Active Stabilization of Multi-THz Bandwidth Chirp Lasers for Precision Metrology

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1. Introduction

Frequency Modulated Continuous Wave (FMCW) ladar (i.e. coherent chirped ladar, swept wavelength interferometry, optical frequency domain reflectometry, et al.) is an attractive technique for many applications including optical coherence tomography, synthetic aperture imaging ladar (SAIL, or SAL)[1], non-contact precision metrology, and 3D imaging. Most of FMCW's advantages accrue from the use of heterodyne mixing with a local sample of the linearly chirped waveform for simultaneous demodulation and detection of the ladar return. After digitizing, the range profile can be obtained through a Fast Fourier Transform (FFT). This technique allows high sensitivity shot noise limited detection, a great reduction of the required IF detection bandwidth, and increased dynamic range through sampling of the ladar return field with relatively low bandwidth high dynamic range analog to digital converters (ADC's).

Although dominant in the RF and Microwave domains, FMCW ladar has been held back in the optical domain due to a lack of suitable tunable laser sources. Commercial tunable diode laser sources in the telecom bands allow multi-THz continuous frequency sweeps, which should in provide range resolutions on the ten micron scale, but in general are not sufficiently linear or stable to take advantage of the full resolution their bandwidth would provide. To achieve their potential resolution, ultra-wideband FMCW ladar systems generally require a reference delay or interferometer (usually fiber based) to provide a simultaneous calibration of the laser frequency sweep to compensate the nonlinearity of the chirp by providing triggering signals to the analog-to-digital converter (ADC)[2] or in post-processing of a regular time spaced samples[3].

The Spectrum Lab at Montana State University and Bridger Photonics Inc. have utilized the interferometric signal as an error signal for an active servo loop that applies electronic feedback to the laser frequency thereby actively stabilizing the frequency chirp of the laser[4]-[6]. By actively stabilizing the laser chirp, the range compression can be accomplished by a simple FFT of the time sampled heterodyne signal. This paper describes the techniques utilized for active stabilization of multi-THz chirps, the characterization of the resulting chirp linearity, and demonstrations utilizing the chirps for precision metrology applications.

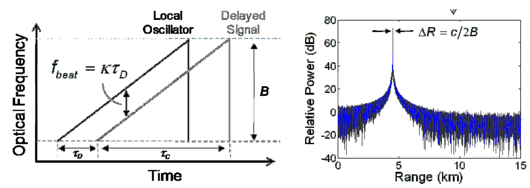

Figure 1. Conceptual diagram of the FMCW ladar technique using coherent demodulation on receive. The heterodyne detection allows the bandwidth requirements of the photodetector and backend electronics to be greatly reduced.

2. Chirp Stabilization

FMCW ladar utilizes swept frequency waveforms that when coupled with coherent detection yields a range dependent heterodyne signal or "beat note" of frequency , where is the round trip delay to the target and the chirp rate, — , is the derivative of the instantaneous optical frequency (see Figure 1). If the chirp rate is not constant (i.e. a nonlinear or unstable chirp) the frequency of the beat note will vary and the Fourier transform of the time domain data will not fully compress a point return to a single frequency and some method must be used to either compensate or stabilize the chirp .
To diagnose the chirp nonlinearities a fiber based interferometer in the Mach-Zehnder geometry is used as a reference. An acousto-

optic modulator is placed in one path of the interferometer to shift the interferometric signal away from DC allowing positive and negative shift frequencies (and thus positive or negative chirp rates) to be measured. The signal from the interferometer, whose frequency is proportional to the chirp rate, is than compared to a reference frequency that is chosen to correspond to the desired chirp rate. The phase comparison is performed with a digital phase detector (DPD), which has the feature of also determining the sign of the absolute phase difference. The output of the (DPD) is then filter and amplified with servo amplifiers which can apply feedback to multiple frequency actuators of the laser including laser diode current, cavity length, and the angle of the external grating.

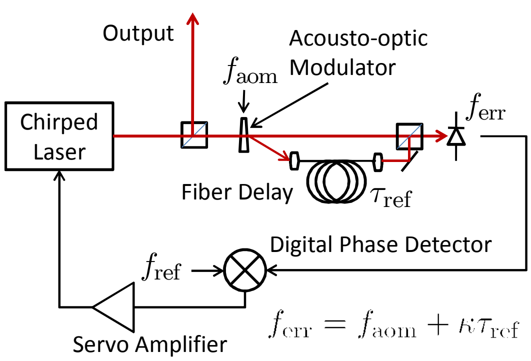

Figure 2. Schematic of the chirp stabilization method. A fiber based heterodyne interferometer generates a beat note proportional to the chirp rate, which is then compared and phase locked to a reference frequency using a digital phase detector and servo amplifier feeding back to multiple frequency actuators on the chirp laser.

Figure 2 shows the resulting improvement in the linearity of the chirp from a commercial external cavity diode laser (Thorlabs, PicoD) that is continuously tunable from 1520nm to 1620nm. In this case, a chirp of about 5 THz bandwidth at a chirp rate of 5 THz/s had about 600 MHz peak-to-peak variations from linearity before the active feedback was applied and after the variations were reduced to about 170 kHz rms. When used to perform a ranging measurement using no post processing or other compensation other than the active feedback system, the resulting range return off a single delay was reduced from a peak width of ~400 mm without stabilization to a nearly Fourier limited peak width of 47 µm with stabilization.

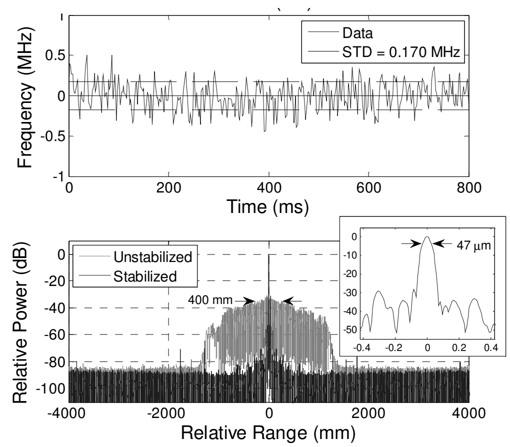

Figure 3.

Using this technique, Bridger Photonics Inc. and Montana State University have successfully stabilized multiple frequency swept lasers including MEM's based external cavity diode lasers (LUNA, Phoenix) and even standard telecom distributed feedback (DFB) lasers. The different types of lasers each have tradeoffs in terms of tuning bandwidth, tuning speed, power, and linewidth.

There are several advantages of this active stabilization technique over the techniques that use the reference interferometer either for post processed based compensation, or for triggering of ADC's. First, because the phase of the interferometric beat note is stabilized (not just the frequency) the feedback stabilizes instantaneous frequency of the laser not just the chirp rate. This has the effect of narrowing the linewidth of the laser, as demonstrated by locking the laser at a chirp rate of zero and comparing against a narrow linewidth single frequency fiber laser. It also has the effect of returning the FMCW signal power to the carrier, improving the pre-processed SNR of the detection (see Figure 3). Second, once the chirp laser has been stabilized, FMCW ladar measurements are simple and efficient requiring only a single channel ADC and a single FFT, with no other post-processing steps required. In addition, the post-processing algorithms or the triggering circuits do not have to be modified if one desires to change the center of the range window or the sample rate of the ADC. Third, the chirp stabilization does not preclude using the post processing compensation methods or the ADC triggering methods on top of the stabilized chirp laser. As with any active feedback technique limited feedback gain and bandwidth prevents the servo amplifier from completely suppressing all fluctuations, so further compensation can help.

3. Ultra-broadband Chirp Lasers for Metrology

The resolution of any time-of-flight ranging system is governed by the bandwidth of the transmitted waveforms as ΔR = c/2B, where ΔR is the range resolution defined in analogy to the spatial Rayleigh criterion as the ability to distinguish two point returns at the half power points, c is the speed of light, and B is the bandwidth. Range precision, defined as the minimum detectable change in range to a single point target, depends on the range resolution as a starting point but also depends on the signal-to-noise ratio (SNR) of the measurement. As SNR is highly specific to the measurement system, range resolution (or bandwidth) is the best metric to make apples-to-apples comparisons of different ranging techniques.

The multi-THz actively stabilized chirp lasers have great promise for precision ranging applications including metrology. By starting with a range resolution of only several tens of microns, an multi-THz FMCW metrology system only has to achieve an SNR of 20 dB to achieve ranging precisions of less 10 µm. This level of SNR should be achievable under most situations, including non-cooperative targets at moderate ranges. For cooperative (i.e. retro-reflective) targets our ranging demonstrations regularly show signals above the detection noise floor of 60 to 90 dB or more. This level of SNR has allowed the demonstration of range precisions as low as 2.8 nm (measurement of the spacing of two range peaks (front and back) of a 637 µm thick optically transparent wafer (see Figure 4)). In general, for measuring ranges in air the precisions are limited by atmospheric turbulence and average index of refraction fluctuations.

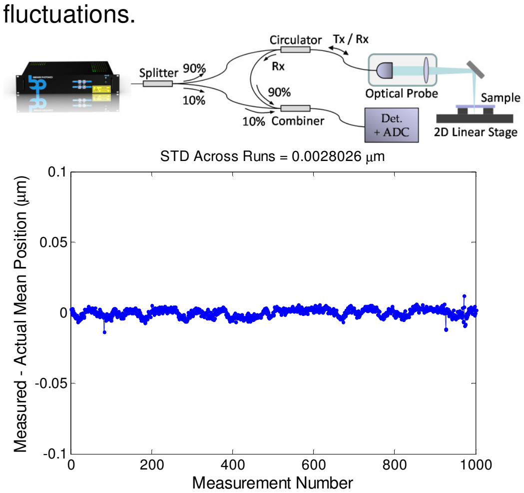

Figure 4. Series of thickness measurements of an optically transparent wafer of 637 µm mean thickness. The standard deviation of the measurements is 2.8 nm. The range resolution of the measurement system was 60 µm, and the return peak was about 70 dB above the noise floor.

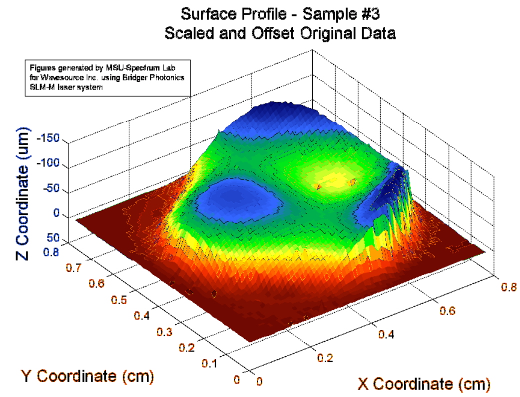

Figure 5. Surface profile of a complex surface machined into an optical flat by WaveSource Inc. The surface was measured by MSU using an actively stabilized laser built by Bridger Photonics. The surface has very large surface gradients approaching 50%.

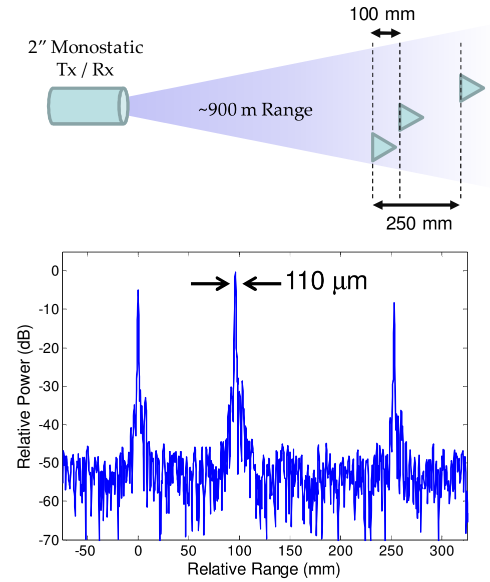

Figure 6. Demonstration of long range (900 m) FMCW precision ranging using the actively stabilized chirp laser with about 2 THz of bandwidth. The ranging system demonstrated a near Fourier (Hanning window) limited 110 µm range resolution at this range and can easily resolve the 10 cm spacings of the retro-reflectors.

In addition to achieving good range precisions, for metrology applications the measurements must be stable and traceable to the SI meter. To assure accuracy of the measurements of the FMCW ladar system the chirp rate must be well calibrated. We have demonstrated calibration accuracy on the part per million level can be obtained by calibrating the chirp rate to a molecular gas absorption references such as Acetylene and Hydrogen Cyanide, which is generally sufficient for metrology applications in air. For more accurate calibrations and characterization of the chirp, we performed comparisons of the ultra-wideband actively stabilized chirp laser against an accurate optical frequency comb at NIST in Boulder, CO. This characterization showed that after removing low order nonlinearities due to dispersion of the reference interferometer[7], the chirp laser showed a linearity of less than 60 kHz for a 5 THz sweep and a calibration of the chirp rate 1.5×10^{-8} fractionally[8].

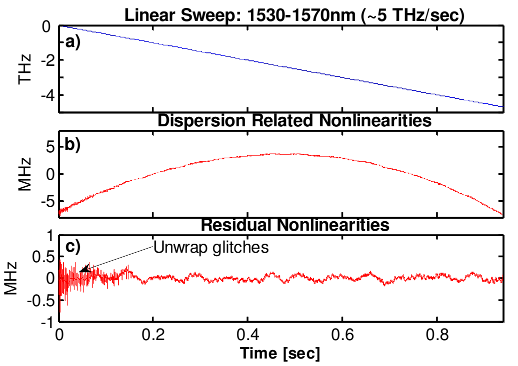

Figure 7. Calibration of fiber stabilized chirp laser against an accurate fiber based optical frequency comb [8].

3. Conclusions

FMCW ladar using actively stabilized chirp lasers has many advantages for precision ladar applications. Active stabilization of the linear frequency sweep allows one to access the unmatched range resolution (~50 µm) provided by multi-THz bandwidth tunable laser sources in the telecom region at long ranges, large range windows, and without the need for computationally expensive post-processing. The coherent detection technique also allows very large signal-to-noise and dynamic range, which aids in the determination of distances with precisions at a small fraction of a wavelength.

The resolution and precision of these new stabilized FMCW sources opens up new applications for ladar in area of precision length metrology. In addition, by removing the need for complicated post-processing FMCW ladar becomes more suitable for computationally hungry 2D and 3D imaging applications such as synthetic aperture imaging ladar.

Some of the disadvantages of this technique is the lack of long coherence length, broadband (> THz) and rapidly tunable (10^{14} chirp rates) laser sources. The lack of rapidly tunable sources makes the ranging system more susceptible to Doppler related shifts and vibrations. However, pairing the FMCW ladar system with a co-aligned CW interferometer to provide vibration compensation may be possible.

In this paper, we have described how multi-THz chirped lasers can be actively stabilized to stable fiber delay lines, and how those sources can be utilized for precision FMCW ladar and metrology.

4. Acknowledgements

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5. References

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