Real-Time Femtosecond Ranging Lidar Based on All-Optical Signal Processing

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Abstract—A real-time ranging lidar with 0.1 Mega Hertz update rate and few-micrometer resolution incorporating dispersive Fourier transformation and instantaneous microwave frequency measurement is proposed and demonstrated. As time-stretched femtosecond laser pulse passing through an all-fiber Mach-Zehnder Interferometer, where the detection light beam is inserted into the optical path of one arm, the displacement is encoded to the frequency variation of the temporal interferogram. To deal with the challenges in storage and real-time processing of the microwave pulse generated on a photodetector, we turn to all-optical signal processing. A carrier wave is modulated by the time-domain interferogram using an intensity modulator. After that, the frequency variation of the microwave pulse is uploaded to the first order sidebands. Finally, the frequency shift of the sidebands is turned into transmission change through a symmetric-locked frequency discriminator. In experiment, A real-time ranging system with adjustable dynamic range and detection sensitivity is realized by incorporating a programmable optical filter. Standard deviation of 7.64 μm, overall mean error of 19.10 μm over 15 mm detection range and standard deviation of 37.73 μm, overall mean error of 36.63 μm over 45 mm detection range are obtained respectively.

Index Terms—Distance measurement, frequency measurement, laser radar, optical interferometry, remote sensing.

I. INTRODUCTION

Femtosecond laser has been a promising tool for ultrafast and precise detection applications, such as high speed gas spectral measurements [1]-[3], microscopic imaging [4] and ultrafast distance measurements [5]-[9], due to its high repetition rate, short exposure time, wide spectral range and high stability [10]. Ultrafast ranging with high resolution and high acquisition rate is attractive to ultrafast dynamic research and high-speed industry tests. By introducing the dispersive Fourier transformation technology [11]-[13], single-shot ultrafast range detection can be realized at large dynamic range with nanosecond acquisition time and nanometer accuracy [14], [15]. The detection of fast flying target at speed of tens of kilometers per second has been reported [16]-[18]. However, the measured signal data size can be tremendous because a high sampling rate analog to digital converter (ADC) is usually needed. For oscilloscope with 80 GHz sampling rate and 8-bit vertical resolution, the data size can approach 150 GBs per second with binary data format. It is a great burden to achieve data storage and real-time processing continuously. Short time data storage and time-consuming post-processing hinders its implementations where continuous detection and real-time feedback is required.

In recent years, microwave photonics has shown immense potential to overcome the problems mentioned above and realize real-time signal processing with integrated functionality. Using microwave photonics methods, electrical domain signal from photodetector (PD) can be converted into optical domain signal by an electro-optic modulator and processed in optical links directly [19]. One of the focused topics in microwave photonics is instantaneous microwave frequency measurement and has been densely investigated in recent years. It is of great importance for high-resolution real-time applications. Fortunately, in the ultrafast ranging lidar based on dispersive Fourier transformation, displacement is encoded into the frequency of time-domain interferogram which is a pulsed microwave signal [20]-[23]. The frequency information can be processed instantaneously by using microwave photonic approaches.

In direct-detection of optical frequency, there is a so-called edge technique in lidar applications. For example, in a Doppler lidar, Fabry–Perot interferometer (FPI) is used as an optical frequency discriminator. The Doppler shift of either the Rayleigh or the Mie backscattering signal is converted into its transmission change through the FPI [24]-[26]. Recently, using InGaAs/InP single photon detector (SPD) [27], [28],...
up-conversion SPD [29]-[31] or superconducting nanowire SPD [32], [33], direct detection of Doppler shift at single photon level is achieved at 1.5 micrometer working wavelength.

For microwave frequency measurement, the same thought can be adopted. One commonly used scheme is by introducing a monotonous frequency-intensity mapping, namely amplitude comparison function (ACF). The ACF can be realized by different schemes, such as Sagnac loop [34], fiber Bragg grating [35], Echelle diffractive grating [36], birefringence effect in polarization-maintaining fiber (PMF) [37], a two-tap finite impulse response filter [38], photonic Brillouin filter [39], [40], frequency dependent DC output produced by optical mixing method [41], fade function generated by dispersive medium [42]-[46] or integrated photonic chips [47]-[50]. For multiple frequency measurement, approaches such as frequency to time mapping [51], [52] and frequency shifter [53] are proposed. Other approaches can be found elsewhere [54], [55].

Here, we demonstrate a real-time range detection method based on all-optical signal processing, where the displacement is finally mapped to the transmission (signal intensity ratio) variance. The procedure is shown in Fig. 1.

Step 1: the displacement is encoded into the frequency shift of microwave pulse by a technique called dispersive Fourier transform interferometer.

Step 2: the frequency shift of microwave pulse is uploaded into 1st order sidebands of carrier wave under intensity electro-optic modulation.

Step 3: by adopting optical frequency direct-detection, the frequency shift of the above sidebands is converted into its transmission variance on a frequency discriminator.

II. PRINCIPLE

The schematic diagram of the ultrafast femtosecond ranging system with all-optical signal processing is shown in Fig. 2. The displacement measurement is based on dispersive Fourier transformation method. The optical source is a femtosecond laser (FSL), with its repetition rate locked via a closed-loop control. Then the femtosecond laser pulse is filtered and sent to a spool of dispersion compensation fiber (DCF) for time stretching followed by an Erbium-doped fiber amplifier (EDFA) for chirp pulsed amplification. The dispersed and amplified pulse is coupled into a Mach-Zehnder interferometer (MZI) and split into its detection arm and reference arm. The light in detection arm is transmitted through circulator and collimator to a retroreflector, the retroreflector is mounted on a nanometer linear positioning stage (NLPS) which is driven by a servo controlled Piezoelectric transducer (PZT). In the reference arm, an optical fiber delay (OFD) is used to adjust time delay difference between the two arms. Then the light from the two arms are combined to generate time-domain interferogram. The polarization controllers (PC1, PC2) and inline polarizers (ILP1, ILP2) are used to obtain high contrast ratio of the interferogram.

Fig. 2. Schematic diagram of ultrafast femtosecond laser ranging based on all-optical signal processing. RRL: Repetition Rate Locking system; FSL: Femtosecond laser; OTF: Optical tunable filter; DCF: Dispersion compensation fiber; EDFA: Erbium-doped fiber amplifier; C: Coupler; Cir: Circulator; PC: Polarization controller; ILP: In-line polarizer; OFD: Optical fiber delay; R: Retroreflector; NLPS: Nanometer linear position stage; PD: Photodetector; BPF: Band-pass filter; Amp: Microwave amplifier; CWL: Carrier wave laser; IM: Intensity modulator; PF: Programmable filter; OSC: Oscilloscope

The interferogram is detected on a photodetector yielding a microwave pulse train. A broadband electrical band-pass filter (BPF) is used to eliminate the direct current component and low frequencies disturbance such as repetition rate of laser and its harmonic components. A carrier wave laser is modulated by the amplified microwave signal through an intensity modulator which operates at carrier suppression mode. Then modulated light with two sidebands are generated and divided into two channels. One channel includes a programmable filter and the other one is set as reference channel. The programmable filter is used as frequency discriminator. By changing the filter bandwidth, adjustable detection sensitivity can be realized. Note that, high sensitivity is achieved at sacrifice of detection range. Finally, the optical signals at two channels are detected at two low-bandwidth photodetectors and sent to an oscilloscope for signal processing.

In the first step, the displacement relative to reference point is mapped to frequency of microwave pulse. The principle of displacement detection proposed in our previous work is briefly recalled here [14], [15]. The MZI in the system adopts balanced structure by adjusting the optical fiber delay. Displacement to be measured can be obtained by time of flight \( r \), which is contained in time delay between the two arms of MZI. For fast detection, DCF is used to stretch the femtosecond pulse and generate time-domain interferogram which contains time delay information. Dispersive Fourier transformation of the fiber in the system builds a unique relationship between time delay and frequency change. With third-order dispersion considered, the instantaneous optical frequency of time-stretched pulse can be written as [15], [23]:
The intensity modulator is a Mach-Zehnder modulator (MZM) and biased at its minimum transmission point to treat the displacement which corresponding to the delay is input optical power, $\beta$ is modulation depth, $\lambda$ is center wavelength of optical pulse, $\Delta f$ is microwave bandwidth which is limited by the bandwidth of bandpass filter and modulator. Nowadays, modulators exceed 100 GHz are commercially available. According to (3), dynamic range can be enhanced by increasing dispersion or microwave bandwidth.

In previous works, signal processing of time-domain interferogram is complex. Several mathematical manipulations are needed, including time-frequency transformation, interpolation, resampling in the frequency domain, inverse Fourier transformation and curve fitting. Here in order to simplify the process, microwave photonics approach is adopted.

Hence in the second step, the microwave frequency change is treated by all-optical signal processing. The operation principle of signal processing is shown in Fig. 3. The microwave pulse train can be expressed by a convolution of a delta function $\delta(t-nT)$ and microwave signal $u(t) = V_m a_m(t) \cos(2\pi f_m t)$, where $T$ is pulse period, $V_m$ and $f_m$ are microwave amplitude and frequency respectively. The optical field of modulated light in single pulse period is given by [56]:

$$ E(t) = \sqrt{P_m} \exp(i2\pi f_m t) \sin[\beta a_m(t) \cos(2\pi f_m t)] $$

(4)

where $P_m$ is input optical power, $f_m$ is optical carrier frequency, $\beta = \pi V_m / V_a$ which is modulation depth, $V_a$ is half-wave voltage of intensity modulator.

The intensity modulator is a Mach-Zehnder modulator (MZM) and biased at its minimum transmission point to suppress the optical carrier. In practice, most MZMs are non-ideal and suffer from modulation chirp [57]. However, with small signal modulation regime, the chirp parameter of the modulator is fixed with time and independent of the power of microwave signal [58]. The modulation chirp effect can be canceled by two-channel detection with one channel set as reference. Furthermore, small signal modulation can suppress higher order modulation sidebands effectively. The optical field at small modulation condition can be written as:

$$ E(t) \approx \frac{\sqrt{P_m} \beta}{2} a_m(t) \{ \exp[i2\pi(f_m + f_m)\tau] + \exp[i2\pi(f_m + f_m)\tau] \} $$

(5)

Fig. 3. Operation principle of all-optical signal processing

It shows two sidebands are generated with equal frequency separation relative to carrier frequency. That means the frequency information of the microwave signal is uploaded to the sidebands. The two sidebands are then divided into two channels for transmission detection. A programmable filter is locked symmetric by setting its minimum transmission point at the frequency of the carrier wave. Then the transmission of the sidebands varies along with the frequency shift of microwave pulse.

The transmission function of detection channel can be written as:

$$ T(f) = D(f) \otimes A_m^{-2}(f) $$

(6)

Where $D(f)$ and $A_m(f)$ are designed filter profile and Fourier transformation of $a_m(t)$ respectively.

For low bandwidth PDs, only the envelop of modulated signal can be captured, thus the output of detection and reference channel can be written as:

$$ I_{det}(t) = \frac{c_1 R_1 P_m \beta^2}{2} a_m^{-2}(t) T(f_m + f_m) $$

(7)

$$ I_{ref}(t) = \frac{c_2 R_2 P_m \beta^2}{2} a_m^{-2}(t) $$

(8)

where $c_1$, $c_2$ are coupling ratio of two channels and $R_1$, $R_2$ are responsivity of two PDs. It is shown that the frequency of microwave signal fed to the modulator is mapped to optical intensity through optical filter in detection channel. Thus, the transmission function, so-called ACF of detection channel and reference channel can be obtained by $r(f_m) = k T(f_m + f_m)$, where $k = c_1 R_1 / c_2 R_2$. Taking the ratio operation can eliminate the influence of optical power jitter and modulation depth fluctuation during the measurement.

In the third step, the displacement is mapped to a transmission function $r(f_m)$ which is designed to be monotonic. When the displacement varies, time delay of MZI in the sensing module and the frequency of time-domain interferogram varies accordingly. Thus the transmission in the...
all-optical processor will vary along with displacement. Finally, the mapping of displacement to a transmission function is established by calibration.

The higher order dispersion effect induced by DCF used in the system and frequency response of the devices used in the all-optical signal processing module can be compensated in the calibration process. With a calibrated line of $r_{fa}$, the measured transmission data can be used to retrieve the displacement information in real-time.

III. EXPERIMENT

In experiment, a homemade femtosecond laser (AICC, TC1550-2G) has average output power of 30 mW and pulse width of about 93 fs. The pulse repetition rate is locked to 50 MHz with fluctuation in mHz level. A small portion of the femtosecond laser pulse is filtered out with spectrum width of 8.2 nm centered at 1553 nm. The total dispersion used with two spools of DCF (ofs, DCM(D)-C-G.652-DCF) is -2298 ps/nm. The NLPS (PI, N-565.260) has a positioning resolution of 0.5 nm and bidirectional repeatability of 50 nm with a closed-loop control (PI-E861.1A1). The PD1 (Alphalas, UPD-15-IR2-FC) used for pulsed microwave detection is an InGaAs ultrafast photodetector with 25 GHz bandwidth. The electric BPF (Wainwright, WHNX6) used before modulation has passband of 2.3-26.5 GHz. A continuous wave laser (Keyopsys, PEFL-EOLA) with center wavelength of 1548.495 nm is used as optical carrier. By tuning the time delay, reference point of the Retroreflector (zero position) is settled, when the center frequency of the microwave pulse is 2.3 GHz. Since the bandwidth of intensity modulator (Photline, MXER-LN) is 20 GHz, so the microwave bandwidth can be treated as span from 2.3 GHz to 20 GHz in this work. The maximum displacement measurement dynamic range is 4.87 cm according to (3). The bandwidth of PD2 and PD3 (Thorlabs, PDB430C) is 350 MHz. Key parameters of the system are listed in table 1 for reader’s convenience.

| Parameters                  | Values |
|-----------------------------|--------|
| **Sensing Module:**         |        |
| Femtosecond laser:          |        |
| Center wavelength           | 1560 nm |
| Repetition rate             | 50 MHz  |
| Pulse width                 | 93 fs   |
| Average power               | 30 mW   |
| Total dispersion of DCF     | -2298 ps/nm |
| Bidirectional repeatability of NLPS | 50 nm |
| **Microwave Processor:**    |        |
| Passband of electric BPF   | 2.3-26.5 GHz |
| Carrier wave laser wavelength | 1548.495 nm |
| Bandwidth of intensity modulator | 20 GHz |
| Bandwidth of PD1            | 25 GHz  |
| Bandwidth of PD2, PD3       | 350 MHz |

To avoid effects of environment fluctuations and vibrations during measurement, room temperature is set about 24 °C and all fiber devices and positioning stage are mounted on an air floating platform. The intensity modulator is placed in a thermostank at 24 °C with temperature fluctuation less than 0.01 °C.

Several specific displacements to be measured are chosen within the dynamic range. The microwave pulse is captured by an Oscilloscope (Teledyne Lecroy, LabMaster MCM-Zi-A) with 80 GHz sampling rate. As shown in Fig. 4, three waveforms at different displacements (5 mm, 15 mm, 25 mm) are plotted. One can see the obvious frequency change related to the displacement.

![Fig. 4. Microwave pulse waveform with specific displacements](image)

The microwave pulse train is then amplified by a broadband microwave amplifier (SHF, L806A) and sent to the intensity modulator. As shown in Fig. 5, the sidebands corresponding to different center frequencies of the microwave pulses are plotted, which are measured by an optical spectrum analyzer (OSA, Yokogawa, AQ6370C). The frequency is defined relative to the absolute optical frequency (193.6025 THz) of the carrier wave. The position of the two sidebands are symmetrically located about the carrier frequency and shift away from the center along with increased displacement.

![Fig. 5. Spectrum of modulated signal with specific displacements](image)
the collimator from space to the polarization-maintaining fiber decays, resulting a weaker microwave power fed to the modulator. So the intensity of the sidebands drops down.

The modulated signal then divided into two channels for transmission detection. In the detection channel, filter functions are specifically designed to be a symmetrical linear function relative to carrier frequency. Thus the dynamic range of displacement detection can be adjusted by setting the bandwidth. There is a trade-off between dynamic range and detection sensitivity. Higher detection sensitivity can be obtained at the expense of dynamic range by decreasing the bandwidth of the filter.

In experiment, two filters with different detection sensitivity are designed. Dynamic range of filter 1 is designed to be 15 mm and filter 2 is 45 mm. The programmable filter used here is WaveShaper (FINISAR, 1000A), the input optical signal is first dispersed by a conventional diffraction grating and then processed by a Liquid Crystal on Silicon (LCoS) optical processor. Thus, spectral attenuation profile can be designed. As shown in the Fig. 6, the frequency response of the two filters are measured by an OSA with an amplified spontaneous emission (ASE) source. The sweep resolution of the OSA is set to 2.5 GHz. Thus, the actual measured filter response curves broaden due to the convolution of response of the filters and the OSA. Through the filters, a monotonic transmission function versus frequency shift of sidebands is established.

Once the mapping relation between the displacement and transmission is established, real-time, ultrafast and continuous displacement measurement can be performed.

Before the range measurement, the system requires careful calibration. At different positions of retroreflector controlled by NLPS, transmission values are measured. The detection signal and reference signal should be synchronized firstly in the time domain, by tuning the time delay between the two channels on the oscilloscope. Thus, the transmission can be calculated directly.

During the transmission measurement, the sampling rate of the oscilloscope is set to 1.25 GHz with 12-bit vertical resolution. The calibrated transmission line of two filters with different dynamic ranges by 3rd order polynomial fitting are shown in Fig. 7. The calibration equation can be expressed by:

\[ y = ax + bx^2 + cx^3 + d \]  

The coefficients of calibration equation for 15 mm and 45 mm are shown in table II. With calibration line determined, corresponding displacement can be obtained immediately through measured transmission data.

![Fig. 6. Measured filter response with different sensitivity](image)

![Fig. 7. Transmission Calibration lines with different dynamic range using 200 μs averaged data](image)

| Coefficient | 15 mm calibration equation | 45mm calibration equation |
|-------------|----------------------------|---------------------------|
| \(a\)       | 0.05291                    | 0.01594                   |
| \(b\)       | 0.00690                    | 0.00211                   |
| \(c\)       | \(-2.3166 \times 10^{-4}\) | \(-2.6388 \times 10^{-5}\) |
| \(d\)       | 0.70997                    | 0.30690                   |

The intensity signal from PDs in detection and reference channels are captured by an oscilloscope (Teledyne Lecroy, HDO6034).

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IV. CONCLUSION

A femtosecond laser ranging lidar with tunable dynamic range based on dispersive Fourier transformation and all-optical signal processing is experimentally demonstrated. Real-time displacement-frequency-transmission mapping are built. The data size can be tremendously reduced to achieve real-time data storage and processing. According to different applications requirements, the detection sensitivity is tunable by changing the bandwidth of programmable filter. A higher sensitivity can be achieved with a sacrificed dynamic range. The dynamic range can be further improved using either larger dispersion or faster modulators.

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Fig. 8. (a) 15 mm range 10 μs averaged results (b) 45 mm range 10 μs averaged results. There are 100 times measurements at each displacement. Data are shown in format of (standard deviation, mean error)
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