Dual-comb absolute distance measurement of non-cooperative targets with a single free-running mode-locked fiber laser

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We demonstrate dual-comb time-of-flight absolute distance measurement with a free-running dual-wavelength dual-comb mode-locked Er-fiber laser. An anodized aluminum plate with 1.6-μm RMS roughness that locates at a distance of ∼3.46 m serves as a scattering target. The echo has been collected non-coaxially with a 5-inch aperture telescope. The target time-of-flight is acquired by linear optical sampling, which relies on interference between the two combs with spectral overlap. We find that the wavelength of the overlapped spectra determines the fringe density of the interferograms, thus the accuracy of time-of-flight extraction algorithm. The ranging precision is ∼10 μm when the collected optical power is ∼1/5000 of that emitted from the launcher. By using Kalman filtering, an improved ranging precision of 225.7 nm has been obtained. The measurement has been conducted at a fixed update rate of 20 Hz, mainly limited by the real-time-based computer data processing speed. Additional measurements of fixed height steps assembled by standard gauge blocks and surface profiling applications have been demonstrated to verify the accuracy of the ranging system. The presented technique is promising for future dual-comb based high precision lidar and remote sensing applications.

0. Introduction

A pair of phase-locked optical frequency combs (mode-locked lasers) with slight comb-line spacing (repetition rate) difference constitutes a dual-comb setup. The multi-heterodyning interference between the two combs produce a radio frequency counterpart, allowing the acquisition of intensity and phase information encoded in the optical frequency combs by standard high-speed electronics. The dual-comb system has been firstly applied to molecular spectroscopy [1–10] by providing an enabling Fourier transform spectroscopic tool without mechanical delay line. It has opened up broad applications in many other fields, such as hyperspectral imaging [11,12], strain sensors [13,14], as well as absolute distance measurement (ADM) [15–22].

Dual-comb ranging does not require the adjustment of the repetition rate to align the reference pulses and target pulses that is essential for single comb ranging [23,24]. Dual-comb based absolute ranging utilizes linear optical sampling (LOS) or nonlinear asynchronous optical sampling that maps the periodic ultrafast echoes from target into a stretched time-scale where the pulse time-of-flight (TOF) can be determined straightforwardly. LOS generates the interferograms (IGMs) between the echoes and local pulses [17]. The distance is calculated by using the phase spectrum information of the IGMs or the envelopes of the IGMs [18–21]. The process of nonlinear asynchronous optical sampling relies on intensity cross-correlation implemented by sum-frequency generation (SFG) between the two combs [22]. The pulse TOF can be directly acquired from the peaks of optical cross-correlation trace and the coherence between the two combs is not essential. Both linear and nonlinear sampling methods allow distance measurement with ultra-high precision (<1 μm), high-update-rate (~kHz) and large-unambiguous range (~m), unattainable for conventional TOF laser ranging methods. As long as the precision of dual-comb absolute ranging precision reaches λ/4, the TOF ranging can be taken over by carrier wave interferometry and the precision can be further improved to nanometers [17,25].

The implementation of two optical frequency combs and the sophisticated phase-locking electronics is the major obstacle for practical applications of dual-comb ranging technique. In recent years, there has been a trend for using a single free-running mode-locked laser to generate two pulse trains with slightly different repetition rates [2, 26–33]. The methods of generating dual-comb in one cavity include transmission direction multiplexing [26–29], polarization multiplexing [30], and wavelength multiplexing [2,31–33]. Considering that

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the two pulse trains share one cavity, the technical fluctuations that may cause decoherence between the two combs are common-mode noise and effectively canceled. The ranging precision is fundamental limited by ASE noise which is quantum noise in nature and cannot be eliminated by sharing a single cavity [32]. More details on dual-comb generation from one single laser source and its spectroscopic applications could be found in a recent review [34].

Meanwhile, dual-comb technique has been recognized as a promising tool for lidar applications, enabling both range-resolved measurement and fine spectral characterization in remote sensing. As a prerequisite, the TOF measurement with non-cooperative targets is required. The range resolved vibrometry of diffuse surfaces has been performed, enabling recovery of sounds from various vibrating surfaces [35]. In a microresonator-based dual-comb ranging experiment, the trajectory of a moving gun projectile has been characterized [36]. In an electro-optic dual-comb ranging experiment, the surface topography of a 20 Euro-cent coin has been measured [37]. Those experiments conduct measurements at very high update rate. In a recent dual-comb hyperspectral lidar experiment, the target at ~20 m has been characterized. However, the TOF measurement still relies on direct photo-detection of echoes. The measurement resolution is limited to centimeters [11].

In this paper, we demonstrate dual-comb absolute ranging of a scattering target at a distance of ~3.46 m. A single free-running mode-locked Er-fiber laser with dual-wavelength outputs is used for dual-comb ranging. The laser pulses emitted by signal comb is directed to an anodized aluminum plate with 1.6-μm RMS roughness. The lidar echoes from the target is non-coaxially collected and mixed with local comb. The local comb has been spectral broadened so as to spectrally overlap with the signal pulse. Therefore, interferograms (IGMs) can be generated by LOS. The target TOF is retrieved from the peaks of the envelope of the IGMs. We find that the central wavelength of the overlapped spectra determines the fringe density of the IGMs, thus the accuracy of TOF extraction algorithm. At an optimized wavelength for LOS, we achieve distance measurement precision of ~10 μm without averaging at a 20 Hz update rate, which is limited by the speed of real-time computer data processing. This number can be dropped below 2 μm with 2 s averaging. While, this precision is improved to 225.7 nm without averaging [38–40]. The accuracy of the system has been validated by measuring standard gauge blocks, and the measurement residuals is within several micrometers. The range resolving capability of this method is also tested by profiling the surface of a gauge block and a test chart.

1. Principle

The principle of dual-comb LOS to acquire an IGM is shown in Fig. 1(a). The repetition rates of the signal pulses and local pulses are \( f_1 \) and \( f_2 \) respectively, with a slight offset. The corresponding time intervals are \( T_1 \) and \( T_2 \). The difference \( \Delta T \), between \( T_1 \) and \( T_2 \) causes local pulses to walk through signal pulses during each repetition period with a step of:

\[
\Delta T = T_1 - T_2 = \frac{1}{f_1} - \frac{1}{f_2} = \frac{\Delta f}{f_1f_2} \tag{1}
\]

where \( \Delta f \) is the repetition rate difference between \( f_1 \) and \( f_2 \). A full IGM between local pulses and signal pulses in stretched window is acquired every \( T_{update} \). As a result, the signal pulses are scaled up by a factor of \( N \):

\[
N = \frac{T_{update}}{\Delta T} = \frac{1}{f_1f_2} \frac{\Delta f}{\Delta f} = \frac{f_1}{\Delta f} \tag{2}
\]

In the distance measurement system, the signal pulses are separated into two parts. One part is reflected by target mirror and the other is reflected by reference mirror, contributing to target pulses and reference pulses, as shown in Fig. 1(b). The time delay of the target pulses and the reference pulses in stretched window is \( \Delta t \), and the actual distance \( L \) between the target and the reference can be expressed by:

\[
L = \frac{c}{2n_0} \cdot \Delta t = \frac{c}{2n_0} \cdot \frac{t_1 - t_2 + nT_{update}}{N} = \frac{c}{2n_0} \cdot \frac{(t_1 - t_2 + nT_{update})4f_1}{f_1} \tag{3}
\]

where \( c \) is the speed of light in vacuum, \( n_0 \) is group refractive index of air, \( t_1 \) and \( t_2 \) are the timing of the neighboring target pulse and reference pulse in stretched window. The integer “m” is the multiple of unambiguous range (NAR) which is about 3 m in our experiment. The NAR can be resolved by coarse measurements or Vernier effect [41]. Therefore, the distance between target and reference mirror can be readily calculated since \( f_1, \Delta t, n_0, \) and \( T_{update} \) can all be measured through fast data acquisition electronics.

2. Experimental setup

2.1. Free-running dual-comb fiber laser

The free-running dual-comb fiber laser in our system is based on a ring cavity configuration, as schematically shown in Fig. 2(a). Pump light from a 980-nm laser diode is coupled into the cavity by a 980/1550 WDM in clockwise direction. The ISO ensures the counterclockwise propagation of the pulses in the cavity. A fiber coupler couples out 30% optical power as laser output. A piece of CNT film sandwiched between two fiber connectors acts as the mode-locker. A FPBS, a segment of PMF and FBG serve as a Lyot spectral filter in the laser cavity. The spacing of the filter is set by \( \Delta \lambda = \lambda^2 / BL \) (23 nm in this case), where \( \lambda, B \) and \( L \) (0.25 m in this case) are central wavelength, birefringence and length of PMF, respectively. With this intra-cavity spectral filter, dual-wavelength mode-locking could be achieved by adjusting PC. The optical spectrum of the dual-wavelength laser has two peaks centered at \( \lambda_1 = 1555 \text{ nm} \) and \( \lambda_2 = 1532 \text{ nm} \), as blue curve in Fig. 2(b). To separate the two spectra, the pass band of the CWDM needs to be centered at \( \lambda_1 \) and \( \lambda_2 \). In the experiment, a standard CWDM has been used to separate the two pulse trains and the isolation easily reaches 40 dB. The repetition rates of the two pulse trains are \( f_{r1} = 50.566 \text{ MHz} \) and \( f_{r2} = 50.568 \text{ MHz} \), as shown in Fig. 2(c). This slightly repetition rate offset is attributed to the negative net cavity dispersion. The repetition rate offset is recorded by a frequency counter. \( f_{r1} \) and \( f_{r2} \) drift with the similar trend in a long-term and the standard deviation of repetition rate offset is about 0.14 Hz within 30 min, as shown in Fig. 2(d). Note that, long-term drift of \( \Delta f \) does not influence the measurement result. In this work, the target distance is measured based on Eq. (3), where \( T_{update} \) is related with repetition rate difference \( \Delta f \) by \( T_{update} = 1 / \Delta f \). \( T_{update} \) is directly measured by fast electronics. Accordingly, \( \Delta f \) is also updated from one measurement to the other. The average power of the two pulse trains are \( P_1 = 430 \text{ μW} \) and \( P_2 = 145 \text{ μW} \), respectively. In our distance measurement setup, one pulse train \( (f_{r1}, \lambda_1) \) is served as the signal pulse train and the other \( (f_{r2}, \lambda_2) \) is served as the local pulse train. Compared with two actively phase-locked mode-locked lasers, dual-comb mode-locked fiber laser benefit from its simpler setup.

2.2. Distance measurement

The experimental setup is shown in Fig. 3. The signal pulse train is amplified up to ~30 mW by the home-built EDFA1. Then the signal pulses’ spectrum is filtered out by an FBG centered at 1553 nm with 1.1 nm bandwidth. The local pulse train is amplified and spectral broadened by the home-built EDFA2 and then filtered by an identical FBG to overlap with the signal pulses’ optical spectrum.

In LOS, the interference signal should satisfy Nyquist sampling theorem to avoid aliasing [1,15]. The relationship between the Nyquist
frequency in radio frequency range and optical bandwidth could be calculated by:

$$|d\lambda| = \left| -\frac{\lambda}{c} \frac{d\nu}{d\lambda} \right|$$  (4)

The bandwidth of the down-sampled comb must not exceed $f_r/2 = 25$ MHz in our system, which corresponds to an optical spectral width of $\Delta\nu = N \cdot f_r/2 = 625$ GHz, thus a 5 nm bandwidth centered at 1550 nm. Our FBGs with 1.1 nm bandwidth satisfy the Nyquist sampling theorem. In addition, the central wavelength of FBG is crucial for ranging precision, which will be discussed in detail in Section 3.1.

The signal pulse train is separated by a 90/10 fiber coupler. 90% of the output serves as the seed for the EDFAs for target pulse train and 10% of the output serves as reference pulse train. To improve the SNR of the IGMs, the target pulse train is amplified up to 400 mW by two EDFAs (EDFA3, EDFA4). Here, EDFA4 uses Er/Yb co-doped fiber. A segment of 30-meter-long dispersion compensation fiber (Thorlabs, DCF38) is used to stretch signal pulses properly before the two EDFAs, to reduce nonlinearity in the EDFA. Target pulse train launched by FC1 is reflected by an anodized aluminum plate and collected by a SC telescope (5-in. in diameter, 12 in. in length and 1.2 m in focal length). The optical power collected by SC telescope is about 1/5000 of that emitted from the launcher, and about 85% is lost when coupled into FC2 because of the beam mode mismatch attributing to long free space path and unevenness of the aluminum plate’s surface. It is worth noting that the power of echoes results in the SNR of photon-electric conversion, which has impact on the ranging precision. To support high precision measurement, the tilt angle of the SC telescope should be adjusted properly. The optical power coupled into FC2 is about 12 µW. The SC telescope and the emitted target pulse train are non-coaxial, which is based on the following considerations: If they are coaxial, a small part of target pulse train will be reflected to the launcher directly by the surface of the SC telescope, resulting spurious signal in the IGMs whose

Fig. 1. The principle of dual-comb linear down-sampling to acquire IGMs: (a) the signal and local pulses have different pulse interval, therefore, one pulse train walks through the other linearly. An IGM is acquired after a full scan; (b) The schematic diagram of the distance measurement method. BS: beam splitter; PD: photodetector; R: reference mirror; T: target mirror.

Fig. 2. Free-running dual-comb fiber laser: (a) setup of the laser oscillator; (b) the optical spectrum of the oscillator, the peaks of the wavelengths are $\lambda_1 = 1555$ nm and $\lambda_2 = 1532$ nm; (c) the RF spectrum of $f_1$ and $f_2$; (d) the stability of the $\Delta f$. CNT: carbon nanotube; CWDM: coarse wavelength division multiplexer; EDF: Erbium-doped optical fiber; FPBS: fiber polarization beam splitter; ISO: fiber isolator; OC: optical coupler; PC: fiber polarization controller; PMF: polarization maintaining fiber; WDM: wavelength division multiplexer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
power is even higher than the saturation threshold of our detectors. As a result, it will be hard to be distinguished from the target pulses.

Reference pulse train is separated by a 50/50 fiber coupler. 50% is detected by a PD and recorded by a frequency counter, generating sampling clock for data sampling. Another 50% is combined with target pulse train. The target and reference pulse trains are combined with the local pulse train via a 2x2 optical coupler, and detected by a BPD. As a result, the common-mode intensity fluctuations from the setup is suppressed e.g. intensity noise of laser, beam pointing changes at telescope, etc. To ensure the same polarization state among target, reference and local pulses, a HWP, PC1 and PC2 are used to adjust polarization state. In addition, two VOAs are added in reference optical path and local optical path in order to avoid the saturation of BPD. After an LPF, the interference signal is sampled by a digitizer (PXIe-5122, National Instruments). The data processing will be described in Section 3.1 and Section 3.2.

3. The experimental results and discussion

3.1. IGM processing

Fig. 4(a) shows two pairs of IGMs acquired by the digitizer. $I_r$ is interferometric pattern between reference and local pulses. $I_t$ is interferometric pattern between target and local pulses. We note that the shape of the envelope of $I_r$ is close to Gaussian in Fig. 4(b). The peaks on the left side of $I_r$ are not IGMs. A voltage threshold has been added in IGM extraction algorithm so as to remove these peaks since their amplitudes are typically much lower than IGMs.

The ranging precision highly relies on the shape and the fringe of the IGMs. According to [42], the IGMs can be optimized by tuning $\Delta f_r$ of the two mode-locked lasers. However, this is challenging for a single dual-comb mode-locked laser (For the change of $\Delta f_r$, the adjustment of the birefringence in the laser cavity will be needed). Alternatively, we find that the IGMs can be optimized by adjusting the overlapped wavelength of the spectra from the two combs. We validate this approach by both numerical simulation and experiment, as follows.

Fig. 5 shows the results of numerical simulation. Here, we utilized a Gaussian shaped filtering function with adjustable central wavelength $\lambda_c$ to filter out certain spectra from the two combs, and investigate on the impact of $\lambda_c$ on IGMs. The upper and lower of Fig. 5(a) shows the two combs with slightly different comb-line spacing, respectively. The dashed Gaussian curve illustrates the filtering function. Four bandpass filtering windows with the same frequency interval have been selected between 1555 nm and 1549.83 nm, each has 1 nm bandwidth. The
corresponding four down converted RF spectral bands after LOS have been depicted in Fig. 5(b). The central frequency of these RF spectral bands increases from 0 Hz to \( f_r/2 \), and the highest density has been acquired at \( \lambda_c = 1549.83 \text{ nm} \). Once the down sampled comb overlaps with DC or Nyquist frequency \( f_r/2 \), the information of the interferogram will be partly discarded, resulting in interferogram distortion and low ranging accuracy. Therefore, we adjust the center wavelength of the filter carefully to make the entire down sampled comb locate at baseband (from DC to Nyquist frequency) for achieving the best ranging performance.

In experiment, we utilize fiber Bragg gratings (FBG) to generate the filtering function. Two identical FBGs has been used to filter out the same part of spectrum from the two combs for LOS. We characterized IGMs by utilizing FBGs with different central wavelengths \( \lambda_c \) in experiment. The bandwidth of each FBG is 1.1 nm. As shown in Fig. 6, there are three IGMs corresponding to different \( \lambda_c \) of the FBGs. While, only the envelope of the IGM of \( \lambda_c = 1553 \text{ nm} \) can guarantee high ranging accuracy. The reason is that, in the RF domain, the down sampled comb is located between DC and \( f_r/2 \) and does not overlap with either DC or Nyquist frequency for \( \lambda_c = 1553 \text{ nm} \). Note that the suitable filtering central wavelength changes with \( \Delta f_{CEO} \) between two combs. Therefore, a tunable FBG is preferred in practice.

3.2. Extraction of the envelope of the IGM

The TOF information is encoded in carriers and envelopes of the IGMs. We can measure the distance between target and reference either by calculating the time delay \( \Delta t \) between \( I_t \) and \( I_r \) [18], or by solving the beat frequency phase [19,20]. In our system we use \( \Delta t \) to calculate the distance. The olive-green line in Fig. 7(a) is the original IGM we acquired and the red dotted line is the Hilbert transform signal of the original interference data. In frequency domain, the Hilbert transform is equivalent to a \( \pi/2 \) phase shifting system, which is the imaginary part of the original data. The modulus is calculated from the square root of the sum of the squares of the real and imaginary parts, which is exactly the envelope of the IGM, as the orange line shown in Fig. 7(b). To extract the peak of the envelope more accurately, we use Gaussian fitting (blue line) to fit the envelope. Then the timing information of \( I_t \) and \( I_r \) can be retrieved. The distance between the target and the reference can be calculated by Eq. (3).

3.3. Experimental result

Fig. 8 shows the result of non-cooperative distance measurement. The target is a stationary anodized aluminum plate with 1.6-\( \mu \text{m} \) RMS roughness. We measure the distance between the target and the reference continuously for 100 s. The collected echoes are processed in real time. Although the IGMs are updated at \( \Delta f_r \) of \( \sim 2 \text{ kHz} \), the actual measurement updated rate is limited to 20 Hz given that the algorithm for retrieving TOF costs \( \sim 0.05 \text{ s} \). As shown in the blue curve in Fig. 8(a), the average distance between the aluminum plate and the reference is \( \sim 3.46 \text{ m} \). Due to the low reception efficiency, the distance measurement suffers from low IGM SNR. Thermal noise of photodetector plays a major role in the measurement result. Here, we use Kalman filter (KF) to smooth the large jitter of the ranging data [38–40]. Considering a stationary target object, the state update equation is \( \hat{x}_{n,t} = \hat{x}_{n-1,t} + K_n (z_n - \hat{x}_{n-1,t}) \) and the state extrapolation equation can be described as \( \hat{x}_{n+1,t} = \hat{x}_{n,t} \). For noises with known statistical properties, KF is effective, which estimate the real distance by allocating proper weights to real time measurements and estimates from past results . The ranging data after KF is shown as the red curve in Fig. 8(a). The slow drift of the measurement result may be attributed to temperature change.
Fig. 6. Different fringe density of the IGMs caused by FBGs with different $\lambda_c$.

Fig. 7. (a) Original IGM (olive green line), Hilbert signal of the IGM (red dotted line); (b) the envelope of the IGM (orange line) and Gaussian fitting signal of the envelope (blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. (a) Original ranging data points in 100 s (blue line) and ranging data with Kalman filtering (KF, red line); (b) Allan deviation of ranging data.

The measurement precision is evaluated by Allan deviation, as shown in Fig. 8(b). The Allan deviation of the ranging data without KF (blue curve) and the ranging data with KF (orange curve) are both depicted. The measurement precision is $\sim$10 $\mu$m without averaging and this number will drop below 2 $\mu$m with 2 s averaging. The decreasing of Allan deviation indicates the white noise predominant the ranging results. When the integral time exceeds 10 s, the Allan deviation increases because of the impact of environmental factors, which has not been calibrated in this experiment. While, a measurement precision of 225.7 nm can be acquired without averaging by using KF. Therefore, the high update rate can be maintained. By analyzing the slope of the Allan deviation, we found that the predominant white noise has been filtered out by Kalman filter. In this case, the impact of $f_1$ drift ($<1$ s) is visible since the repetition rate is updated once per second, while the relatively flat slope between 1 s and 6 s indicates a 1/f noise process.
A set of assembled standard gauge blocks are used as a ruler to verify the accuracy of this ranging system. Fig. 9 is the 3-D figure of the assembled gauge blocks. In top view of the 3-D figure, there are three gauge blocks (test gauge blocks) tightly attached to a lying gauge block (reference gauge block) by Van der Waals' force and magnetic force from two magnets, and the thicknesses of the test gauge blocks are 5 mm, 3 mm and 1 mm. Their widths are all 10 mm. Given that the length of the reference gauge block is 35 mm, 5 mm width of the polished surface of the reference gauge block remains unattached. The four polished surfaces constitute 3 steps with height of 1 mm, 3 mm, and 5 mm. By translating the gauge blocks in a direction perpendicular to laser propagation, the four surfaces have been scanned in sequence, and the height of the 3 steps can be measured by dual-comb ranger. Fig. 10 shows the measured step heights versus true date and the measurement residuals. Each measured step height is an averaged result from 100 ranging data. The measurement residuals are within 5.5 μm for the 3 steps.

A 3D surface profilometry experiment is further conducted so as to demonstrate the versatility of the above absolute ranging technology. A USAF 1951 test chart (negative type) and a gauge block with laser printed symbols are used as samples under test. The output at EDFA3 in Fig. 3 has been directly focused on these samples, which are put on a 3-axis stage. The echo laser pulses have been collected coaxially for distance measurement. The surface profile can be retrieved from measured displacements by linearly scanning the stage in a plane perpendicular to laser propagation. Fig. 11 shows the surface profilometry for the test chart, which is a 3-mm thick glass plate with chrome plated on both top and bottom surfaces. The stage step size is 50 μm, which sets the lateral resolution. The surface of the gauge block which contains laser printed symbols is measured in the following. One laser printed
character is measured, as shown in Fig. 12. The measurement shows that the average depth of the engraved lines is 7.58 μm.

4. Conclusion

In this work, we achieved dual-comb absolute distance measurement of a remote non-cooperative target with a single free-running mode-locked Er-laser. Signal comb with 400 mW average power has been directed to a stationary anodized aluminum plate with 1.6-μm RMS roughness at ∼3.46 m distance and the echoes have been collected non-coaxially with a 5-in. aperture telescope. About ∼12 μW of echo power has been coupled to a piece of single mode fiber after the telescope and is combined with the local comb. The slight difference in repetition rate of the local comb enables LOS, making possible the retrieval of target TOF with high precision. The measurement precision in repetition rate of the local comb enables LOS, making possible the telescope and is combined with the local comb. The slight difference in repetition rate of the local comb enables LOS, making possible the retrieval of target TOF with high precision. The measurement precision is ∼10 μm without averaging at an update rate of 20 Hz and will drop below 2 μm with 2 s averaging. This number can be dropped to 225.7 nm by using KF without the loss of update rate.

We also provide a new approach towards measurement precision optimization in dual-comb absolute ranging based on LOS. Specifically, we find that the central wavelength of the overlapped spectra from the two combs determines the fringe density of the IGMs acquired by LOS, thus the accuracy for TOF acquisition algorithm. Therefore, dual-comb ranging precision can be optimized by simply filtering out proper overlapped spectral elements with extracavity FBGs.

Finally, we conduct a surface profilometry experiment of the USAF 1951 test chart and the laser printed numbers on the surface of stainless gauge block. Engraved structures with several micrometer depth have been well resolved.

This work is promising for high precision lidar applications while the performance can be further improved following the directions below. Firstly, balanced avalanche photodetectors (APD) can be used to improve the sensitivity of the ranging system. Combined with high power EDFA, non-cooperative targets at kilometer range can be measured. Secondly, the ranging update rate can be increased to 2 kHz ($\Delta f_c$) as long as high-speed data processing units (such as FPGA) are used, enabling real-time measurements of moving targets. Finally, direct fast Fourier transform (FFT) for the IGMs provides the absorptive spectral information along the laser propagation path, simultaneous high precision absolute ranging and spectroscopy with a simple apparatus is expected.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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