Hybrid Dispersion Laser Scanner

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Laser scanning technology is one of the most integral parts of today’s scientific research, manufacturing, defense, and biomedicine. In many applications, high-speed scanning capability is essential for scanning a large area in a short time and multi-dimensional sensing of moving objects and dynamical processes with fine temporal resolution. Unfortunately, conventional laser scanners are often too slow, resulting in limited precision and utility. Here we present a new type of laser scanner that offers ~1,000 times higher scan rates than conventional state-of-the-art scanners. This method employs spatial dispersion of temporally stretched broadband optical pulses onto the target, enabling inertia-free laser scans at unprecedented scan rates of nearly 100 MHz at 800 nm. To show our scanner’s broad utility, we use it to demonstrate unique and previously difficult-to-achieve capabilities in imaging, surface vibrometry, and flow cytometry at a record 2D raster scan rate of more than 100 kHz with 27,000 resolvable points.
the total chromatic dispersion of the fiber. Our chromatic dispersion hence, provides increased contribution of waveguide dispersion to in the wavelength operation range (typically 5–6 smaller effective mode field diameter (4 69), by temporal dispersion. This step is known as wavelength-to-time spectrum of an optical pulse is mapped into a temporal waveform by temporal dispersion. First, the broadband spectrum of an optical pulse is mapped into a temporal waveform by temporal dispersion. Second, the temporal waveform is converted into a 1D rainbow pulse in space by spatial dispersion. The spatial disperser may be one or more prisms or diffraction gratings. The resultant 1D rainbow pulse is incident onto an object, performing a 1D line scan. Combining the two steps, the spectrum of the pulse is mapped into space, resulting in each frequency component of the spectrum illuminating different spatial coordinates on the target at a different time. Pulses are repeated for repetitive scans at a rate equivalent to the pulse repetition rate.

Results

Principle of the laser scanner. The concept of our laser scanner, which we refer to as the hybrid dispersion laser scanner (HDLS), is shown in Figure 1. Its operation consists of two steps: frequency-to-time conversion and time-to-space conversion. First, the broadband spectrum of an optical pulse is mapped into a temporal waveform by temporal dispersion. This step is known as wavelength-to-time mapping or dispersive Fourier transformation and is performed using large group-velocity dispersion (GVD) in dispersive fibers or chirped fiber Bragg gratings. Second, the temporal waveform is converted by spatial dispersion into a 1D rainbow pulse in space. The spatial disperser may be one or more prisms or diffraction gratings. The resultant 1D rainbow pulse is incident onto an object, performing a 1D line scan. Combining the two steps, the spectrum of the pulse is mapped into space, resulting in each frequency component of the spectrum illuminating a different set of spatial coordinates on the target at a different time in series. The reflected, transmitted, or fluorescence light from the target can be detected by a single photodetector (e.g., a photodiode, photomultiplier tube, or avalanche photodetector). Pulses are repeated for repetitive scans at a rate equivalent to the pulse repetition rate. For 2D raster scans, a complementary scanner (i.e., the slow axis scanner) is used to scan the HDLS rainbow beam along the second planar dimension.

To maximize the practical utility of the HDLS, we design and implement it in the spectral range important for industrial and biomedical settings (i.e., ~800 nm). For this purpose, we perform dispersive Fourier transformation in the 800 nm spectral band for the first time. Previously, dispersive Fourier transformation has been restricted to the fiber-optic communication band centered at ~1550 nm due to the commercial unavailability of dispersive fibers with high dispersion-to-loss ratio outside the ~1550 nm band. On the contrary, shorter wavelengths are desirable since the spectral resolution limited by diffractive elements (or equivalently the HDLS’s number of resolvable points) improves with shorter wavelengths (See Methods). Also, the 800 nm spectral band is suitable for biomedical applications as it enables larger penetration depths in tissue and reduction in auto-fluorescence. To demonstrate dispersive Fourier transformation in this spectral band, we employ a single-mode fiber with a smaller effective mode field diameter (4 μm) than conventional fibers in the wavelength operation range (typically 5–6 μm). The fiber, hence, provides increased contribution of waveguide dispersion to the total chromatic dispersion of the fiber. Our chromatic dispersion measurement indicates a large GVD of ~123 ps/nm/km (Figure 2), enabling dispersive Fourier transformation in this spectral band.

To demonstrate the HDLS, we constructed the apparatus shown in Figure 3. The optical source is a Ti:Sapphire femtosecond pulse laser that generates a train of broadband pulses at a pulse repetition rate of 90.8 MHz. Before entering the dispersive fiber, the pulses are pre-chirped by a prism-based pulse stretcher to avoid undesirable non-linear interactions in the fiber. The pre-chirped pulses then enter the dispersive fiber in which the spectrum of each pulse is stretched into a temporal waveform due to the GVD of the fiber (~583 ps/nm). The AOD scans the pulses in the vertical direction with 132 resolvable points at a scan rate of 105.4 kHz (See Methods). A pair of diffraction gratings with 2200 lines/mm spatially disperses the pulses in the horizontal direction, producing 202 resolvable subpulses (See Methods). When combined, the temporally dispersed pulses are scanned over the target by the gratings in the horizontal direction at 90.8 MHz (equivalent to the pulse repetition rate) and by the AOD in the vertical direction at 105.4 kHz for complete 2D raster scans.

Ultrafast reflection imaging with the laser scanner. To demonstrate the HDLS’s one-to-one mapping between frequency, time, and space, we used it to conduct reflection imaging in real time. Figure 4a compares a CCD image of a test target and a digitally reconstructed image of the target scanned by the HDLS. The HDLS image was reconstructed by mapping the reflection from the target measured by a photodetector into a 2D matrix using a separately measured pulse train and AOD driver signal. Figure 4b shows the performance of dispersive Fourier transformation in the 800 nm spectral range, validating one-to-one mapping between frequency (wavelength) and time and hence between time and space. The captured image clearly shows the word “UCLA,” firmly establishing the HDLS-based imaging.

Ultrafast sub-nanometer-scale surface vibrometry with the laser scanner. To further show the utility of the HDLS, we used it to perform real-time observation of fast nanomechanical surface vibrations with sub-nanometer axial resolution. As stated above, high-speed surface vibrometry is important for non-destructive diagnosis of mechanical components, but its real-time operation has been difficult due to the speed limitation of scanners in conventional laser-scanning surface vibrometers. While stroboscopic imaging can be used to evaluate the dynamics of mechanical systems faster than the scan rate of the imager, it requires their motion to be repetitive (i.e., vibrating, rotating, oscillating, or reciprocating), unable to monitor random or non-repetitive dynamics in the form of transient rogue
Figure 2 | Chromatic dispersion of the dispersive fiber. To demonstrate dispersive Fourier transformation in the ∼800 nm spectral band, a single-mode fiber with a smaller effective mode area than conventional fibers in the wavelength operation range is employed. Consequently, the fiber provides increased contribution of waveguide dispersion to the total chromatic dispersion of the fiber (as large as ∼123 ps/nm/km GVD), enabling dispersive Fourier transformation in this spectral range as indicated by the linear one-to-one relation between wavelength (frequency) and time as well as the small residuals between the data and fit functions.

Figure 3 | Schematic of the HDLS. The optical source is a Ti:Sapphire femtosecond pulse laser that generates a broadband pulse train at 90.8 MHz repetition rate. The pulses are pre-chirped by the prism-based pulse stretcher and enter the dispersive fiber in which the spectrum of each pulse is mapped into the time domain by the GVD of the fiber. A pair of diffraction gratings maps the pulses into space in the horizontal direction, producing 202 subpulses which arrive at different spatial coordinates on the target at different times. Consequently, 1D line scans are performed in the horizontal direction at 90.8 MHz. The AOD scans the pulses in the vertical direction at 105.4 kHz with 132 resolvable points, resulting in the aggregate resolution of 202×132 (horizontal x vertical) (See Methods). The cylindrical lens collimates the pulses deflected at different angles. The colors of the subpulses in the figure are only for illustrative purposes and do not represent the real wavelengths.
events or presence of defects. High-speed laser scanners such as our scanner can address this predicament.

Specifically, we set up the HDLS in an interferometric configuration to monitor the surface profile of a fast-vibrating diaphragm (Figure 5a). As shown in Figure 5b, the axial position of each scanned point on the surface is encoded into the interferometer output (i.e., the interferogram in the time domain), retrieved from the interferogram and its Hilbert transform, and mapped into a 2D matrix for dynamical surface profilometry (See Methods). Figure 5c shows the frame sequence of a 1 kHz nanomechanical surface vibration obtained by the HDLS-based surface vibrometer with a sub-nanometer axial resolution of 0.4 nm at a frame rate of 105.4 kHz. A movie of the diaphragm vibration is available (Supplementary Movie 1). The surface velocity profile of the vibrating diaphragm can also be obtained by differentiating the axial position of the surface profile with respect to time and is made possible by our scanner’s fine temporal resolution of 9.5 μs (corresponding to 105.4 kHz). This is the first time that such a fast nanomechanical surface vibration was measured quantitatively in real time.

**High-precision flow cytometry with the laser scanner.** Finally, to demonstrate the biomedical utility of the HDLS, we applied it to flow cytometry for high-throughput screening of cells with high precision. Flow cytometry is an indispensable tool for counting and analyzing a large heterogeneous population of cells in pathology, immunology, and genetics. Unfortunately, the false positive rate and statistical error of conventional flow cytometers are high due to the lack of spatial resolution, rendering the system theoretically less able to resolve multiple cells (i.e., doublets, triplets, and clustered cells) within the interrogation beam (Figure 6a). The ability to provide spatial metrics (i.e., spectra in the spatial frequency domain) with an ultrafast laser scanner can be used as a simpler and more accurate method than other techniques\(^\text{32}\) to identify these events and hence reduce the false positive rate and statistical error. Specifically, the accuracy of the multiple-cell identification improves by a factor of the number of resolvable points or frequency bins in the spatial frequency domain (~1,000) provided by the HDLS divided by two frequency bins (i.e., forward and side scattering) provided by

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*Figure 4 | Imaging with the HDLS.* (a) Comparison between a CCD image of the test target (left) and a digitally reconstructed image of the target scanned by the HDLS (right). The target consists of the non-reflective word “UCLA” on top of a reflective substrate and was scanned by the HDLS at 90.8 MHz in 1D and 105.4 kHz in 2D for image acquisition. The word “UCLA” appears evident (with the reddish and bluish colors indicating high and low reflectivities, respectively). The number of pixels in the target image is 510×861 (horizontal x vertical) (See Methods). The distortion on the right hand side of the letter “A” is due to the reduced diffraction efficiency of the AOD at a large deflection angle near the edge of the field of view. (b) Horizontal line scans (pulses) at different vertical coordinates (different deflection angles of the AOD) with a time interval of 11 ns, corresponding to the pulse repetition rate of 90.8 MHz. The inset shows one-to-one mapping between the reflection signal from the target measured by the photodetector and the spectrum of the signal measured by a conventional optical spectrum analyzer, clearly establishing the two-step transformation from time via frequency (wavelength) to space in the 800 nm spectral range. The wavelength dependence of the target’s reflectivity is negligible as the bandwidth is less than 20 nm centered at ~800 nm.
conventional flow cytometers. Alternatively, high-speed laser scanners can also be used to perform high-throughput examination of many individual cells without the need for a single stream of cells. To demonstrate HDLS-based flow cytometry, we constructed the experimental setup shown in Figure 6b. Here we employed inertial microfluidic technology to precisely position cells in flow with inertial lift forces while eliminating the need for sheath flow (Supplementary Information). Figure 6c compares size-based histograms of white blood cells and MCF7 breast cancer cells obtained by a conventional flow cytometer and the HDLS-based flow cytometer. It clearly indicates our method’s ability to differentiate MCF7 cells from white blood cells as it can identify multiple white blood cells as false positive events. Consequently, the false positive rate and statistical error of flow cytometry were reduced by virtue of the complete spectrum in the spatial frequency domain provided by the HDLS’s ultrafast laser-scanning capability, yet with high sensitivity and high throughput (Figure 6d). Our method is expected to be useful for high-precision size-based screening of rare cells in complex biological samples and high-throughput scanning of barcoded microparticles.

**Discussion**

In summary, we have proposed and demonstrated a new type of laser scanner that operates at nearly 100 MHz – three orders of magnitude faster than conventional state-of-the-art laser scanners. This is made possible by employing spatiotemporal dispersion of broadband optical pulses, hence performing inertia-free laser scans without the need for mechanical and active electronic components. As a proof-of-principle demonstration, we have shown 1D line scans with 202 resolvable points at 90.8 MHz and 2D raster scans with 202×132 resolvable points at 105.4 kHz. To show the utility of our ultrafast
laser-scanning capability, we have used the HDLS to demonstrate ultrafast reflection imaging, real-time observation of nanomechanical surface vibrations, and flow cytometry with reduced false positive rate and statistical error.

In addition to three potential applications we have shown in this Article, our method can also be applied to a broad range of field applications in defense and manufacturing. Such applications include high-speed LIDAR for target tracking and law enforcement, high-throughput non-destructive evaluation and inspection, laser TV systems with high refresh rates, machine vision in robotics, and surface profilometry in the semiconductor industry. Moreover, the HDLS is also expected to be an effective tool for confocal microscopy and cytometry in advanced biological research and medical practice such as those found in pathology, histology, neurology, immunology, and microbiology. Finally, the HDLS is also applicable to non-industrial and non-biomedical settings including geographical survey, atmospheric science, art restoration, forestry, and archaeological study.

For sensing applications that employ weakly reflective objects and fluorescence detection, a few techniques can be concurrently used with the HDLS to improve sensitivity. First of all, the illumination beam can be made powerful by use of optical amplification in the dispersive fiber to compensate for reduced sensitivity. Since the pulses are stretched out due to the large GVD in the fiber so that the pulse train behaves as a quasi-continuous-wave field, they can be optically amplified by a large factor before target illumination.
Moreover, sensitive detectors (e.g., photomultiplier tubes and avalanche photodetectors) can also be used for sensitive photodetection. For fluorescence detection, since the HDLS’s bandwidth in our proof-of-principle demonstration is comparable the typical absorption bandwidth of fluorophores, their emission efficiency needs to be calibrated, depending on the spatial coordinates of the illumination on the target. To prevent a temporal cross-talk in the fluorescence signal between subsequent illumination points due to the ultrashort dwell time of the HDLS (51 ps in our demonstration), the rise of the fluorescence signal, which is much faster than the decay (typically longer than 1 ns), can be used to locate the origin of the signal, provided that a fast sensitive photodetector is available.

Methods

Designer’s equations for the HDLS. We discuss the “designer’s equations” which predict the performance of the HDLS. Here the key parameters are the number of resolvable points, dwell time, and scan rate. Since these parameters are not independent, but interrelated, values for them need to be chosen carefully in order to optimize the performance of the scanner. First, the number of resolvable points \(n_{\text{HDLS}}\) (determined by the total optical bandwidth \((\Delta \lambda)\) and the spectral resolution limited by the temporal dispersion or the temporal analog of the far-field spectral resolution \(\Delta(\lambda)\) as well as the spectral resolution limited by the spatial dispersion \(\Delta(\lambda)\)) is given by

\[
\frac{n_{\text{HDLS}}}{\max(\delta x, \delta y)} = \frac{\Delta(\lambda)}{\max(\delta x, \delta y)}
\]

\[\text{(1)}\]

where \(\delta x \) and \(\delta y \) are given by

\[
\delta x = \frac{\Delta(\lambda)}{\sin (\theta/\cos (\theta/2))},
\]

\[\text{(2)}\]

respectively. Here we have assumed that the temporal and spatial dispersers are a dispersive fiber and free-space grating, respectively, \(\chi\) is the speed of light in vacuum, \(\lambda_0\) is the central wavelength of the broadband pulse laser in vacuum, \(D\) is the temporal dispersion or GVD, \(G\) is the Littrow blaze angle of the incident beam with respect to the grating, \(N\) is the groove density of the grating, and \(d\) is the diameter of the beam on the grating. It is desirable to match the values of the two spectral resolutions to avoid any unnecessary dispersion. In our demonstration, they have comparable values based on the measured central wavelength \((\lambda_0=814\ nm\), optical bandwidth \((\Delta \lambda=17.5\ nm)\), GVD \((D=583\ ps/\nm)\), groove density \((N=2200\ lines/mm)\), beam diameter \((d=3\ mm)\), and Littrow blaze angle \((\theta=60^\circ)\), resulting in 202 resolvable points in the second, the time during which the HDLS dwells on each resolvable point or the so-called dwell time \(t_{\text{dwell}}\) is found to be

\[
N_{\text{HDLS}} = \Delta(\lambda) / \max(\delta x, \delta y).
\]

\[\text{(3)}\]

In our demonstration, the dwell time is found to be 51 ps. Finally, the scan rate is equivalent to the pulse repetition rate of the broadband pulse laser. However, there is an upper limit on the scan rate \(t_{\text{dwell}}\) to avoid overlaps of consecutive temporally-dispersed pulses. The limit is given by

\[
R_{\text{dwell}} < R_{\text{scan}} = \left(\frac{\Delta(\lambda)}{\delta x}\right)^{-1}.
\]

\[\text{(4)}\]

In our demonstration, the limit on the scan rate is found to be \(\sim 98\) MHz, which is higher than our scan rate (90.8 MHz) and hence satisfies the requirement. All these equations are important for designing the HDLS and optimizing its performance.

Performance of the AOD. The number of resolvable points along the AOD’s scan direction is given by

\[
n_{\text{AOAd}} = 2\beta(1 - \pi/\sqrt{\nu})/\nu x,
\]

where \(x\) is the AOD’s aperture, \(B\) is the acousto-optic bandwidth, \(\nu\) is the acoustic velocity, \(T\) is the total frequency modulation scan time, and \(\beta\) is the characteristic beam shape parameter. In our proof-of-principle demonstration \((T=105.4\ kHz)\), the number is found to be \(n_{\text{AOAd}} = 132\) from \(x = 6\ mm\), \(B = 100\ MHz\), \(\nu = 4.2\ km/s\), and \(\beta = 1\).

Dispersion measurement. To measure the GVD of our dispersive fiber, we employed the method reported by Hult et al., which is based on a time-of-flight technique combined with a supercontinuum light source. It enables measurement of GVD with high spectral resolution. In the proof-of-principle experiment, the axial resolution \((2/\lambda = 0.615\ nm/\nu)\), beam diameter \((d=3\ mm)\), and Littrow blaze angle \((\theta=60^\circ)\) resulting in 202 resolvable points in the second, the time during which the HDLS dwells on each resolvable point or the so-called dwell time \(t_{\text{dwell}}\) is found to be

\[
N_{\text{HDLS}} = \Delta(\lambda) / \max(\delta x, \delta y).
\]

\[\text{(5)}\]

where \(x\) and \(y\) are the transverse axes orthogonal to the propagation axis of the incident light.

Surface vibrometry with the HDLS. We discuss the method for generating axially resolved surface profiles. To precisely measure the surface profile of the vibrating target, we employ Michelson interferometry in which the vibrating target and a fixed reference mirror are placed at the end of the interferometer’s sample and reference arms, respectively (Figure 5a). Here the axial position of each scanned point on the surface is encoded into the output intensity of the interferometer (i.e., the interferogram in the time domain), which is given in the form of

\[
I(x,y,z) = I_0(y) + I_1(x,y) \cos(\phi_1 + \phi(x,y,z)).
\]

\[\text{(6)}\]

where \(I_0(y)\) is the intensity profile of the incident light on the target, \(I_1(x,y)\) is the intensity profile of the reflected light from the target, \(\phi_1\) is the initial phase difference between the two arms of the interferometer, and \(\phi(x,y,z)\) is the phase profile of the target. Here \(x\) and \(y\) are the axes in the transverse plane while \(z\) is the axis along the axial direction. By introducing a relatively large phase shift between the two arms, the second term can vary much more rapidly than the first term. Then, high-pass filtering \(\phi_0\) removes the first term, yielding

\[
I_H(x,y,z) = I_1(x,y) \cos(\phi_1 + \phi(x,y,z)).
\]

\[\text{(7)}\]

Applying Hilbert transformation to the high-pass filtered interferogram generates

\[
I_H(x,y,z) = I_1(x,y) \sin(\phi_1 + \phi(x,y,z)).
\]

\[\text{(8)}\]

Hence, the phase profile of the surface can be retrieved from Eqs. (7) and (8), \(\phi(x,y,z) = \tan^{-1}[H[I_H(x,y,z)]/I_H(x,y,z)] - \phi_1\), and hence the axial displacement profile of the surface is given by

\[
d(x,y,z) = \phi(x,y,z)/\lambda(x,y,z) = \lambda(x,y,z)/2\pi.
\]

\[\text{(9)}\]

where \(\lambda(x,y,z)\) and \(\lambda(x,y,z)\) are the wavenumber of wavelength of the incident light, respectively, and depend on the spatial coordinates of the interrogation point. In our proof-of-principle experiment, the axial resolution \(\Delta z\) is found to be 0.4 nm from the expression \(\Delta z = \lambda^2/\pi \sin(2\sigma z)/2\), where \(z_0\) is the initial offset to the sample arm length with respect to the reference arm length \((h_0-kz_0)\) and \(\sigma\) is the digitizer’s improved effective number of bits (ENOB) \((\sim 8.3\ bits)\) (Supplementary Information). The number of pixels in the image of the vibrating target is the same as in the reflection imaging experiment (510 × 816 pixels).

Conventional flow cytometry. MCF7 breast cancer epithelial cells were harvested from culture and fixed by a 10-minute incubation in 4% formaldehyde. Cells were washed and resuspended in PBS. White blood cells were washed and resuspended in PBS. MCF7 and white blood cell suspensions were analyzed with the FACS Calibur system in the Flow Cytometry Core Laboratory at UCLA.

Flow cytometry with the HDLS. The microfluidic device was fabricated in thermoset polyester (TPE) (Supplementary Information). We used samples of white blood cells and MCF7 breast cancer cells identical to those used for analysis with the FACScanCalibur system. The volumetric flow rate of cells was controlled by a syringe pump, and a uniform velocity of 1 cm/s was achieved by positioning cells precisely in a microchannel via an objective lens with a numerical aperture of 0.4. The 2D spatial metrics of cells were obtained by the combination of forward scattered light from 1D HDLS scans and the flow. The scattered light was collected via the same objective lens with a high-speed photodetector with 12 GHz bandwidth, and the output signal was digitized by the real-time digitizer with 16 GHz bandwidth and 50 GS/s sampling rate (identical to the detector and digitizer used in the experiment for Figure 4).
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**Author contributions**

K. G. conceived the idea. K. G. and A. F. designed the optical layout for the HDLS. K. G. designed and performed the imaging experiment and A. F. performed digital image processing. K. G. and A. M. designed and performed the vibrometry experiment and A. M. performed digital signal processing. K. G. designed and K. G., C. W., Y. L. and R. B. performed the flow cytometry experiment and J. A. and A. A. performed digital image processing. D. R. G., E. S., O. M., E. C., Y. L., N. S. and R. B. provided materials for the experiments. K. G., D. R. G., D. D. and B. J. wrote the manuscript. D. D. and B. J. supervised the project.

**Additional information**

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

**Competing financial interests:** The authors declare no competing financial interests.

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