Optics Communications 410 (2018) 591–597

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Ghost image in enhanced self-heterodyne synthetic aperture imaging ladar

Guo Zhang [a,b], Jianfeng Sun [a,*], Yu Zhou [a], Zhiyong Lu [a], Guangyuan Li [a,b], Mengmeng Xu [a,b], Bo Zhang [a,b], Chenzhe Lao [a,b], Hongyu He [a,b]

[a] Key Laboratory of Space Laser Communication and Detection Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Science, No. 390, Qinghe Road, Jiading District, Shanghai 201800, People's Republic of China

[b] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

A R T I C L E   I N F O

Keywords:
Lidar
Synthetic aperture radar
Coherence imaging
Remote sensing

A B S T R A C T

The enhanced self-heterodyne synthetic aperture imaging ladar (SAIL) self-heterodynes two polarization-orthogonal echo signals to eliminate the phase disturbance caused by atmospheric turbulence and mechanical trembling, uses heterodyne receiver instead of self-heterodyne receiver to improve signal-to-noise ratio. The principle and structure of the enhanced self-heterodyne SAIL are presented. The imaging process of enhanced self-heterodyne SAIL for distributed target is also analyzed. In enhanced self-heterodyne SAIL, the phases of two orthogonal-polarization beams are modulated by four cylindrical lenses in transmitter to improve resolutions in orthogonal direction and travel direction, which will generate ghost image. The generation process of ghost image in enhanced self-heterodyne SAIL is mathematically detailed, and a method of eliminating ghost image is also presented, which is significant for far-distance imaging. A number of experiments of enhanced self-heterodyne SAIL for distributed target are presented, these experimental results verify the theoretical analysis of enhanced self-heterodyne SAIL. The enhanced self-heterodyne SAIL has the capability to eliminate the influence from the atmospheric turbulence and mechanical trembling, has high advantage in detecting weak signals, and has promising application for far-distance ladar imaging.

1. Introduction

Synthetic aperture imaging ladar (SAIL) can enable fine resolution and two dimensional (2D) active imaging at long ranges by using small diameter optics. It is necessarily work in side-looking mode, employs synthetic aperture imaging in ladar platform moving direction and ranging in transverse direction, a number of laboratory experiments [1–11] and flight demonstrations of side-looking SAIL were reported [12,13]. The reconstructed target image of side-looking SAIL is mainly determined by the beat frequency between the return signal and local oscillator. However, the phase of return signal is disturbed by atmospheric turbulence, and the phase of local oscillator is disturbed by mechanical trembling. Thus, the image quality of side-looking SAIL is seriously influenced by atmospheric turbulence and mechanical trembling. Based on the key ideas of wavefront transformation and regulation by optical techniques, the down-looking SAIL was proposed [14] and a number of experiments in laboratory [15,16] and outdoor were reported [17]. The down-looking SAIL with a transmitter of two coaxial and orthogonal-polarization beams, and a receiver of self-heterodyne detection, self-heterodynes two polarization-orthogonal signals to eliminate the phase disturbance caused by atmospheric turbulence and mechanical trembling, significantly relaxes the difficulties in side-looking SAIL. The experiment of airborne down-looking SAIL was reported, and the laser power was 20 W for imaging the target at 3 km [18]. In down-looking SAIL, the echo signal is weak during the far-distance imaging, and the laser power is limited, the laser with high power can damage the optical components. Self-heterodyne detection has extremely low signal-to-noise ratio (SNR) when echo signal is weak. Thus, the down-looking SAIL is limited in far-distance imaging. However, the interference of weak echo signal and strong local oscillator can effectively improve the SNR in heterodyne detection [19,20].

The enhanced self-heterodyne SAIL is similar to down-looking SAIL, with a transmitter of two coaxial and orthogonal-polarization beams, whereas with a heterodyne receiver instead of self-heterodyne detection. In the process of digital signal processing, the enhanced self-heterodyne SAIL self-heterodynes two polarization-orthogonal signals to eliminate the phase disturbance caused by atmospheric turbulence and mechanical trembling. A point target was reconstructed in enhanced self-heterodyne SAIL as well as in down-looking SAIL experiments,

* Corresponding author.
E-mail address: sunjianfengs@163.com (J. Sun).

https://doi.org/10.1016/j.optcom.2017.10.079
Received 24 August 2017; Received in revised form 23 October 2017; Accepted 29 October 2017
0030-4018/

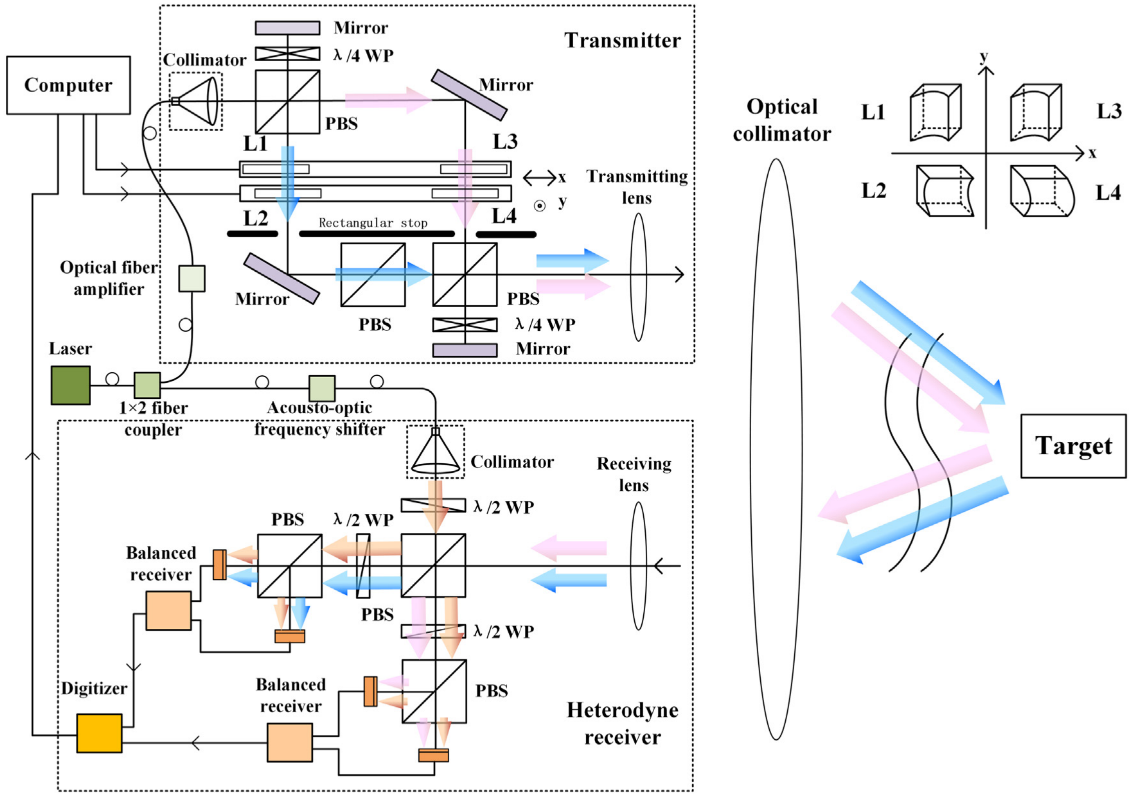

Fig. 1. Structure of enhanced self-heterodyne SAIL; x is the cylindrical lenses L1 and L2 moving direction (orthogonal direction of travel), y is the cylindrical lenses L3 and L4 moving direction (travel direction).

the SNR of the point target final image in enhanced self-heterodyne SAIL was higher than that in down-looking SAIL [21]. The enhanced self-heterodyne SAIL can improve the SNR of target image, has high advantage in detecting weak signals, and has promising application for far-distance ladar imaging. In down-looking SAIL, the phases of two orthogonal-polarization beams are modulated by four cylindrical lenses in transmitter to improve resolutions in orthogonal direction and travel direction [14], which will generate ghost image in enhanced self-heterodyne SAIL. Thus, we propose a method to eliminate the ghost image, which is significant for enhanced self-heterodyne SAIL far-distance imaging.

This paper is organized as follows. In Section 2, the imaging process of enhanced self-heterodyne SAIL for distributed target is analyzed. In Section 2.1, the generation process of ghost image is mathematically detailed. In Section 2.2, the method of eliminating ghost image is proposed, and the imaging process of enhanced self-heterodyne SAIL without ghost image is presented. Section 3 concerns the laboratory demonstration of enhanced self-heterodyne SAIL. In Section 3.1, imaging results of enhanced self-heterodyne SAIL with ghost image are discussed. Section 3.2 describes imaging results of enhanced self-heterodyne SAIL without ghost image. The conclusion is presented in Section 4.

2. Imaging process of enhanced self-heterodyne SAIL for distributed target

The structure of enhanced self-heterodyne SAIL as shown in Fig. 1. The 1×2 polarization maintaining fiber coupler is used to split the laser into two beams, signal light and local oscillator. Signal light is amplified by an optical fiber amplifier and transmitted to the transmitter. Local oscillator is frequency-shifted by the acousto-optic frequency shifter and interferes with signal light. A rectangular stop near cylindrical lenses is used to adjust the size of the inner beam. In order to improve resolutions in orthogonal direction and travel direction, the phases of two polarization-orthogonal beams are modulated by four cylindrical lenses L1, L2, L3 and L4 in transmitter. Plano-concave cylindrical lenses L1, L2, L3 and plano-convex cylindrical lens L4 are placed on the focal plane of the transmitting lens. Cylindrical lenses L1 and L2 move fast along the orthogonal direction, the shift of L1 and L3 produce a linear phase in the orthogonal direction of travel. L2 and L4 move slowly along the direction of travel to produce a spatial quadratic phase history, instead of move the target.

2.1. Ghost image in enhanced self-heterodyne SAIL

In Fig. 1, the inner optical fields of the two polarization-orthogonal beams at the focal plane of the transmitting lens can be described by [14]

$$e^0_{DH}(x, y; t_f, t_s) = \mathrm{C} \times \mathrm{rect}\frac{x}{L_x}\mathrm{rect}\frac{y}{L_y} \times \exp(-j\frac{\pi}{\lambda}(\frac{(x - v_x t_f - S_b)^2}{R_1} + \frac{(y - v_y t_s)^2}{R_1})). \quad (1)$$

$$e^0_{DV}(x, y; t_f, t_s) = \mathrm{C} \times \mathrm{rect}\frac{x}{L_x}\mathrm{rect}\frac{y}{L_y} \times \exp(-j\frac{\pi}{\lambda}(\frac{(x + v_x t_f - S_b)^2}{R_1} - \frac{(y - v_y t_s)^2}{R_2})). \quad (2)$$

where λ is the wavelength of signal light, R_1 is the equivalent curvature radius of L1, L2 and L3, R_2 is the equivalent curvature radius of L4, L_x and L_y are the size of rectangular stop, t_f is the fast scanning time, t_s is the slow scanning time, v_x is the scanning velocity in the x direction (orthogonal direction), v_y is the scanning velocity in the y direction (travel direction), S_b is the distance between the center of cylindrical lens L1 and the corresponding propagation beam. The inner field is imaged onto the focal plane of the optical collimator with an amplification factor of M, $M = F/f_t$. The focal length of the optical collimator is F, the focal length of the transmitting lens is f_t.