Single-shot ranging and velocimetry far beyond the coherence length of CW lasers

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Single-shot ranging and velocimetry far beyond the coherence length of CW lasers

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Abstract

The spectral linewidth of the continuous-wave (CW) lasers is one of the key limitations on the coherent lidar systems, which defines the maximum detection range. Furthermore, precise phase or frequency sweeping requirements is a deterrent in many applications. Here, we present the Phase-Based Multi-Tone Continuous Wave (PB-MTCW) lidar measurement technique that eliminates the necessity of using high coherence laser sources as well as any form of phase or frequency sweeping while employing coherent detection. In particular, we modulate a CW laser source with multiple radio-frequency (RF) tones to generate optical sidebands. Then we utilize the relative phase variations between the sidebands that are free from laser phase noises to calculate the target distance via post-processing and triangulation algorithms. We prove that the PB-MTCW technique is capable of performing single-shot ranging and velocimetry measurements at more than $500 \times$ the coherence length of a CW laser in a benchtop experimental demonstration.

Introduction

Digital cameras, Radars, and lidars (light detection and ranging) are considered to be three enabling technologies in autonomous terrestrial and aerial vehicles\textsuperscript{1,2}. Lidars, the optical version of Radars, operate by generating a point cloud of the environment based on the information encoded in the echoed light. The emerging needs of high resolution ranging and imaging in the areas such as terrestrial altimetry fueled the interest in lidar systems\textsuperscript{3,4}. Lidars perform ranging by either measuring the time-of-flight (ToF) of a laser pulse traveling from laser source to a target and back to a photodetector, or by generating the so-called radio frequency beat tones through the interference of reference light and the reflected light from a target by using continuous wave (CW) laser and a coherent detection system\textsuperscript{5-9}. The conventional ToF lidars provide a robust ranging methodology by using high peak power laser impulses. However, velocity information of a target-
in-motion can only be mined through a comparison of consecutive frames, which is in practice prone to errors due to interference and the movement of the target\textsuperscript{10,11}.

Alternatively, coherent detection facilitates simultaneous ranging and velocimetry by exploiting the Doppler effect\textsuperscript{12–14}. One of the most popular coherent detection techniques is the frequency-modulated continuous-wave (FMCW) lidar. In this approach, a linearly chirped or frequency-swept laser beam is transmitted to the target. The back-reflected signal interferes with a fraction of the swept laser source that acts as the reference beam and generates a radio frequency beating tone at the photodetector. The frequency of the tone corresponds to the difference between the instantaneous frequencies of the reference and the collected signal at the time of the interference measurement\textsuperscript{15–18}. The relationship between the beating frequency ($f_B$), propagation time ($\Delta t$), bandwidth ($B$), and sweep period ($T$) yields the range information by 

\[
f_B = \frac{\Delta t \times 2B}{T},
\]

while the encoded Doppler shifts in the resultant frequencies provide the velocity information. In terms of sensitivity and resolution, FMCW lidar is advantageous compared to the ToF alternatives due to the difference in photon flux levels\textsuperscript{19}. Adversely, the maximum measurable distance is not solely limited by the power of the source, but by the quality of the laser. In other words, the optical linewidth ($\Delta f$) of the CW laser integrated with the FMCW lidar dictates the coherence length of the light as $L_{coh} = c / \pi \Delta f$, where $c$ is the vacuum velocity of light\textsuperscript{20}. The lidar operation beyond the coherence length of the laser can result in degradation of the signal quality and yields an error in the measurements\textsuperscript{19,21}. The narrow-linewidth lasers are a solution for the coherence, but the cost of such lasers is a concern for the commercialization of FMCW lidars. Similarly, fast and linear frequency sweeping requirements exhibit another challenge in terms of electronics for the FMCW lidar along with the temporal coherence of the laser\textsuperscript{6}. 

\[\text{ft B T} = \text{D} \pm \text{coh L} \pm \text{p} \pm 2,\]
**Concept of Phase-Based Multi-Tone Continuous Wave Lidar**

Previously, Multi-Tone Continuous Wave (MTCW) lidar relying on the phase and amplitude variations has been studied for single-shot ranging and velocimetry\(^{22-24}\). In those experiments, we have used amplitude variations due to constructive or destructive interferences at selected RF tones generated by free-running RF sources for ranging. Similarly, instead of amplitude variations, we have also utilized the phase variations in the RF tones to perform ranging. The experimental setup and relevant algorithms in phase measurements use a fraction of the modulated source laser as a reference to facilitate extraction of absolute phases of individual RF tones, which includes the phase variations in the reference and the phase of the echo signal, to extract valuable ranging information. Such an approach, similar to FMCW lidar suffers from coherence length limitations.

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**Fig. 1 | Working principle of the Phase-Based Multi-Tone Continuous Wave Lidar.**

**a.** The electric field spectrum of the laser after modulation with \(\omega_1, \omega_2, \omega_3, \ldots, \omega_N\) frequencies by a Mach-Zehnder modulator (MZM) before leaving the collimator. Each tone has an initial phase of \(\phi_0\) before ranging.

**b.** The resultant photocurrent (\(I_{pd}\)) spectra acquired after collection of the echo light.

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\[ E(\omega) = \phi_0, \phi_0, \phi_0, \phi_0, \ldots \]

\[ I_{pd}(\omega) = \phi_1, \phi_2, \phi_3, \phi_N, \ldots \]

\[ I_{pd}(\omega) = \phi_1^-, \phi_2^-, \phi_3^-, \phi_N^-, \ldots \]

---

**b.** The resultant photocurrent (\(I_{pd}\)) spectra acquired after collection of the echo light.
from a stationary tree and a car in-motion with a velocity (v), respectively. The tones accumulate different phases of $\phi_1, \phi_2, \phi_3, \ldots \phi_N$ with respect to the target distance $L_{ij}$. In the case of the car, the optical carrier and the sidebands realize a Doppler frequency shift of $\omega_d$. $\phi$ represents the acquired phases of each Doppler-shifted modulation. c. Schematic design of the proposed PB-MTCW lidar. A continuous-wave laser is split into two through a fused fiber coupler with a coupling coefficient of $\beta$. All the fibers are polarization-maintaining (PMF) to inhibit potential polarization mismatches. The measurement branch of the system is further modulated by an MZM with multiple RF tones generated by phase-locked RF synthesizers operating with a common clock. The modulated light is then fed to a circulator that is followed by a collimator for both transmission and reception. The collected light is sent to a second coupler for heterodyning with the local oscillator branch, which is further connected to a high-speed photodetector. d. The flowchart of the signal processing starts with the interpolation of the time-domain data. Each modulation tone or shifted peaks are filtered out for post-processing. If $\omega_d \neq 0$, the target speed is computed, then the individual tone phases are generated. Using the phase difference between the tones, the initial target distance ($L_{ij}$) is computed, which is followed by the triangulation of the actual target distance with multiple $L_{ij}$ to achieve ranging.

We hypothesize that if we use a fraction of the source laser before encoding the RF tones at the amplitude modulator, and use proper algorithms in a new experimental setup, we can come up with a solution that removes the common noise terms and impact of coherence length limitations. In this technique, which we call it Phase-Based Multi-Tone Continuous Wave lidar (PB-MTCW), instead of employing any form of frequency, phase, or amplitude sweeping, we modulate a CW laser with multiple phase-locked radio-frequency (RF) tones to generate stable sidebands using a Mach-Zehnder modulator (MZM) under a linear modulation configuration. Then we utilize the phases of individual tones that are encoded in the echo signal after heterodyning with the unmodulated local oscillator as demonstrated in Fig. 1c. Since the absolute value of the phase differences between the reference, i.e. local oscillator, and the echo signal are impaired due beyond the coherence length of the laser, we utilize the phase differences between RF tones that are free from common noise terms. The phase difference of the individual sidebands reveals the target distance, while the acquired Doppler shift produces the target velocity, simultaneously. Here, we present theoretical and experimental proof of single-shot ranging and velocimetry measurements at more than 500× (limited by the experimental setup) the coherence length of the laser. Experimental results show that there is a negligible difference in measurements performed by a highly coherent laser and low coherence laser. Hence, the novel experimental system and
signal processing algorithms presented here paves the way for lidar measurements beyond the existing capabilities of the current phase-based lidar technologies.

To give a brief theory of the proposed concept let’s assume that an amplitude-modulated CW laser source emits a light toward the target with an electric field profile of

\[ E_{\text{in}} = A_0 \sqrt{2} \sqrt{1-\beta} \left[ \exp(j\omega_0 t + j\phi_0(t)) - \frac{m}{4} \sum_{i=1}^{N} \left( \exp[j(\omega_i + \alpha_i) t + j(\phi_i + \phi_{RF}^i) + j\phi_i(t)] + \exp[j(\omega_i - \alpha_i) t + j(\phi_i - \phi_{RF}^i) - j\phi_i(t)] \right) \right] \]

as illustrated in Fig. 1a. The \( \omega_0 \) and \( \omega_i \) indicate the angular frequency of carrier and \( i^{th} \) tone among a total of \( N \) tones, respectively, and \( \phi_{RF}^i \) is the initial phase of the corresponding RF modulation, which is locked to a fixed value for all tones. \( A_0 \) is the field amplitude of light, \( m \) represents the modulation depth, \( \beta \) is the coupling coefficient of the fiber coupler, \( \alpha_f \) depicts the fiber loss. The reflected signal from a target that is \( L_m \) meters away will be Doppler shifted if the target is nonstationary. The current generated at the photodetector after the interference of the echoed signal and the reference signal (unmodulated source laser) can be expressed as

\[
I_{\text{pd}} = R\beta A_0^2 \alpha_f^2 \cos\left(\omega_0 t + \frac{2L_m}{c} \omega_0 + \frac{L_m}{c} \omega_0 + \Phi(t, \tau)\right) + \frac{Rm(1-\beta)A_0^2 \alpha_f^2}{16} \sum_{i=1}^{N} \cos\left(\omega_i t + \frac{2L_m}{c} \omega_i + \phi_{RF}^i + \Phi(t, \tau)\right) + \frac{Rm(1-\beta)A_0^2 \alpha_f^2}{16} \sum_{i=1}^{N} \cos\left(\omega_i t + \frac{4L_m}{c} \omega_i\right) - \frac{Rm(1-\beta)A_0^2 \alpha_f^2}{2\sqrt{2}} \sum_{i=1}^{N} \cos\left(\omega_i + \omega_0\right) + \frac{2L_m}{c} \left(\omega_i + \omega_0\right) + \frac{L_m}{c} \omega_0 + \Phi_{RF} + \Phi(t, \tau)\right) \]

The optical carrier will experience a Doppler frequency shift \( (\omega_d) \) that is proportional to the velocity of the target \( (v) \) by \( \omega_d = (2v/c)\omega_0 \) as indicated in Fig. 1b. Here, \( R \) is the responsivity of the detector and \( \alpha_m \) represents the scattering loss. The phase noise of the CW laser before and after a travel time \( \tau = 2L_m / c \) are \( \phi_0(t) \) and \( \phi_0(t-\tau) \). Therefore the phase difference due to laser phase
noise can be represented as $\Phi(t, \tau) = \phi_n(t) - \phi_n(t - \tau)^{25}$. If the target is static, the resultant $I_{pd}$ equation will be

$$I_{pd} = Rm^2 \alpha_i \alpha_j \gamma \beta (1 - \beta) + \frac{3Rm^2 \alpha_i \alpha_j \gamma \beta (1 - \beta)}{16} \sum_{i=1}^{N} \cos(\omega_i + (\omega_b + \omega_i) \frac{2L_m}{c} + \phi^{RF} + \Phi(t, \tau)) + \sum_{i=1}^{N} \cos(\omega_i - (\omega_b - \omega_i) \frac{2L_m}{c} - \phi^{RF} - \Phi(t, \tau))$$

$$+ \frac{Rm^2 \alpha_i \alpha_j \gamma \beta (1 - \beta)}{8} \sum_{i=1}^{N} \cos(\omega_i + \omega_i \frac{2L_m}{c} + \phi^{RF}) + \sum_{i=1}^{N} \cos(\omega_i + \omega_i \frac{2L_m}{c} - \phi^{RF})$$

$$+ \frac{Rm^2 \alpha_i \alpha_j \gamma \beta (1 - \beta)}{8} \sum_{i=1}^{N} \cos(2\omega_i + \omega_i \frac{4L_m}{c})$$

(2)

Our goal is to develop an algorithm that can calculate the phase and frequency information independent of common noise terms, and then extract the velocity and range of the target. In the case of dynamic targets, $A_i \cos\left((\omega_i \pm \omega_j) t \pm \frac{2L_m}{c} (\omega_o \pm \omega_d) \pm \frac{L_m}{c} \omega_d \pm \phi^{RF} \pm \Phi(t, \tau)\right)$ can be used to define a single tone. As is clearly seen from this definition, a frequency shift in the carrier frequency or any tone frequencies reveals the Doppler shift, and hence the velocity of the target$^{23,24}$. However, range information is stored in the phase term and it is mixed with noise terms. To eliminate the common noise terms we mix two of these individual tones at $\omega_i$ and $\omega_j$ ($i \neq j$), either electronically or in the digital domain, the resultant intermediate frequency (IF) tone will be $A_i A_j \cos(\Delta \omega_{i,j} t \pm \Delta \phi_{i,j})$, where $\Delta \phi_{i,j}$, and $\Delta \omega_{i,j}$ are the phase and frequency differences of $i$th and $j$th tones, respectively. As a result, the common phase and frequency terms related to the optical carrier and the Doppler shift are eliminated with inter-tonal mixing that also eliminates the impact of the coherence length of the laser. Similarly, we can use RF mixing of carrier frequencies of a static target with individual tones defined as $2A_i \cos\left(\frac{2L_m}{c} \omega_b + \phi^{RF} + \Phi(t, \tau)\right) \cos(\omega_i t + \frac{2L_m}{c} \omega_i)$, to eliminate common noise terms. After the RF mixing, the phase of IF tones will be free from phase and the amplitude noise of the source and reveal only the range information of the target.
where \( n \) is an integer. As a result, PB-MTCW lidar methodology is immune to the phase variations induced by the laser phase noise, and hence it is possible to perform ranging beyond the coherence length of the laser.

The modulo-2\( \pi \) cyclic behavior of phase will lead to a periodic range estimation. Similar to global positioning systems that use multiple satellites to triangulate the exact position, we need redundancy of multiple agents for accurate range information. Here, we use multiple RF tones to pinpoint the value of \( L_m \) by using a triangulation algorithm. In particular, for a given \( \Delta \phi_{i,j} \), which corresponds to \( \Delta \omega_{i,j} \) the total length will be \( L_m = nL^{i,j} + L^{i,j}_0 \), where the spatial period is \( L^{i,j} = 2\pi c / \Delta \omega_{i,j} \) and the residual length is \( L^{i,j}_0 = c \Delta \phi_{i,j} / \Delta \omega_{i,j} \). If the integer value of \( n \) is swept, the potential \( L_m \) values can be computed for each \( \Delta \omega_{i,j} \). After concatenating all the possible combinations of \( L_m \) into a data matrix \( M_{k,l} \), where \( k \) is equal to the predefined sweep limit (\( n_{max} \)) that is set according to the maximum expected range, and \( l \) is the number of available \( \Delta \omega_{i,j} \) combinations. The standard deviation of each row is calculated as \( \sigma_k = \sqrt{\sum_{l=1}^{l_{max}} (M_{k,l} - \bar{M}_k)^2 / l_{max}} \), where \( \bar{M}_k \), the mean of the \( k \)th row, which yields the minimum \( \sigma_k \) corresponds to the actual target distance \( L_m \) as depicted in Fig. 1d. However, the minimum \( \sigma \) repeats itself at every \( L_{rep} = 2\pi c / \omega_{gcd} \), where \( \omega_{gcd} \) stands for the greatest common divisor of the \( \Delta \omega_{i,j} \), such phenomenon is called an unambiguity length in lidar systems. One way of avoiding recursive solution or unambiguity length is the selection of the tones in a fashion to make sure \( L_{rep} \) is longer than the maximum expected range. For extremely long measurement lengths, instead of using very low-frequency modulation tones to increase \( L_{rep} \), an introduction of a quasi-CW pulsation will be more advantageous. Not only that such a quasi-CW approach facilitates time gating to generate coarse
range information without unambiguity length limitation, but also results in higher signal-to-noise ratio measurements compared to an equal power pure CW approach.

**Experimental verification**

To prove the proposed concept two separate sets of experimental measurements on dynamic and static targets are performed. In particular, we conducted ranging and velocimetry measurements on the dynamic target and only the ranging measurements on the static target. Both experiments are performed by using a highly coherent laser with 100kHz linewidth and about 1km corresponding coherence length, and a low coherence laser with 5.3GHz linewidth and about 1.8cm corresponding coherence length. In both cases, we use a reflector as a target that is placed on a motorized translational stage with a maximum speed of 11cm/s in motion. In each experiment, the effective optical path difference between the reference signal and the measurement arm is about 9m, where about 2m of this path difference is in free space and the rest is in fiber. While this path difference is about $100\times$ smaller than the coherence length of the first laser, it is about $500\times$ larger than the coherence length of the second laser. In existing CW lidars, the second laser should not work at such path difference. 10 consecutive measurements are performed to verify results for each set. The further details of the experimental parameters are listed in the Methods Section.

In the case of the dynamic target, FFT is performed after data acquisition and the resultant RF spectra were scanned with the algorithm to acquire the Doppler frequencies and the instantaneous target speed as demonstrated in Fig. 2b and Fig. 2c for high and low coherence lasers, respectively. The measured Doppler shifts vary between 177.5kHz – 212.5kHz that yields a target speed between 9.12cm/s – 11.3cm/s. This matches the specifications of the motor operating on the stage. The difference is attributed to the fact that the electrical motor accelerates and decelerates very rapidly due to the limited stage length, thus the reflector speed varies. The
velocimetry resolution is associated with the frequency resolution \((d\omega)\) of the RF spectrum, which can be formalized as \(\Delta v = \left(\pm d\omega / \omega_0\right)c\). In this experiment, the achieved velocity resolution is \(~0.53\text{cm/s}\) due to the 5kHz frequency resolution.

The range triangulations of the moving target by using high and low coherence lasers are illustrated in Fig. 2d and Fig. 2e, respectively. The measurements are performed while the target is moving around a distance that is about 1m away from the beamsplitter, which is also indicated as \(L_2\) (1.03m) in Fig. 2a. Data are captured by using a manual trigger, and hence there is a slight variation in the actual range of the target at each measurement. Among 10 trials with a high coherence laser, range measurements vary between 0.92m and 1.02m. Similar measurements with a low coherence laser yield a range measurement that changes between 0.97m to 1.08m. The ranging resolution is proportional to the time resolution of the system that is computed as \(~1\text{cm}\) after interpolation. On the other hand, along with the global minimum, several local minima points appears in the calculation. The response of the triangulation algorithm will be improved by increasing the number of phase-locked RF modulation frequencies, and hence these local minimas will disappear.

In the case of stationary target ranging, the reflector is placed at three different locations as \(L_1\sim83\text{cm}\), \(L_2\sim103\text{cm}\), and \(L_3\sim121\text{cm}\) as illustrated in Fig. 2a. As a sanity check, the coarse measurements of the target distances from the output facet of the BS are performed by using a measuring tape with an estimated accuracy of \(\pm1\text{cm}\). The ranging measurements while the target is placed at \(L_2\) with a high coherence laser source are presented in Fig. 3a. The mean value of the measured target distance for \(L_1\), \(L_2\), and \(L_3\) are 83.13cm, 102.64cm, and 120.44cm, respectively. Hence, the displacements between \(L_1\)-\(L_2\) and \(L_2\)-\(L_3\) are measured as 19.51cm and 17.81cm. The
resultant standard deviations for each set of data are <1cm, which verifies the ranging accuracy of the PB-MTCW methodology.

Fig. 2 | Dynamic target ranging results with high and low coherence lasers. a. Schematic representation of the experimental test bench. First, a 1064nm CW laser with <100kHz linewidth (Lcoh~1km), then another 1064nm CW laser with 20pm linewidth (Lcoh~18mm) is used to demonstrate ranging further than the laser coherence length. The source is followed by a fiber isolator (ISO), which is connected to a 1x2 fiber coupler to realize the unmodulated local oscillator. The measurement branch is modulated through an MZM with 3RF tones via phase-locked RF synthesizers that are triggered by a clock generator, which also triggers the digitizer. The outputs of both branches are connected to two separate collimators (CL). A free-space optical beamsplitter (BS) is placed in front of both CLs to realize beating after collection on the photodetector (PD). The motorized stage carrying the target reflector is anchored 83cm away from the output facet of the BS. Three measurement distances are L1~83cm, L2~103cm, and L3~121cm for stationary target ranging. v represents the target speed during dynamic target ranging. b. Acquired Ipd spectrum using the <100kHz linewidth laser of one measurement with a dynamic target, where the tones and the Doppler-shifted frequencies are indicated. The inset magnifies the vicinity of 500MHz tone displaying the f2±fd peaks. c. Similar Ipd spectrum using the 5.3GHz linewidth laser. d. Results of the triangulation algorithm using the highly coherent laser that represents the ranging of the moving target for 10 trials, where the Lmin corresponding to the minimum σ yields the target distance. e. Ranging results using the low coherence laser.
The same set of measurements are performed for the similar three positions using the low coherence laser and the results for $L_2$ are presented in Fig. 3b. Here, the mean values of the trials per location are 82.29cm, 101.79cm, and 121.24cm, respectively. Similarly, the standard deviation of the acquired data is <1cm for all positions. As a result, this proves that the PB-MTCW lidar is capable of ranging a target placed at $>500\times$ larger than the coherence length of the CW laser. It is important to note that $500\times$ is limited by the current measurement setup.

**Fig. 3 | Stationary target ranging results with high and low coherence lasers via PB-MTCW technique**

- **a.** Stationary target ranging results of 10 trials while the target is placed at $L_2$ (~1.03m) using the narrow linewidth laser.
- **b.** Stationary target ranging results at the same position using the low coherence light source.

**Discussion and Conclusion**

Overall, we introduced the Phase-Based Multi-Tone Continuous Wave lidar that enables simultaneous ranging and velocimetry beyond the coherence length of the CW laser. This new approach has the potential to overcome maximum-range limitations for coherent systems, particularly for long-range applications such as satellite-based systems or surface mapping with airborne lidars for oceanography and forestry. Here, we described the working principle of PB-MTCW lidar and the corresponding post-processing approach to extract the valuable ranging and velocimetry information. We presented the stationary target ranging results using a high coherence laser with less than 100kHz linewidth and a low coherence laser with 5.3GHz linewidth, which corresponds to coherence lengths of more than 1km and about 1.8cm, respectively. The measurement variations were found to be <1cm for both experiments. Finally, the dynamic target
velocimetry and ranging are demonstrated with a target moving at a maximum speed of 11 cm/s. It is observed that the same methodology is applicable for moving targets even with a low coherence laser.

A potential implementation of the proposed PB-MTCW lidar to long-range measurements, such as airborne lidar or satellite-based measurements, can utilize so-called quasi-CW lasers (pulsed laser with very broad pulse width). Since the peak power of pulses will be much larger than its CW counterpart, it will generate a higher signal-to-noise ratio. Also, time of flight measurement of such pulses can be used for coarse range measurements, and hence supports the triangulation algorithm. In other words, the quasi-CW approach combines the advantages of PToF lidars and CW lidars without using and frequency, phase, or amplitude scanning and provides precise measurements at ranges far beyond the coherence length of the laser. Such an implementation of the PB-MTCW lidar has the potential to be one of the leading methodologies for spacecraft and airborne applications.

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Methods

PB-MTCW simultaneous ranging and velocimetry testbench

The testbench in Fig. 2a is built by using two different lasers. The highly coherent 1064nm laser diode has $<100$kHz linewidth (RPMC Lasers - R1064SB0300PA) and the output optical power is set to $\sim$50mW. The low coherence 1064nm laser has a 5.3GHz linewidth (QPhotonics - QFBGLD-1060-100) and operates at the same output levels. All the fibers in the optical system are polarization-maintaining (PMF) to prevent polarization mismatching to achieve beating. The CW laser is followed by an isolator and then split into two branches. The local oscillator arm is pigtailed to a collimator. The measurement branch is connected to a high-speed Mach-Zehnder electro-optic modulator (iXblue – NIR-MX-LN series), which is optimized for 1064nm and has a 30dB extinction ratio. The MZM is biased near the quadrature point that is 1.6V. The modulation tones are set through phase-locked RF synthesizers (Windfreak Technologies - SynthHD (v2)) and their
phase matching is realized through a trigger clock of 10MHz provided by a stable frequency generator. The same clock triggered the oscilloscope (Tektronix - MDO34) to achieve robust phase measurements. The oscilloscope is set to have a 200µs time window with a 5GSa/s sampling rate ($10^6$ data points). Phase-locked RF frequencies are transmitted to MZM after getting combined in a 4-way RF power splitter (Mini Circuit - ZN4PD1-63HP-S+). The modulated light inside the PMF is brought to free space through an additional collimator. The two collimators are placed in a fashion to form a cross-like configuration. A 1064nm 50/50 beamsplitter is placed at the intersection point of two light beams. Light coupling to the free space high-speed PIN photodetector (Thorlabs – DET08C) is optimized with a microscope lens. The stage carrying the target reflector is placed and aligned ~83cm away from the output facet of the BS. A free-space optical attenuator with a total of ~20dB attenuation is placed on the path of propagation to mimic the potential scattering losses.

**Tone selection**

Tone selection plays a vital role in PB-MTCW lidar. The tones are selected in a fashion to prevent any second harmonic overlaps. Similarly, intermodulation tones are calculated to forestall possible frequency matchings to preserve the tone phases. Moreover, the tones should be phase-locked, and to achieve this, the tones that are divisible by the trigger frequency of 10MHz are selected. In this experiment, tones are selected as 500, 700, and 950MHz, which satisfy the aforementioned conditions. The greatest common divisor of these tones is 50MHz that indicates the unambiguity length of the resultant minimum standard deviation point is ~3m to generate the target distance. Since the target is set to <3m, the unambiguity length didn’t alter the results.
Calibration

PB-MTCW lidar is calibrated before performing the measurements by placing a dummy mirror 6.5cm away from the BS. This calibration allows the system to acquire the initial tone phases due to the initial phase of the RF synthesizers and the fiber path length. The post-processing algorithm generates a pseudo measurement distance at the position of the dummy mirror based on the measured tone phases after averaging results of 10 trials. This pseudo calibration range is set as the zero-point for the lidar and the ranging measurements are adjusted accordingly by considering the excess 6.5cm, as well.

Digital Signal Processing

The measurement data generated by the oscilloscope is interpolated to $2^{23}$ data points to improve the resolution that eliminates potential distortions during phase calculations since the phases are highly dependent on the time resolution. The time-domain data is converted to frequency domain through fast Fourier transform to localize the modulation frequencies and get the Doppler frequency if the target is in motion. The algorithm scans the interval between the first tone and the baseband to obtain the Doppler shift. The signal is then further processed by a digital second-order bandpass Butterworth filter with a 1MHz bandwidth around each measured modulation tone. The phase of the filter is compensated by performing zero phase distortion filtering that is processing the input data in both the forward and reverse directions. The refined tones are then compared with frequency-matched 0-phase digital cosine signals, which yield the phase of the individual tones. Then the triangulation is performed by setting the sweep length of the integer $n$ to 20, which allows the system to span up to ~15m.

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**Author Contribution**

O.B. conceived the concept, established the theoretical model of the PB-MTCW lidar, and supervised the work. M.M.B. developed the digital signal processing algorithms, built the PB-MTCW lidar, and conducted simultaneous ranging and velocimetry measurements. X.L. and G.N.G. developed algorithms that provide control over the experimental setup as well as data acquisition and assisted the experiments. J.E.V. supervised the work. All authors discussed the manuscript, M.M.B. and O.B. wrote the manuscript.
Supplementary Files

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- SupplementaryInformation.pdf