15th Coherent Laser Radar Conference

Precision ranging LIDAR using femtosecond fiber lasers

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Abstract

We discuss a coherent laser radar that uses two coherent femtosecond fiber lasers to perform absolute ranging at long distance. One coherent femtosecond fiber lasers acts as a source and the other as a local oscillator for heterodyne detection of the return signal from a cooperative target. The system simultaneously returns a time-of-flight range measurement for coarse ranging and an interferometric range measurement for fine ranging. Furthermore, it is insensitive to spurious reflections that can cause systematic errors. The range is measured with 3 μm precision in 200 μs and 5 nm precision in 60 ms over a 1.5 m ambiguity range. This ambiguity range can be extended to 30 km by simply reversing the roles of the signal and LO sources. We will also discuss the possibilities of using such a system for precision vibrometry and for even more rapid absolute ranging.

1. Introduction

Although frequency combs are normally considered in the frequency domain where they produce a comb of well-defined, narrow linewidth optical frequency lines, these same sources can also be viewed in the time-domain where they produce a train of well-defined, coherent optical pulses.[1-4] These optical pulses can be very short in duration, i.e. have a large bandwidth, and can be arranged to have a high carrier phase coherence with an underlying optical cw "clock" laser. They very much resemble a coherent RADAR pulse train, except that the carrier frequency is shifted up into the optical region and their bandwidth can be significantly larger. As a consequence, these sources are interesting for high-resolution coherent LIDAR systems.[5,6]

One challenge of taking full advantage of these high-bandwidth, coherent sources in a coherent LIDAR system lies in effectively detecting the return signal. The optical pulses have very high bandwidth (i.e. THz or greater) and standard direct or heterodyne detection would require an equivalently large bandwidth receiver, which does not exist. There are a number of ways to circumvent this problem; here we discuss a method where a second coherent frequency comb is heterodyned against the return signal and effectively down-converts the full bandwidth of the return signal to baseband, where it can be detected by relatively low bandwidth detectors (see Fig. 1).[7-11] In the frequency domain, this picture is equivalent to massively parallel heterodyne detection between the "teeth" of the signal and local oscillator (LO) frequency comb. In the time domain, it is equivalent to linear optical sampling. In Ref. 6, we used this technique to measure absolute range with 1.5 meter ambiguity range to high precision by "handing over" an effective time-of-flight measurement to an inteferometric measurement. The time-of-flight measurement gave 3 μm precision in 200 μs; with averaging it dropped below a quarter wavelength after 60 ms at which time the interferometric range measurement gave 3 nm precision. Such a system might be suitable, for example, for precision positioning of satellites in a coherent formation. In Section 2 below, we briefly review this experiment and some of the results. This particular experiment used a single ~0.4 THz detection channel and laser combs with a 100 MHz repetition rate (which yielded the 1.5 meter ambiguity range). However, exactly the same approach could be taken with higher-repetition rate lasers and with multiple detection channels. Indeed, there are significant tradeoffs between ambiguity range, precision, signal power, number of detection channels, and update rate; the optimum configuration will depend on the application. The product of resolution and update rate -- a reasonable figure-of-merit -- scales strongly with the repetition rate providing significant advantages to a 1 GHz-comb based system, although at the cost of a reduced ambiguity range. Section 3 discusses these tradeoffs and scaling rules. In Section 4, along these lines, we propose a configuration that would allow 3D scanning of a surface with high resolution. Finally, in Section 5 we briefly discuss the applicability of comb-based LIDAR to vibrometry and synthetic aperture LIDAR, and finally conclude.

2. Absolute Ranging

Figure 1 shows a basic conceptual picture of the setup for heterodyne detection between two mutually coherent frequency combs in both the time and frequency domains. The two fiber-based comb sources produce light from ~1520 to 1600 nm and are phase-locked to two underlying cw reference lasers at 1550 nm and 1535 nm through feedback to the cavity length, pump power, and an external acouso-optic modulator (AOM). This stabilization is critical to permit phase-coherent heterodyne detection. The optical bandpass acts as a "pre-selector" to avoid aliasing in the frequency domain, or equivalently, to insure that the linear optical sampling in the time domain occurs below Nyquist frequency.

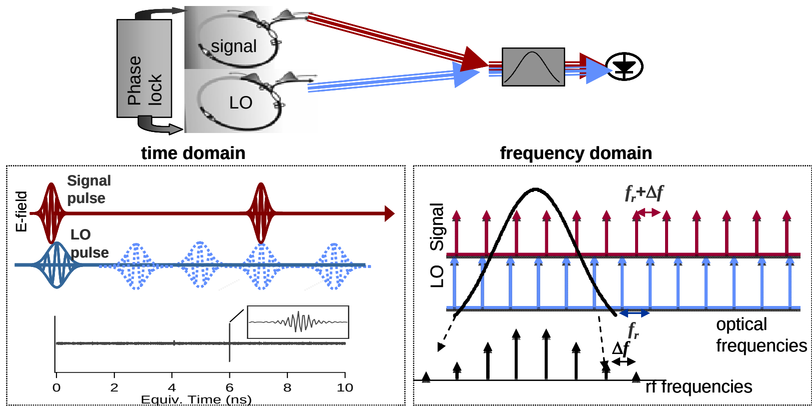

Figure 1. Basic concept of heterodyne detection between a Signal comb and an LO comb in the time domain and the frequency domains. The repetition rate of the LO and signal combs are f_r and $f_r + \Delta f$, respectively. In the time domain, the LO pulse train advances with respect to the signal comb pulse train by $\Delta T \sim \Delta f \,/\, f_r^2$ every pulse, effectively "walking" over the signal pulses. The overlap between the signal and LO pulses is digitized at each step, ΔT, to generate the sampled signal pulse train vs time, shown in the lower trace. In the frequency domain, the detection effectively maps the optical comb to the rf. Inverse Fourier transformation of the rf comb, shown on the right, and scaling to effective time yields the same time domain signature shown on the left.

In order to measure the range to an object, the signal pulse is directed to both a reference plane and the target plane; the LIDAR measures the reflection from both surfaces. Since both the pulse envelope and the carrier phase are measured, we simultaneously retrieve a pulse time-of-flight and an interferometric measurement of the distance. Alternatively, one can view this as a massively parallel multi-wavelength interferometry system. Figure 2 shows the basic laboratory setup used to measure the absolute range and an example of a range vs. time measurement. In the experiment of Ref. [6], a single detection channel achieved the precision quoted earlier, namely ~ 3 μm out of the 1.5 m ambiguity range at the 200 μs update rate and 3 nm precision after 60 ms of averaging. However, we have also conducted measurements with dual spectral channels, as shown in Figure 2. Such measurements can, in principle, yield faster update rates since the effective bandwidth of the system is increased. However, this improvement is only realized if the limiting noise source is uncorrelated between the two channels, for example as is the case for shot noise. In Ref. 6, at our powers, the limiting noise source came from the ~20 fs pulse-to-pulse timing jitter between the pulse trains from the two combs and we did not observe significant improvement with the two channels (although the second channel does provide an important check on systematics for absolute range measurements).

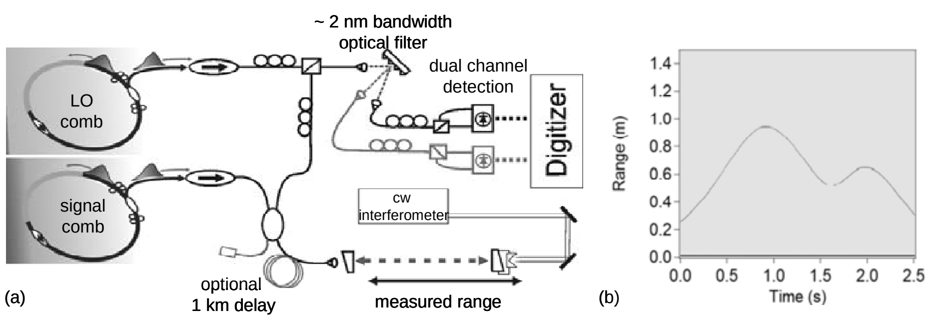

Figure 2. (a) Schematic of the laboratory setup to measure the absolute range between two optical flats. The two detection channels have the same bandwidth but can be centered at different carrier frequencies under the ~ 10-20 nm wide comb spectral output. Their signals can then be coherently combined. (b) Example measurement of range versus time when the target reference plane (on the cart) is moved by hand across ~ 0.8 meters of distance. The distance is measured to 3 μm at an update rate of 200 μs, given by the inverse of Δf.

3. Scaling laws: repetition rates and multi-channel detection

As with any ranging LIDAR system, the achievable distance resolution, ΔR, is

$$\Delta R \sim \frac{c}{2 \times BW \times SNR} \tag{1.1}$$

where c is the speed of light, BW is the transmitted optical bandwidth, and SNR is the signal-to-noise ratio. For absolute ranging, there are also contributing systematic errors. This equation applies to time-of-flight pulse measurement, where the BW is inversely proportional to pulse width, and reflects how well one can estimate the pulse center. It also applies to the interferometric measurement provided the BW is replaced by the carrier optical frequency, ν, and the SNR by the fractional pulse-to-pulse phase noise $\delta\varphi/(2\pi)$. In our system, a "single" measurement takes an update time $t_{update} = 1/\Delta f_r$, which is the time for the LO comb to fully sweep across the signal comb.

In our case, there is a tradeoff between bandwidth and update rate,

$$BW < t_{update} \frac{f_r^2}{4} = t_{update} \frac{c^2}{16 R_A^2} \tag{1.2}$$

where f_r is the repetition rate, and $R_A = c/(2f_r)$ is the ambiguity range. This equation can be derived in the time domain by requiring the LO pulse never "misses" the signal pulse or in the frequency domain by requiring there is never any aliasing of multiple optical heterodyne beats onto a single rf beat (See Fig. 1). Assuming the SNR is close to shot-noise limited at $SNR \sim \eta \sqrt{P_{return} / f_r}$, where P_{return} is the total detected return power, then Eq.(1.1) and (1.2) yield a "figure-of-merit",

$$\Delta R \times t_{update} \sim \frac{2c}{\eta \sqrt{P_{return}}} f_r^{-3/2} , \tag{1.3}$$

i.e. the product of resolution and update rate, which we would like to be as small as possible. The overall performance improves dramatically with increasing repetition rate, at the cost of a lower ambiguity range.

The source bandwidth typically far exceeds the detection bandwidth, BW. Therefore, we can clearly add multiple detectors to take advantage of the full available bandwidth. Figure 2 shows two channels, but it would certainly be experimentally feasible to use a linear array of photodetectors after the grating-based (or other) spectral filter and detect multiple spectral bands at once. In that case, Eq. (1.1) has an extra factor of $1/M$, where M is the number of detectors (or spectral channels, each with bandwidth BW that satisfies Eq. (1.2)) and the SNR per channel is modified to $SNR \sim \eta \sqrt{P_{return} / M f_r}$ to yield,

$$\Delta R \times t_{update} \sim \frac{2c}{\eta \sqrt{P_{return}} \sqrt{M}} f_r^{-3/2} \tag{1.4}$$

Once ΔR has dropped below a quarter wavelength, then the interferometric data provides much more precise ranging. In practice, the resolution of (1.4) is reached only if the systematics are sufficiently low, which requires either active locking of the two combs, or, alternatively, accurate monitoring of their relative coherence and a software correction.

4. 3-D surface imaging

The nm-scale ranging that is possible with the combs is excessive for many terrestrial applications. However, the system is flexible in terms of trading off precision for speed, as indicated in Eq. (1.1) to (1.4). While these scaling laws relate to the measurement of a single range, the system can also be configured so that the M channels each measure the range to a different point on the surface, as shown in Fig. 3. In that case, the same basic scaling of (1.3) applies to each channel independently, and P_{return} is the power per measurement point. Each channel retains the ability to "handover" the time-of-flight range measurement to an interferometric measurement with nm-level precision. This ability to measure the absolute range at nm-level precision and with reasonable (cm to meter) ambiguity range is a feature not easily found in current 3D laser radar systems. Such a system would provide much higher potential range resolution than current Geiger-mode APD based 3D imaging systems[12] although it would require significantly more return power and would therefore only be suitable at shorter distances and when such increased range resolution is warranted.

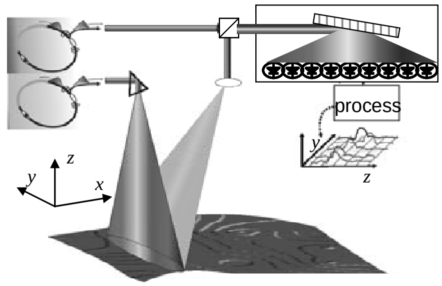

Figure 3. Example of multi-channel detection using a combination of spectral filtering and a linear sweep to generate a 3D image of an object. In general, the spectral domain can be freely traded for increased range resolution or for increased spatial resolution.

5. Conclusion

We focus in this paper on the ranging application of a dual-comb coherent LIDAR system. However, it is a coherent LIDAR and can act as a high-resolution vibrometer as well. In fact, the broad comb bandwidth lends itself to spectral averaging to reduce the limiting effects of speckle on high-resolution vibrometry signals.[5] The use of dual combs relaxes the significant range restriction of the previous comb-based vibrometer of Ref. [5], and one could conceivably configure the system to loosely lock onto a target for high-resolution vibrometry data, although such a system would require more complete control of the combs than demonstrated here. Another potential application of coherent frequency combs is in the area of synthetic aperture LIDAR particularly given the analogy of this source to a coherent pulsed RADAR source.

Highly coherent frequency combs have the potential to enable very high resolution coherent LIDAR systems for ranging and vibrometry, as well as a host of other applications including synthetic aperture LIDAR and multispectral LIDAR. To fully exploit their broad bandwidth does require an increase in transmit power over a single wavelength system but the dual-comb system here is completely compatible with chirped pulse amplification. Unlike “metrology-grade” frequency combs,[1,2] the sources here are considerably simpler since they do not require a full octave of output bandwidth. Nevertheless, more work is required to either further improve the robustness of fiber-based combs,[13,14] or alternatively, to base these systems on other types of compact and robust modelocked lasers.[15]

Acknowledgments

We acknowledge assistance with the data analysis from Ljerka Nenadovic and helpful discussions with Paul Williams.

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