Ultrafast Three-Dimensional Surface Imaging Based on Short-Time Fourier Transform

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***Abstract*— A novel approach to achieving ultrafast three-dimensional (3-D) imaging based on space-to-wavelength-to-time mapping and short-time Fourier transform (STFT) is proposed and experimentally demonstrated. The fundamental concept to achieve 3-D imaging is to encode the depth information of a sample by interfering two delayed pulses that are reflected from the surface of the sample and an additional reference plane on the top of the sample. The interference pattern that contains the depth information in the frequency domain is converted into the time domain based on dispersive Fourier transform and then analyzed based on STFT. Thus, ultrafast 3-D imaging is achieved. The proposed approach is experimentally evaluated. The imaging of a sample with a depth of 1.5 mm using an ultrafast pulse laser source with a beam width of ∼2 mm at a repetition rate of 48.8 MHz is demonstrated.**

***Index Terms*— 3-D imaging, ultrafast pulse, optical time stretch, space-to-wavelength-to-time mapping, short-time Fourier transform.**

I. Introduction

TIME stretch of an ultra-short optical pulse using a dispersive element has been considered an effective solution for ultra-fast signal processing which can find numerous applications such as real-time spectrometry [1], single-shot digitization [2], [3], and ultrafast surface imaging [4]. It was proved that an optical waveform at the output of a dispersive element is the Fourier-transformed version of an input ultra-short pulse. Thus, a dispersive element can be used to perform real-time Fourier transform, a technique widely known as dispersive Fourier transform or real-time Fourier transform [5], [6], which can find important applications in optical signal processing. For example, to sample an electrical signal with a bandwidth that is beyond the sampling speed of a digitizer, the signal can be slowed down by temporally stretching the pulse based on dispersive Fourier transform. Since the modulated pulse is temporally stretched, the bandwidth of the signal is reduced which can be sampled by a low-speed digitizer [7]–[9]. Another example is the use of dispersive Fourier transform to perform ultra-fast imaging. For ultra-fast imaging, the surface information of a sample is directly encoded in the spectral intensity of an ultra-short pulse which is then mapped to the time domain based on dispersive Fourier transform. The temporal waveform is then digitized and processed in a digital processor, and the surface information is reconstructed [10], [11].

Most of the techniques proposed in the past are for two-dimensional (2-D) imaging. For many applications, however, three-dimensional (3-D) imaging is needed. 3-D surface imaging plays an important role in automated visual inspection for industrial applications, such as 3-D shape measurements for quality control [12]–[14] and metrology [15]. Limited by the response time of a conventional image sensor, such as a charge-coupled device (CCD) or a complementary metal-oxide-semiconductor (CMOS) based image sensor, the readout rate, a critical productivity factor, is restricted to the sub-megahertz range. It is important to improve the speed of 3-D surface inspection systems for further cost reduction. Serial time-encoded amplified microscopy (STEAM) based on time stretch is a solution to achieve real-time optical imaging with a high frame rate up to 10 MHz [16]–[18]. In an STEAM system, a broadband mode-locked laser source is used with a combination of a spatially and temporally dispersive elements to achieve ultrafast single pixel imaging [19]–[21]. However, the reported approaches can only encode 2-D information [22]. Generally, by adding a reference arm, a 3-D image can be obtained from a temporal interference waveform [23], [24]. However, the use of a two-arm interferometric structure would not only increase the system complexity, but also increase its sensitivity to the environmental changes. In addition, the depth information is extracted from the phase of the interference patterns which is limited to 2π, or the surface profile of a sample should be continuous without any steps to enable a correct recovery of the depth information without phase ambiguity when the phase information is more than 2π. Obviously, this would restrict the approach for real applications.

In this letter, we propose a novel ultrafast imaging system based on space-to-wavelength-to-time mapping and short time Fourier transform (STFT) for 3-D imaging without using

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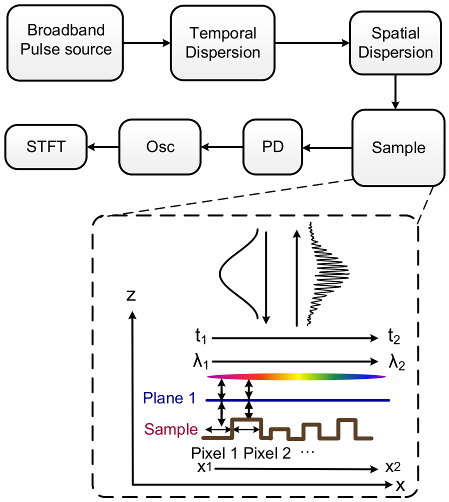

Fig. 1. The principle of the ultrafast time-stretched interferometric 3-D surface imaging system with a single arm based on STFT. Here the temporal dispersion is performed by a fiber, and the spatial dispersion is performed by a grating. PD: photodetector; Osc: oscilloscope.

a reference arm. The fundamental concept to achieve 3-D imaging is to create a reference plane and to encode the depth information of a sample by interfering two delayed pulses that are reflected from the reference plane and the surface of the sample. The depth information is encoded in the interference pattern, and the depth information in the frequency domain is converted to the time domain based on dispersive Fourier transform. The interference signal represents the surface information of the sample including the depth information obtained by estimating the frequency of the interference signal in the time domain based on STFT. It is different from the configuration where two arms are used [23], [24], the sample to be imaged may not be limited to have a smooth surface to avoid the phase ambiguity existing in a two-arm system. The proposed approach to 3-D imaging is experimentally evaluated. The imaging of a sample with a depth of 1.5 mm using an ultrafast pulse laser source with a beam width of ∼2 mm at a repetition rate of 48.8 MHz is demonstrated.

II. Principle

The principle of the proposed ultrafast time-stretched interferometric 3-D imaging scheme is illustrated in Fig. 1. A pulse train from a broadband femtosecond mode-locked pulsed laser source is sent to a dispersive element to perform dispersive Fourier transform. Then the time-stretched pulses are sent to a diffraction grating that serves as a one-dimensional (1-D) spatial disperser, and the sample is translated in the orthogonal direction controlled by a stepper motor, thus 2-D imaging can be achieved. As shown in the dashed box in Fig. 1, a rainbow beam from the diffraction grating is first incident on the upper plane (plane 1) that has a certain reflection. Part of the incident pulse is reflected from plane 1 (called sub-pulse 1) and the other part of the pulse is transmitted and incident on the sample surface, and then reflected (called sub-pulse 2). Sub-pulse 1 is directly reflected from plane 1 and its

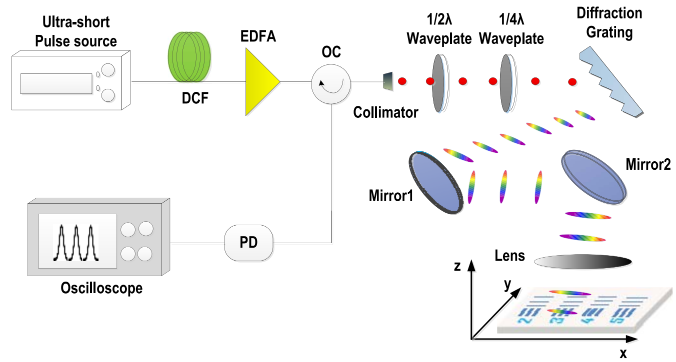

Fig. 2. Schematic of the proposed ultrafast time-stretched 3-D microscopic imaging system. DCF: dispersion compensating fiber; EDFA: erbium-doped fiber amplifier; OC: optical circulator; PD: photodetector.

spectrum remains unchanged. However, the spectrum of sub-pulse 2 is encoded with the 2-D information of the sample. The operation is identical to spectrally encoded confocal microscopy (SECM) [25]. The two reflected sub-pulses interfere. Here we note that the bandwidth of a pulse in the pulse train and the dispersion value are, respectively, B (nm) and DL (ns/nm), where D is the dispersion parameter (ns/nm/km) and L is the length of the dispersion fiber (km). The temporal duration of a temporally stretched pulse is given by $\Delta\tau = BDL$. It should be noted that a greater value of the pulse bandwidth would make the stretched pulse have a wider temporal width $\Delta\tau$ for a given value of dispersion DL, which would make the detected temporal waveform carry more details (pixels) about the sample, thus with an increased pixel number. After dispersive Fourier transform, a temporal waveform is obtained which is encoded with the depth information of the sample. This temporal signal is detected at a photodetector, digitized by an oscilloscope, and then processed using STFT in a digital processor. Specifically, the temporal waveform along the x-axis (see Fig. 1) is divided into a set of sub-waveforms and each sub-waveform here is noted as a pixel. Assume the depth within a pixel is constant and it can be estimated based on STFT. For pixel i, the frequency is f_i, then the depth corresponding to the frequency f_i is given by [26]

$$d_i = \frac{\lambda^2 DLf_i}{2n} \tag{1}$$

where λ is the center wavelength of the pulse laser source, f_i is the frequency of the i-th sub-waveform (pixel) achieved based on STFT, c is the speed of light in a vacuum, and n is the refractive index of the material between plane 1 and the sample surface. Based on (1), the depth information of the sample along the x-axis direction can be calculated.

On the other hand, the detected intensity distribution of the temporal waveform represents the gray level information of the sample surface, which is identical to what obtained based on STEAM. By combining the depth information with the 2-D gray-level information, a 3-D image is constructed.

III. Experiment

Fig. 2 shows an experimental setup to perform the proposed 3-D imaging. The pulsed optical source used for imaging is a passively mode-locked ultra-short fiber laser (IMRA femtolite 780). The pulse width, center wavelength, bandwidth, and pulse repetition rate are 300 fs, 1558 nm, 8 nm, and 48.8 MHz, respectively. The pulse train from the pulsed laser source is sent to a dispersive fiber (dispersion compensating fiber or DCF) with a group-velocity dispersion value of −945 ps/nm. The reason that the dispersive fiber is placed before the diffraction grating is to reduce the peak power of the optical pulse to avoid damaging the optical components in the free-space link. Since the system is linear time-invariant (LTI), the re-location of the dispersive fiber before the free-space link will not affect the over function of the system. The time-stretched pulse train is amplified by an erbium-doped fiber amplifier (EDFA) and is sent to the free space optical link, where a diffraction grating is used to perform wavelength-to-space mapping to spatially disperse the pulse to produce a one-dimensional (1-D) rainbow beam along the x-axis direction, as shown in Fig. 2. The diffraction grating has a groove density of 1200 lines/mm. A singlet spherical lens with a focal length of 100 mm is used to focus the rainbow beam on the surface of the sample where the beam is extended along the x-axis direction. Consequently, a different wavelength corresponds to a different spatial coordinate along the x-axis direction. Due to the existence of the reference plane, one incident pulse to the sample is reflected from the reference plane and the sample surface, to form two sub-pulses. The interference between the two sub-pulses will encode the depth information of the sample. The encoded pulse train is reflected back and directed via an optical circulator to a photodetector with a bandwidth of 25 GHz. The signal power to the photodetector is −3 dBm. The detected signal is then digitized using a high-speed oscilloscope with a bandwidth of 7 GHz and a sampling rate of 20 Gs/s (Tektronix TDS7704B). The sampled signal is post-processed in a digital signal processor, where STFT is performed to estimate the depth information. By combining the 2-D gray-level information with the depth information, a 3-D image is obtained.

First, a plane glass plate with a thickness of 1.5 mm is used as a sample to demonstrate the ability of the approach for depth estimation. Fig. 3(a) shows a perspective view of the sample. The upper surface has 30% reflection and the lower surface is coated with silver with full reflection. For an incident pulse, two sub-pulses are produced which are reflected from the upper and lower surfaces, which interfere with an interference pattern containing the depth information. An interference waveform in the time domain is then obtained due to dispersive Fourier transform. Fig. 3(b) shows a temporal interference waveform which is sampled by the high speed oscilloscope. The sampled waveform is analyzed in a digital signal processor by STFT and the frequency-time plot is shown in Fig. 3(c). As can be seen a single frequency at 2 GHz appears within the beam width, which indicates that the sample has a constant depth along the beam width (the x-axis direction). In the experiment, the center wavelength of the pulse train is 1558 nm, the refractive index of the glass is 1.513, and the total dispersion value (DCF+EDFA) is −935 ps/nm. Based on (1), the thickness of the sample is calculated to

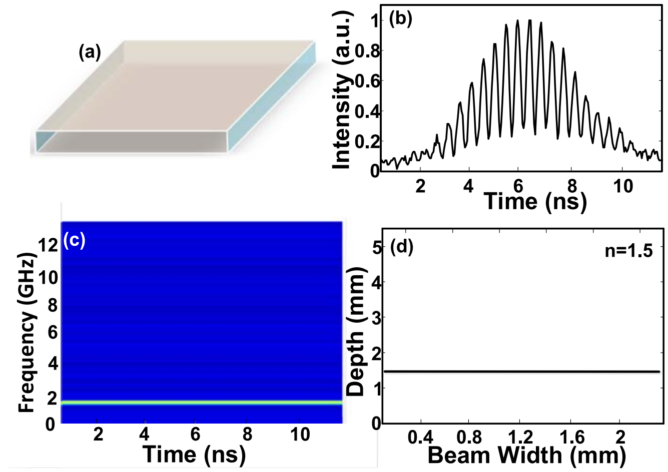

Fig. 3. Depth estimation for a glass plate with a thickness of 1.5 mm. (a) The perspective view of the glass sample that has the refractive index of 1.5; (b) The temporal waveform obtained from the interference of two sub-pulses reflected from the upper and lower surfaces of the plate; (c) The frequency-time relationship achieved from the temporal waveform based on STFT; (d) The depth of the sample calculated based on (1).

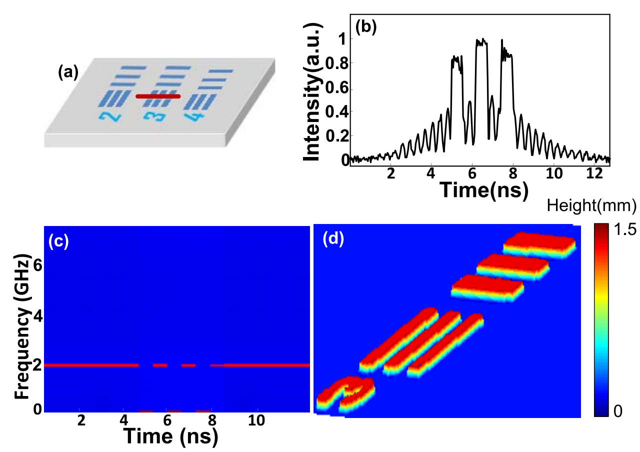

Fig. 4. 3-D imaging for a sample with coated patterns on the upper surface. (a) The perspective view of the glass sample that has the refractive index of 1.5 and the surface is coated with silver patterns; (b) The temporal waveform obtained from two sub-pulses that are reflected from the upper and lower surfaces; (c) The frequency-time plot achieved from the waveform based on STFT; (d) The reconstructed 3-D image of the sample.

be 1.5 mm, which is identical to the actual thickness of the sample.

Then, we use another sample, which is also a 1.5-mm thick glass plate, but with some patterns on the upper surface that are coated with silver to emulate an object with two different depths. The silver-coated patterns on the sample surface have full reflection and the lower surface is also coated with silver with full reflection. Fig. 4(a) shows the perspective view of the glass sample. The reflected temporal waveform is shown in Fig. 4(b), which is obtained when the rainbow beam from the lens is located at the position of the red line, as indicated in Fig. 4(a). As can be seen from Fig. 4(b), a temporal waveform with high- and low-intensity segments is obtained. The high-intensity segments in the temporal waveform indicate that the light is reflected from the patterns coated with silver. The constant value of the high-intensity segments indicate that all light is reflected from the patterns with an identical reflection and without interference. Due to partial reflection of the glass surface where no coated patterns are produced, two sub-pulses which are reflected from the coated patterns on the upper surface and the lower surface are obtained, thus optical interference is produced in the temporal waveform, which are shown as the lower-intensity segments in Fig. 4(b). Based on STFT, the frequency information of the temporal waveform is obtained, which is shown in Fig. 4(c). As can be seen two frequencies at 0 and 2 GHz appear within the beam width along the x-axis. Again, based on (1), the depth information is obtained, which clearly shows two different depths of 0 and 1.5 mm. By translating the sample along the y-axis, an entire 3-D image of the sample, which is shown in Fig. 4(d), is obtained.

IV. Discussion and Conclusion

For real applications, we may place a semi-transparent glass plate with its upper surface coated with partial reflection and the lower surface anti-reflection coated. Then, two sub-pulses will be reflected from the upper surface of the glass plate and the surface of a sample which is placed under the glass plate. The depth information of the sample can be obtained by subtracting the distance between the glass plate and the sample surface.

The value of dispersion will affect the performance of the system. If the dispersion is greater, the interference frequency can be smaller which would enable the use of a low-frequency photodetector, to reduce the system cost. However, for a given pixel size, a lower interference frequency may make the frequency estimation based on STFT have a greater error. Therefore, the dispersion value has to be selected to have a best trade-off between the system cost and the depth estimation accuracy. In addition, greater dispersion may make the width of the rainbow beam along the x-axis wider, thus covering a large area when scanning the surface of a sample. By increasing the pulse bandwidth in the pulse train, the width of the rainbow beam can also be wider, which can also increase the scanning area.

In conclusion, we have proposed and experimentally demonstrated a novel approach to ultrafast single-arm 3-D imaging based on the space-to-wavelength-to-time mapping and STFT. Instead of using a two-arm system, here we place a semi-transparent glass plane above a sample. Two sub-pulses reflected from the upper surface of the glass plate and the surface of the sample were obtained, and the interference of the two sub-pulses would contain the depth information. By STFT, the frequency of the interference temporal patterns was calculated, which was converted to the depth information if the parameters of the system were known. Thanks to the simplicity and stability of the system, the use of the proposed approach to achieving ultrafast 3-D imaging with improved accuracy would be possible, which can find important applications in manufacturing such as 3-D shape measurements for quality control.

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