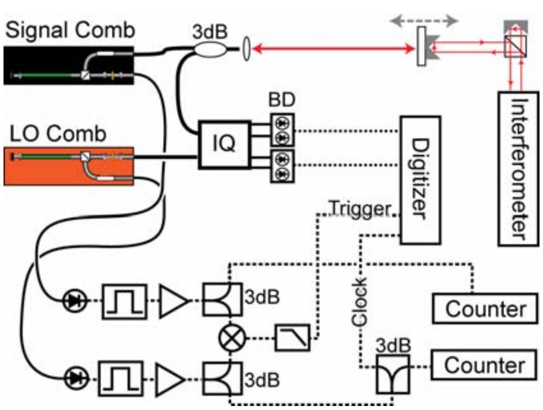

Figure 2: Schematic of the setup. The two combs operate at 200 MHz with a 7 kHz difference in repetition rate. The overlap between the reflected signal and LO pulses is digitized synchronously with the LO comb pulses and stored for analysis. The counted signal pulse repetition rate provides the time-axis for the scaling the measurements.

As shown in Fig. 2, we now base the system on free-running "combs". In this case, we use the term comb loosely, as the combs are free-running fs Er fiber lasers constructed from a simple linear cavity and saturable absorber.[14] The combs have repetition rates of ~ 200 MHz that differ by 7 kHz. Although the two comb sources are not actively phase-locked, their intrinsic noise is low enough that they maintain their phase-coherence over the single interferogram shown in Fig. 1. The effective Nyquist sampling bandwidth of the dual-comb system is given by $(200\text{ MHz})^2/(2\times 7\text{kHz}) \sim 3$ THz, or 22 nm which is much broader than the comb spectral width. It is necessary to adjust the current to the lasers such that the down-sampled signal has an rf frequency that is offset from zero to avoid aliasing effects,[13] but this adjustment is required only occasionally and could be performed by a slow servo. In laboratory measurements, we find that this system can support better than 300 nm precision in a 20 ms acquisition period, or a factor of 2 improvement over our previous system[13], despite the simpler setup. Figure 3 shows an Allan deviation measured at 1 m range.

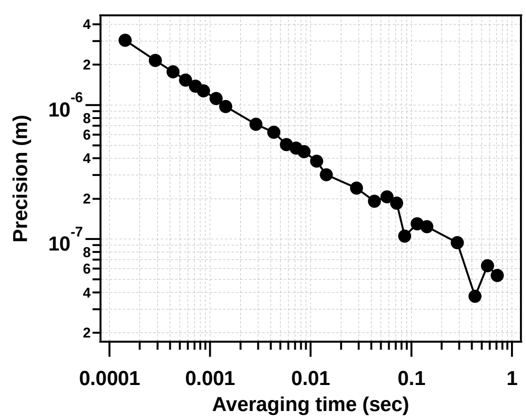

Figure 3: Measurement precision (Allan deviation) of the range from the reference to the target at a 1 meter distance. The minimum acquisition time is 1.4 ms, corresponding to the 7 kHz difference in comb repetition rates, and has a standard deviation of 3 micrometers.

2. Comb metrology on tunable swept lasers: towards fast comb-assisted fm lidar

A major issue with any of the ranging approaches that use the comb directly is that they require significant return power; Indeed, all the comb based experiments thus far have relied on a specular reflection from either a corner cube or glass plate to achieve sufficient return power. For direct comb measurements the reasons for this are twofold. First, the power per comb tooth is low. Second, these comb based methods are essentially cross-correlation techniques and therefore effectively "down-sample" the returning signal to achieve higher bandwidth. This down-sampling translates to a reduction in SNR in a given time period, which must be offset by an increase in power. Much higher sensitivity can be expected from a conventional swept fm lidar approach since there is a higher power per spectral element, equal to the power of the swept cw laser rather than the power per tooth. However, rapid, high-resolution ranging in an fm LIDAR setup has its own set of severe technical challenges. Specifically, one must achieve a very linear sweep (to avoid distortions) over a broad bandwidth (to achieve high resolution) and over a short time (to achieve fast update rates).

In recent work, a highly linear, 5 THz laser sweep laser has been demonstrated by locking the chirp frequency to an unbalanced fiber intereferometer. When used for ranging, this system achieved a resolution below 50 micrometers and sub-wavelength precision.[15,16] The linearity of the sweep can be calibrated against a comb in the laboratory to investigate possible systematic errors.[17] For these measurements, the total sweep time was about one second, limited by the need to stay locked to the interferometer. As lasers continue to develop, particularly in the telecom band, much faster sweeps are becoming available, which should allow for much higher update rates. However, one expects the linearity of the sweep to degrade as the speed increases and, furthermore, the ability to feedback with enough bandwidth becomes increasingly challenging. Therefore, active linearization of the sweep may not be possible. An alternative approach is to passively measure the laser frequency versus time and apply post-corrections to the data, as in Fig 1.

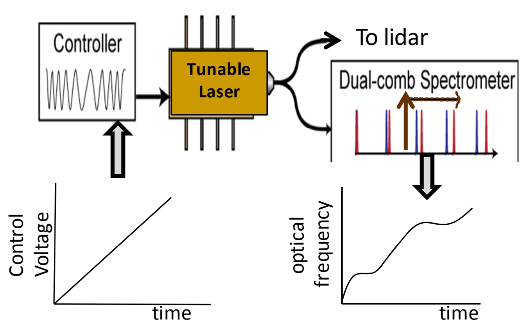

Figure 4: Conceptual setup for a comb-assisted fast-swept laser. While the control voltage may be intended to cause a linear frequency sweep, the laser will not respond perfectly. Therefore, the true output waveform must be calibrated. The dual comb spectrometer can accomplish this calibration to measure the actual frequency versus time of the laser waveform.

Following the concept of Fig. 1, we have recently conducted a series of experiments to explore the ability of a dual-comb interferometer to measure the output of a rapidly tuned laser.[18,19] We are interested not only in the simple linear ramp, but in more complicated waveforms such as stepped, sinusoidal or chirped waveforms. In Figure 5, we show the results of a measurement of a mems-based external cavity laser with a chirped sinusoidal frequency output. We plot both the measured frequency versus time and its derivative (i.e. the chirp) of the laser over a 100 ms time period. The dual-comb spectrometer can support measurements at instantaneous frequency sweeps (chirps) of up to 1500 THz/sec (or 3 THz sweeps every 5 ms). In this case, a dual-comb spectrometer was used and the optical frequency is absolute since it can be determined by comparing the heterodyne beat of the cw laser with the two combs. However, often only a precise relative frequency measurement is needed and in this case, a single comb will suffice.

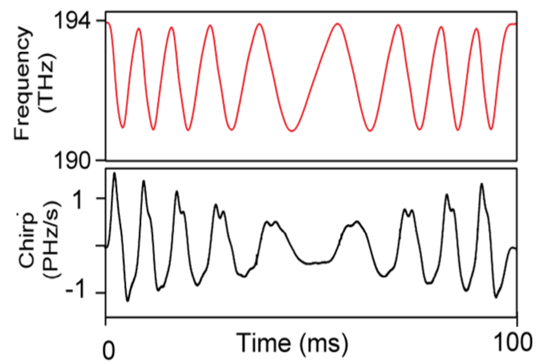

Figure 5: Measured waveform from a MEMS-based ECL laser [19]. The control voltage was a chirped sine wave. The laser output follows this fairly well, but not perfectly as can be seen in the derivative signal. Instantaneous sweep rates up to 1500 THz/sec (12,000 nm/sec) can be successfully tracked.

At a minimum, such a system can be used to calibrate the linear portion of a swept laser for use in an FM lidar configuration.[15] However it is also intriguing to consider using the entire sweep and, through post processing, "demodulate" the measured heterodyne return signal from a target to establish its range. Such an approach will clearly be computationally intensive but may be possible with modern compact telecom-based receivers combined with fast digitizers and field programmable gate arrays. It may also be possible to use such a highly-calibrated, but non-linear source to support other more advanced coherent lidar systems such as synthetic aperture lidar.

3. Conclusion

As a calibrated, broadband optical source, combs present an interesting new technology for precision applications in coherent LIDAR. Much of the recent work has focussed on laboratory-based absolute ranging experiments and quite a few different comb-based ranging systems have been demonstrated. The combination of a comb and a fast swept laser may allow for the use of combs in other challenging coherent LIDAR systems, such as multi-static coherent LIDAR or synthetic aperture LIDAR.

4. References

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