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A scheme of pulse compression lidar with enhanced modulated bandwidth for detection through scattering media

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ABSTRACT

This paper presents a scheme of pulse compression lidar with enhanced electrical modulated bandwidth. An ultra-wideband linear frequency modulated signal with a bandwidth of 50 GHz is generated using femtosecond laser and superimposed linear chirp fiber Bragg gratings in the transmitter, which separates the echo of the target from the backward scattered noise with low modulated frequency. An optical pulse compression system based on a negative dispersion fiber Bragg grating is used to compress the ultra-wideband linear frequency modulated signal in the receiver. *SNR* and range resolution of the proposed scheme are numerically simulated to prove its feasibility. The simulation results indicate that an enhancement of *SNR* by 15.8 dB can be achieved using the scheme, and the range resolution of the scheme increases from 0.68 m to 0.0027 m. It is therefore concluded that the proposed scheme is suitable for detection through scattering media.

1. Introduction

Lidar systems are widely used for such applications as estimation of atmospheric parameters [1,2], identification of target [3], measurements of velocity and vibrations [4], remote sensing [5], and imaging [6]. When applied in detecting targets in fog, faze, smoke and other scattering media, modulated lidars are commonly restrained by the influence of rapid attenuation of the laser pulse scattered along the transmission path. In these modulated lidar systems, high frequency modulated signal is utilized in order to separate target echo from the backward scattering noise of the scattering media with low frequency [7–9].

Up to now, the performance of reported pulse compression lidars cannot yet satisfy the practical application requirements because of the limitation of the electronical modulation bandwidth of drive signal for modulators [10,11]. It has been demonstrated in recent reports that photonic technologies can be applied for generation and detection of microwave radar signals [12,13], which supposes the possibility of an architecture of wideband modulated lidar by employing photonic technologies.

In this paper, a scheme of pulse compression lidar with ultra-wideband modulated signal is proposed using photonics technologies. And the structure of the proposed lidar is shown in Fig. 1, a femtosecond laser of 1550 nm is utilized as laser source, and a pair of superimposed linear chirp fiber Bragg gratings (SLCFBG) are utilized to generate ultra-wideband modulated pulses in the transmitter [14]. In addition, single mode fiber (SMF) and a gain flatten filter (GFF) are used as a frequency-to-time mapping system. SMF is used to map the modulation waveform form frequency domain to time domain through broadening the femtosecond laser pulse according to the difference of dispersion between wavelengths, and GFF is employed to pick out linear frequency modulated(LFM) signal without distortion by band-pass filtering on the spectrum. By properly setting the parameters of SLCFBG and frequency-to-time mapping system, ultra-wideband LFM signals can be generated with an intended bandwidth of 50 GHz. The modulated pulse echo can then be picked out by the optical pulse compression using a negative dispersion fiber Bragg gratings (NDFBG), which is a LCFBG with a negative dispersion coefficient [15]. The compressed pluses are collected by a high speed photodetector and transmitted to the data processing system where the distance information of target is calculated. Therefore, both high-speed processing and compact solutions can be achieved using the laser modulation and optical pulse compression in full optical fiber components with excellent performance.

2. System description and theory analysis

The structure of the proposed pulse compression lidar is shown in Fig. 1, the pulses from femtosecond laser are modulated using a

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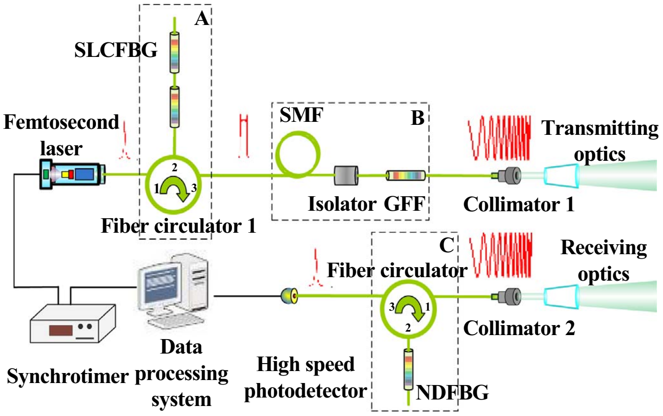

Fig. 1. The structure of proposed pulse compression lidar with ultra-wideband modulated signal: A: modulation system; B: frequency-to-time mapping system; C: optical pulse compression system.

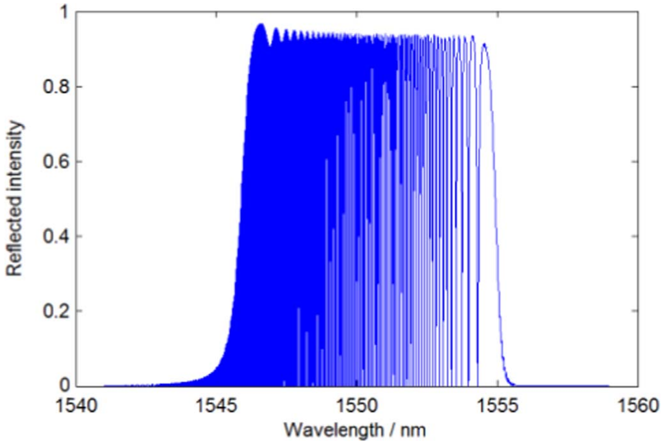

Fig. 2. Simulated reflection spectrum of SLCFBG: Chirp rate $F_1=-F_2=2.8$ nm/cm; $L_1=L_2=1.5$ cm; $h=0$.

modulation system in dashed box A. The modulation system consists of a pair of superimposed linear chirp fiber Bragg gratings with lengths L_1 and L_2, chirp coefficients F_1 and F_2, and spacing h. In addition, a fiber circulator is utilized to route the modulated pulses to the following optical fiber components.

SLCFBG is equivalent to a series of Mach–Zehnder cavities with different cavity lengths which correspond to different wavelengths. The reflection spectrum of SLCFBG can be expressed as [16]:

$$R_{F-P}=\frac{r_1+r_2-2|\rho_1||\rho_2|\cos(2\beta h-\phi_1-\phi_2)}{1+r_1r_2-2|\rho_1||\rho_2|\cos(2\beta h-\phi_1-\phi_2)},\tag{1}$$

where $\beta=2n\pi/\lambda$, n is the refractive index of fiber, and λ is the wavelength of input laser. ρ_1 and ρ_2 are the reflection coefficient, r_1 and r_2 are the reflectivity of cascaded SLCFBG. The transmitting procedure of each LCFBG can be analyzed using transmission matrix method. For a single LCFBG with length L and chirp rate F, the transmission matrix can be expressed as [17]:

$$\mathbf{F}=\prod_{j=1}^{N}\mathbf{F}_j,\tag{2}$$

where N is the number of LCFBG sections. Each section can be calculated as a uniform fiber grating. According to Ref. [18], the transmission feature of a real LCFBG normally requires $N>50$. $\mathbf{F}_j$ is the transmission matrix of j-th section:

$$\mathbf{F}_j=\begin{bmatrix}\cosh(\gamma_B\Delta L)-i\frac{\hat{\sigma}}{\gamma_B}\sinh(\gamma_B\Delta L) & -i\frac{\kappa}{\gamma_B}\sinh(\gamma_B\Delta L)\\ i\frac{\kappa}{\gamma_B}\sinh(\gamma_B\Delta L) & \cosh(\gamma_B\Delta L)+i\frac{\hat{\sigma}}{\gamma_B}\sinh(\gamma_B\Delta L)\end{bmatrix}_j,\tag{3}$$

where ΔL is the length of each section, and $\gamma_B=\sqrt{\kappa^2-\hat{\sigma}^2}$ is the coupling coefficient related to ac coupling coefficient κ and dc self-coupling coefficient $\hat{\sigma}$. Depending upon the boundary conditions, the output of femtosecond laser pulses modulated by LCFBG can be given by:

$$\begin{bmatrix}R_N\\ S_N\end{bmatrix}=\mathbf{F}\begin{bmatrix}R_0\\ S_0\end{bmatrix}=\mathbf{F}\begin{bmatrix}1\\ 0\end{bmatrix},\tag{4}$$

where R_N and S_N represent the forward and reverse mode of laser pulses. Reflection coefficient ρ_S and reflectivity r_S of SLCFBG can be derived as below:

$$\rho_S=-\frac{\mathbf{F}_{21}}{\mathbf{F}_{22}},\tag{5}$$

$$r_S=|\rho_S|^2.\tag{6}$$

Combining (1), (5) and (6), the simulated reflection spectrum of SLCFBG is shown in Fig. 2. It can be found that the output of SLCFBG is a linear chirp modulated signal which varies with wavelength. In other words, the output signal is a linear amplitude modulated signal in frequency domain.

Considering that the output of SLCFBG is still a narrow laser pulse in time domain, a frequency-to-time mapping system is placed after the fiber circulator. A piece of SMF is utilized in this section for dispersion, and a GFF consisting of long-period fiber gratings is adopted to pick out the laser pulse with intended bandwidth by band-pass filtering on the spectrum [19]. In this system, the modulated bandwidth of LFM will change with the total dispersion of the standard SMF G652 whose dispersion coefficient is about 17 ps/nm/km. For example, to generate a modulated bandwidth of 50 GHz of the LFM signal corresponds to a dispersion of 5 ns, 36.7 km G652 fiber is required in frequency-to-time mapping system. As the modulated bandwidth decreases, longer SMF is required.

After frequency-to-time mapping system, the intensity of laser pulse is then mapped into LFM signal, which can be approximated as:

$$P(t)=P_0 rect\left(\frac{t}{\tau}\right)\exp\left[j2\pi\left(f_0t+\frac{1}{2}Kt^2\right)\right],\tag{7}$$

where τ is the width of LFM pulse, $K=B/\tau$ is the modulation slope, and P_0 is the peak power of LFM pulse. The waveform of output signal is shown in Fig. 3. Thus, stable LFM pluses with high bandwidths can be generated by setting appropriate SLCFBG parameters.

It should be pointed out that the time-bandwidth product of a signal is determined by SLCFBG which enhances the *SNR* of a compression lidar, while the SMF and GFF can be used to adjust pulse width T and bandwidth B of LFM signal only.

The echo signal collected by the receiving optics consists of the reflected echo from the target with an ultra-high bandwidth, and the low-frequency backward scattering noise from the scattering media after multiple scatterings, which can be derived from the lidar equation as shown below [20]: