Frequency-resolved range/doppler coherent LIDAR with a femtosecond fiber laser

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Abstract: We present a frequency-resolved coherent LIDAR (FReCL) based on a frequency comb source that provides higher performance than that of conventional pulsed range/Doppler LIDARs, reduces local oscillator timing requirements, and compensates for path dispersion.

OCIS codes: (140.3510) Lasers, Fiber; (280.3640) Lidar; (120.0280) Remote sensing

Femtosecond frequency combs provide broadband, coherent light sources and have revolutionized optical frequency metrology [1]. It is natural to consider extending their use to remote sensing, in particular, to coherent light detection and ranging (CLIDAR), since the broad spectrum supports high range resolution and the narrow linewidths of each comb tooth support high Doppler resolution. Fiber laser-based frequency combs at 1.5 μm [2, 3] are eye-safe and compatible with high-power erbium-doped fiber amplifiers (EDFA). Their kilohertz level linewidth [4, 5] is sufficient for long range applications and lower linewidths may be possible [6]. Indeed frequency combs have been employed in a ranging LIDAR [7] and proposed for measuring absolute distance in space [8].

However, several factors complicate CLIDAR with a wide source bandwidth, λ_{BW}, reflecting from a remote rough surface. First, high range resolution is achieved only if the return signal is detected, which requires the local oscillator (LO) and signal reach the detector simultaneously; for λ_{BW} =25 nm, the LO must arrive within ~150 fs of the signal regardless of the relative motion between the source and surface. Second, differential dispersion between the LO and signal arms degrades the range resolution since it stretches the signal pulse in time or range with respect to the LO. Third, any typical surface is rough on the wavelength scale, leading to speckle. Speckle limits the signal-to-noise ratio (SNR) to unity over a speckle correlation time, regardless of the transmitted laser power, and broadens the frequency spectrum to the speckle bandwidth, which is the inverse of the time for a speckle lobe to cross the receive aperture.

To effectively deal with these issues, we demonstrate a Frequency-Resolved Coherent LIDAR (FReCL) [9] in which the heterodyne signal is spectrally resolved into N channels with an arrayed waveguide grating (AWG). The data are processed incoherently to produce a vibration profile or coherently to produce a range image. In either case, this system has performance N-times superior to that of a single-channel, conventional CLIDAR, removes the tight requirements on the delay line, and permits phase-compensation to account for phase distortions caused by differential dispersion between the signal and LO arms. Our system differs significantly from previous demonstrated or proposed comb-based LIDARs [7] [8], and shares features of spectrally diverse CLIDARs [10, 11] and Fourier-Domain Optical Coherence Tomography (FdOCT) [12] . As with spectrally diverse CLIDARs, the Doppler (vibrometry) return is improved by averaging over the N spectral channels; provided the target's range depth is sufficiently large, these channels are uncorrelated, reducing the measurement's variance by a factor of N. Previous spectrally diverse LIDARs used either two narrowly spaced modes of a multimode CW laser [10] or two distinct CW lasers [11]; the single femtosecond laser represents a convenient, compact source that provides a large number of coherent modes. We achieved a Doppler sensitivity of ± 153 Hz (0.12 mm/sec) at a 10 ms averaging time for our N = 6 channels, despite a return signal speckle-broadened to a 14 kHz full-width half-maximum (FWHM). Higher channel numbers would further improve the Doppler sensitivity. As with FdOCT, the range image is generated as the Fourier transform of the N detected channels after any necessary phase compensation for signal path dispersion, and requires no precisely adjustable delay line. Here we achieve a range resolution of 60 μm FWHM after phase compensation (applied in data processing), despite the extra dispersion from 1 km of optical fiber (corresponding to a ~10 km air path), a 20-fold improvement over the uncompensated image's resolution and only 25 % larger than the 48 μm FWHM resolution imposed by the 25 nm source bandwidth. Our range ambiguity is 250 μm; however, higher channel numbers would support larger range ambiguities.

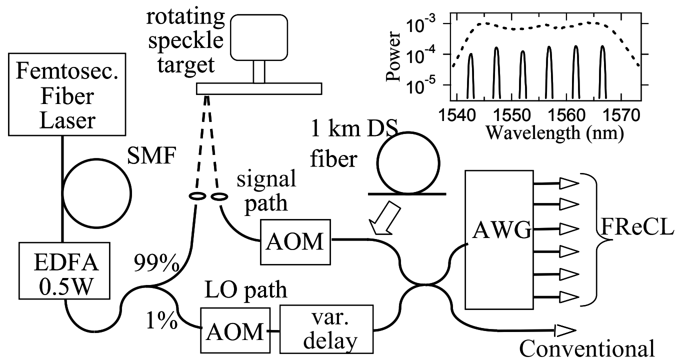

Fig. 1. System layout. Heavy solid lines are fiber paths, dotted lines are air paths. The variable delay line precisely adjusts the relative delay between the two arms and allows scanning the conventional LIDAR's range. AOM: acousto-optic modulator, EDFA: Erbium-doped fiber amplifier, SMF: 800 m of single-mode fiber. Inset: Output spectrum of the amplified source (dashed line) and the individual spectra of the filtered FReCL channels (solid line).

The setup is shown in Fig. 1. The signal beam scatters off the edge of a rough target rotating at about 10 Hz, resulting in a speckle bandwidth of ~2-15 kHz, depending on target tilt. The LO arm is equal to the signal arm modulo the laser repetition rate of 50 MHz. Alternatively, a second phase-locked fiber comb can serve as a phase-locked LO to remove this restriction. The signal bandwidth of λ_{BW} =25 nm is sampled directly in the conventional channel, but is spectrally filtered in the FReCL channels. Here we sparsely sampled the return with N=6 discrete detectors evenly spaced by λ_{sp}=4.8 nm, resulting in a range ambiguity of $\lambda^2/(2\lambda_{sp})$ ~ 250 μm, but retaining the full range resolution of $\lambda^2/(2\lambda_{BW})$ ~ 50 μm. The AOMs were adjusted to generate a heterodyne signal at ~30 kHz, which was processed in software to generate a signal $V_n(t)$, for the nth channel. The FReCL signals are processed coherently to generate a range image or incoherently to generate a Doppler signature of the target.

To generate an image, we construct a range gate at a virtual delay τ by $V(t,\tau)=\sum_{n=0}^{N} V(t)\exp(i2\pi\Delta\nu n\tau)$, where $\Delta\nu$ is the channel spacing and $\Delta\nu n\tau$ is a phase shift added to the n^{th} channel. Figure 2a shows a conventional CLIDAR image taken with fine (0.1 ps) delay line steps. A wobble of ~100 μm in the disk position is evident (and was confirmed by mechanical measurement). Figure 2b shows the single stripe of data representing one target rotation available from the conventional channel at a single fixed delay, while Fig. 2c shows the image acquired by the FReCL data at the same *single* fixed delay. Figure 3 shows a similar data set where the signal path was increased by 1 km of fiber. Dispersion completely destroys the resolution of the conventional channel, while through phase compensation applied in processing [12], the resolution is restored for the FReCL data.

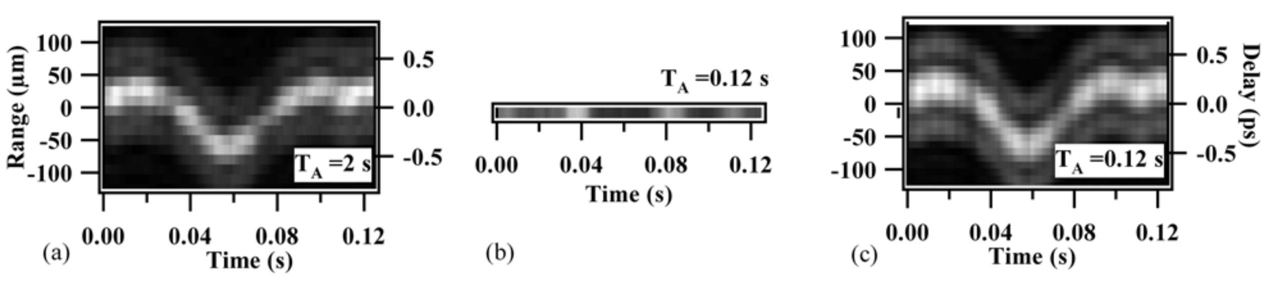

Fig. 2. Range image of the disk for one full rotation (0.12 sec), balanced signal and LO arms. The data are averaged over 10 ms. (a) Data from conventional system at 17 LO delays. (b) Conventional data for a fixed delay. (c) FReCL data at the same fixed delay. Zero padding smooths the image. T_A is the total acquisition time.

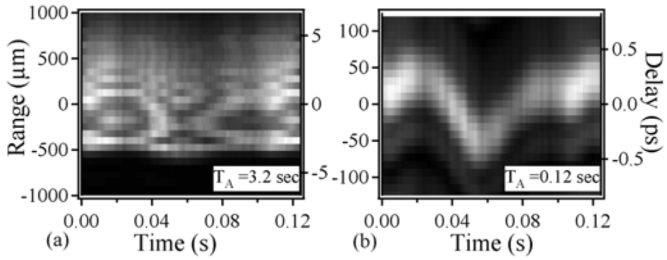

Fig. 3. Range image with 1 km of fiber in the signal path for (a) Conventional data at 27 delay steps of 0.5 ps each, and for (b) FReCL data at a fixed LO delay after phase compensation. Note the ~10x larger range scale in (a) versus that in (b).

Now consider the Doppler signal obtained by incoherently processing the FReCL data. If the target tilt provides sufficient range depth (> 250 µm) the N FReCL channels are decorrelated and incoherent summing can directly improve the SNR, as demonstrated in Fig 4a, and providing an N-times lower variance, as shown in Fig. 4b. Fig. 4c shows the resulting improvement in the measurement of a 50 Hz vibration.

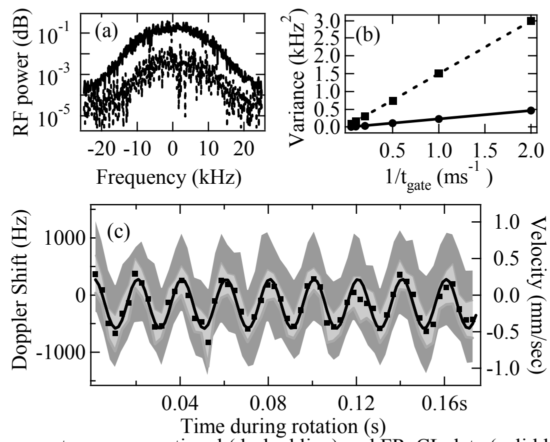

Fig. 4 (a) Example power spectrum: conventional (dashed line) and FReCL data (solid line) for t_{gate} = 10 ms. (b) variance versus the inverse gate time (t_{gate}) for the conventional (dashed line) and FReCL data (solid line). (c) Example vibration measurement. The means of the FReCL channel measurements (solid squares) are in good agreement with the applied vibration (solid line). For a single measurement (one target rotation), the standard deviation for the summed FReCL data is 280 Hz (light grey region), and for the single conventional channel is 700 Hz (dark grey region) for a 3 ms gate time.

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