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SUPPLEMENTARY INFORMATION

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Time-stretch LiDAR as a spectrally scanned time-of-flight ranging camera

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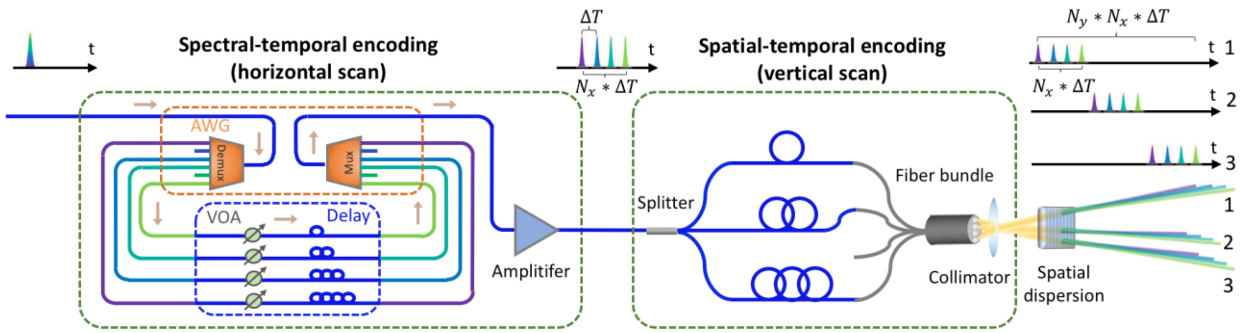
Supplementary material



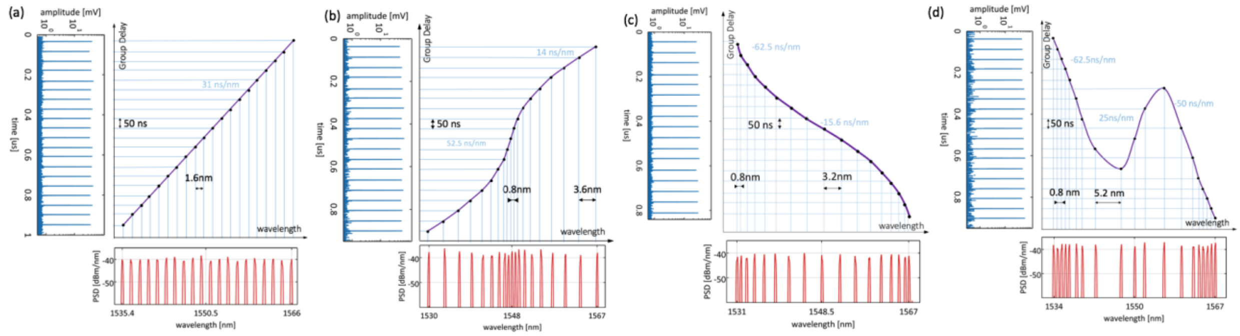
S. Figure 1. Extend time-stretch LiDAR for non-mechanical scanning in two dimensions using spatial-temporal encoding. As before, spectral encoding together with spatial dispersion achieves inertia-free scanning in the first dimension (horizontal). Now, that spatially encoded illumination, generated by the first stage, of a fiber bundle allows scanning of the second dimension (vertical). In the first stage adjacent pulses are delayed by ΔT and the total N_x wavelengths result in a time span of $N_x * \Delta T$. The outputs are then spatially separated by a fiber splitter into N_y copies and aligned in a row by a fiber bundle to provide parallel illumination in the vertical direction. Adjacent channels of the splitter are delayed by $N_x * \Delta T$ so that all N_y copies are concatenated in time with a duration of $N_y * N_x * \Delta T$ for a frame rate of $1/N_y * N_x * \Delta T$. As compared to the mainstream commercial LiDARs that use laser arrays, it differs in several ways. First, it doesn't require parallel control on the lasers or parallel detection and digitization. Only one laser and one detector is used thanks to the true-time delay based temporal encoding. Of course there is "no free lunch" and this simplification comes at the cost of the frame rate being reduced by $1/\mathrm{N_y}$ as compared to using independently controlled lasers. Second, it allows the navigation system to be flexibly configured to better match the application. Foveated illumination in the second dimension can be achieved by selectively choosing fibers that output in the desired angle. For example, more channels in the upper-portion of the bundle can be sampled when a LiDAR is remounted from the bottom to the roof to allow more low-angle points. While with LiDARs using laser arrays, this is not possible without redesigning the source board. Thirdly, as compact packing of laser dies requires thermal control, our proposed fiber-based approach doesn't need that.

Another method that could potentially lead to 2D scanning based on some of our prior work on time stretch microscopy [Goda et al., Nature, 2009]. This method uses a combination of a diffraction grating and a virtual phased array (VIPA). The spectral-temporal trains are diffracted into 2D by these two orthogonally oriented diffractive elements. The first (VIPA) diffracts adjacent frequencies in the vertical dimension and the second one (diffraction grating) resolves the repeating orders. Foveated imaging can also be realized with non-uniformly sampled spectral pulses.

	Methods	Chirp	Delay	Bandwidth	TBP	Tunability	Loss
Discrete	True-time delay	±33ns/nm	1000ns	30nm	$3 * 10^6$	<5000ns/nm	5-10dB
	FDML	±195ns/nm	2924ns	15nm	$11 * 10^6$	No	N/A
Continuous	DCF(23km)	-0.8ns/nm	25ns	30nm	$7 * 10^4$	No	10dB
	SMF(28km)	0.2ns/nm	15ns	30nm	$5 * 10^4$	No	10dB
	CMD(20m)[22]	±0.1ns/nm	2ns	20nm	7500	<0.2ns/nm	2dB
	Chirped FBG[29]	2ns/nm	10ns	6nm	8750	No	4dB

S. Table 1: Comparison between different methods for generating chirped optical waveforms.

The true-time delay method used in the first implementation of our LiDAR samples the spectrum of a broadband pulse using an Arrayed Waveguide Grating (AWG) and assigns a different physical time delay to each. This way, an arbitrary dispersion (wavelength vs. time) profile can be readily created. More importantly, the resulting chirp time-bandwidth product is orders of magnitude larger than that which is achieved using dispersive fibers used in the classical time stretch systems [Mahjoubfar, et al., Nat. Photonics 2017]. The second method demonstrated in this paper temporally samples a chirped quasi-continuous wave produced by an FDML laser. Both configurations produce tens of nanometers sweeping bandwidth, repetition rates in MHz range, a giant chirp time-bandwidth product of over 10^6, and tunable and non-uniform spectral sampling for foveated imaging. The extremely large time-bandwidth products are not necessary in microscopy applications but are crucial in LiDAR applications. Both techniques demonstrated here can be employed at a broad operating wavelength, permitting one to choose between the near-infrared band where there are matured silicon-based imaging sensors and longer wavelengths which are safer to human eyes. Both techniques are fiber-based and hence are robust. As compared to the true-time-delay method where the physical connections inside the recirculating photonics filter (RPF) scales up with the pixel number or detection range, the temporal-encoded FDML laser can be digitally programmed to generate a high number of channels without increasing the system complexity. The table also shows key parameters for dispersive fibers as well as other dispersion devices for generating fast chirped optical waveforms.



S. Figure 2 Discrete time-stretch method based on true-time delay is able to create a spectro-temporal pattern with arbitrary chirp profiles with a long chirp time of over 1 us, and a large sweep bandwidth of 30 nm, resulting in a giant chirped-time-bandwidth product > 10^6. (a) A linear chirp profile where the broadband spectrum is sampled uniformly. (b) A sublinear chirp profile where there are more wavelength samples in the central part of the spectrum. (c) A superlinear chirp profile where there are more wavelengths on the peripheral parts of the spectrum. (d) An arbitrary chirp profile where the mapping function between time and wavelength is nonmonotonic.

Path toward longer range for automotive applications

Automotive LiDAR applications that requires ranges of 100s meters, 1000 of channels (horizontal scan) with large field of view. We discuss the path of scaling-up time-stretch LiDAR to meet those requirements.

a) Time-bandwidth product, Range, and channel number

The range and number of pixels (channel number) scale up with the chirp time, and down with the line rate. As a result, the required time-bandwidth product will increase. To image a target at 100m with 1000 data points requires a chirp time of (100*2*1000)/c = 0.67ms. Assuming a bandwidth of 15nm (=4 THz at 1060nm), the chirped-time-bandwidth-product is $2.6*10^9$.

In this publication we showed an experimental realization of a very large time bandwidth product (TBP) of 1E7. This is orders of magnitude larger than what can be achieved within conventional time stretch systems. The TBP can be further increased by orders of magnitude in several ways: (a) the spectral bandwidth can be increased by a factor of 10 [Kolb et al. Biomed. Opt. Express 2018]. b) the sweep rate can be lowered by many orders of magnitude, leading to a proportional increase in TBP: here we showed sweep rates of 342 kHz but 3kHz, 300Hz or even lower can be realized with FDML configurations with longer cavity and slower sweep rate. C) TBP can be increased by overcoming the current strict requirement for sequential acquisition, using spectrally-multiplexed acquisition. In fact, the unique spectral signature of each pixel channel could be harnessed by a spectrometer or similar spectrally-resolved detection unit that is either capable of detecting time-of-flight LiDAR at sufficient temporal bandwidth or by employing spectrally multiplexed heterodyne detection to achieve highly parallel detection along a line.

b) Angular resolution and field of view.

The angular resolution and field of view can be enlarged using a conventional telescope system. For example, a 10x telescope system that employs a 300 mm lens and a 30 mm lens can extend the field-of-view by 10 times and shrink the beam diameter to increase angular resolution by 10 times.

For long range application, a beam size larger than 1mm is usually required to lower divergence. Because the telescope system increases the field-of-view at the expense of the input beam diameter, it isn't suitable for a system that already has a limited aperture. In systems that use a MEMS mirror for scanning, the mirror is usually smaller <1mm to be able to operate at fast speed. In our proposal, the aperture is not an issue as both systems are fiber based and could use long-focus collimators to achieve ~cm beam size.

The field of view can also be extended using a source with a larger bandwidth. The gain-switched supercontinuum source used in our true-time-delay method produces a bandwidth of nearly 1000nm. Specifically, the supercontinuum source (YSL Photonics) used in the implementation has a uniform spectrum from 1.1um to 2um.

Another constraint on the field of view comes from the detection system. Detectors need to have a large detection area to cover the field of view. Assuming the condensing lens in front of the detector has a focus length of 5 cm, a field of view of 20° requires a detector size of 1.8 cm. Mirroring the illumination system, diffractive optics can be used in front of the receiver to align different returned beams at different wavelengths.

Another option to increase the field of view is to use a detector array. Note that unlike only conventional detector arrays that need to be digitized in serial and is slow, only one ADC is required to digitize the sum of the outputs and the speed is not compromised by pixel number.

Use high-speed spectrometers for detection

In the proposed method, spectral-temporal encoding is utilized to resolve different wavelengths. If a fast spectrometer becomes available, it can resolve multiple wavelengths at single shot and eliminate the need for time multiplexing. Unfortunately, commercially available spectrometers are orders slower than what is required for time-of-flight LiDAR. For example, a “high speed” IR spectrometer from Ocean Optics has a frame rate of 4.5 kHz (Ocean Optics’s OCEAN FX Spectrometers, 4500 scan/second). Such a speed result in a poor distance resolution of 3e8/4.5e3=67km, as compared to the 3mm distance resolution demonstrated in this work.

In the case of spectrometers that use a scanned grating, the speed limitation comes from the mechanical scanning of the grating. In the case of spectrometers that use fixed grating and an image sensor array, the speed limitation comes from the read-out speed of the camera. In both cases, the sensitivity degrades with speed, as during short integration time few photons are collected. To circumvent these issues our group has introduced the time stretch spectroscopy with built-in stimulated Raman amplification during the stretch process [Solli et al., Nature Photonics 2008]. The same amplified-time-stretch module was later employed by our group to introduce the time stretch microscopy [Goda et al., Nature 2009]. Both of these techniques fall under the traditional time stretch techniques which, as explained in the manuscript, cannot achieve the required time-bandwidth product due to the limitation of the dispersive elements. The present work describes an alternative approach to time stretch, and two different implementations of it, which do provide the necessary time-bandwidth product.

Also, one of the drawbacks of the traditional spectrometers is that light is spread spatially and hence the SNR is reduced. This is also a problem in conventional time stretch where the signal is continuously spread across time. The discrete time stretch method proposed and demonstrated in this work has much improved SNR by concentrating the energy into individual pulses with high peak power as discussed in the main paper, allowing us to perform depth imaging in single shot mode. The discrete nature of the new time stretch method along with the very short pulse duration has the added benefit of better rejection of stray light and cross talk.