

Coherent beam combination of multiple phase modulated optical signals for a coherent Doppler LIDAR

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Abstract – This paper presents Coherent Beam Combination (CBC) of two phase modulated optical signals using frequency shifter to phase control for a coherent Doppler LIDAR. When phase locking was obtained, we ensured combining efficiency and phase error is 95[%] and 0.2[deg.] ($\lambda/1800$), respectively. This measurement result is good agreement with designed combining efficiency of 99[%] and phase error of 0.3[deg.].

INTRODUCTION

A coherent Doppler LIDAR is an attractive sensor for remote wind sensing in clear atmospheric condition. All-fiber coherent Doppler LIDAR system has many advantages such as its compactness, eye-safety and reliability thanks to using commercial off the shelf components from telecom products¹. The increasing output transmit power is one of the important issue to enhance measurable distance for wind sensing. Coherent beam combining (CBC) is a promising candidate to increase the output power because of no frequency degradation in transmitting beams. The output power of 100[kW] has been achieved by using a CBC of 7 beams². In this CBC system many grating lobes occurred at far field position caused by side-by-side beam combining. These side lobes are the problem for a coherent LIDAR because of the degradation for receiving efficiency. A method to solve this problem is to superimpose beams on a diffractive optical element (DOE) or beam splitter (BS)³⁻⁴. This approach can remove grating lobes, but it is necessary to use a single photo detector to phase locked⁵. Previously, CBC with a single photo detector has been reported that using a frequency-tagging technique and using phase modulators to phase control^{5,6}. All phase modulators have a limited range of achievable phase shifts ($\pm 2\pi$), limited by saturation phase control voltage on the upper and lower bounds. In order to avoid this saturation, the control voltage should be reset. While the reset circuit is operating, the power of the combined beam and phase stability are degraded because of a finite reset time. A practical solution to this problem is to control phase by using a frequency shifter⁷ since it rolls an instantaneous frequency controller with no phase slip. This technique is applicable for endless phase control to maintain coherent beam combining condition.

In this paper, we demonstrated on grating-lobe-free CBC of phase modulated optical signals using frequency shifter to phase control.

THEORY

In the coherent beam combination of multiple phase modulated, the combining efficiency and phase error are varied by phase modulation depth. Assuming that the phase modulated fields are plane wave and are identically polarized, then the i^{th} element optical fields, $E_{Si}(t)$ are shown in Eq. (1), where E_{Si} and $\Delta\theta_i$ represent the field amplitude and the optical phase of the i^{th} beam, respectively; f_0 , f_m and f_i represent the laser frequency, master oscillator frequency and i^{th} beam phase modulated frequency, respectively; m represents the phase modulation depth. The coupling efficiency (η) is the ratio of power in the phase modulated signal total power to not phase modulated signal total power. The combining efficiency, η is shown in Eq. (2), where N represents total beam number. The phase error is shown in Eq (3) and (4), where SNR represents the signal - to - noise ratio; P_{Si} represents the optical power; J , h and B represent Bessel function, Planck's constant and band width, respectively.

$$E_{Si}(t) = E_{Si} \exp \left[i \left\{ 2\pi(f_0 + f_m)t + m \times \sin(f_i t) + \Delta\theta_i \right\} \right] \quad (1)$$

$$\eta = \frac{\left| \sum_i^N E_{Si} \exp \left[i \left\{ 2\pi(f_0 + f_m)t + m \times \sin(f_i t) + \Delta\theta_i \right\} \right] \right|^2}{\left| \sum_i^N E_{Si} \exp[i 2\pi(f_0 + f_m)t] \right|^2} \quad (2)$$

$$\Delta\theta_i = \tan^{-1}\left(\frac{1}{\sqrt{2 \times SNR}}\right) \quad (3)$$

$$SNR = \frac{P_{Si} \times \{J_1(m)\}^2}{2hfB \times \{J_0(m)\}^2} \quad (4)$$

Fig.1 (a) and (b) show dependence of combining efficiency and phase error on phase modulated depth. We designed phase modulation depth is 0.03 leading to combining efficiency is 99[%] and phase error is 0.3[deg.].

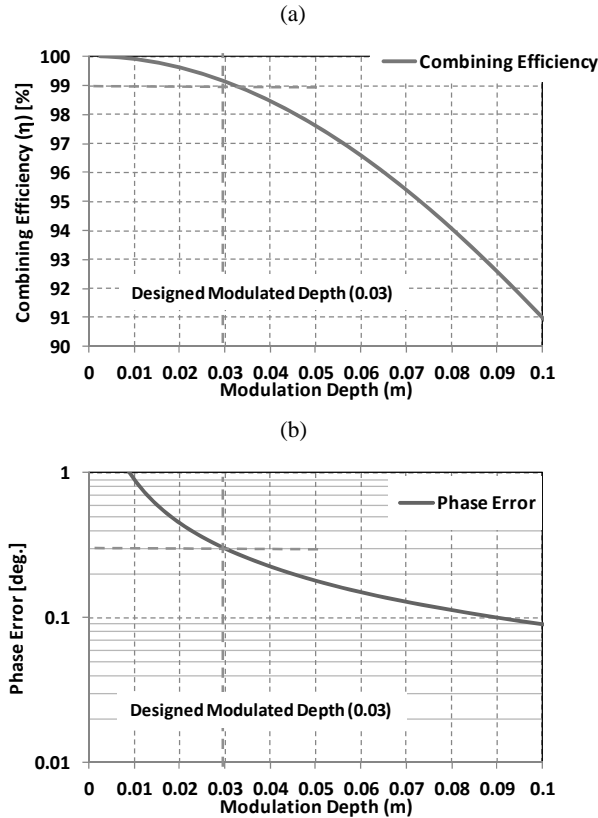


Fig. 1 (a) Dependence of combining efficiency on phase modulated depth. (b) Dependence of phase error on phase modulated depth under shot noise limit. The designed combining efficiency and phase error are 99 % and 0.3 deg., respectively.

EXPERIMENTAL SETUP

The experimental setup of the coherent beam combination of two phase modulated optical signals was shown in Fig.3. Single frequency single polarization fiber laser was used as master oscillator laser (MO-Laser) whose wavelength and line width were 1550 nm and 100 kHz, respectively. The output from a MO- laser was divided into two signal beams and a local beam. Signal beams were coupled to frequency shifter, phase modulator and fiber amplifier.

Signal beams are frequency shifted by a 110 MHz frequency shifter. Each phase modulator were operated at frequency of 40 MHz and 60 MHz with modulation depth of a 0.03. The outputs from a fiber amplifier were collimated with 10 mm in diameter and combined on a beam splitter (BS1). The output from BS1 were focused on an IR camera for monitoring far field pattern (FFP). The other output signal beam from BS1 combined with a local beam (Local) using a BS2. The output from BS2 were coupled a photo diode. Each optical heterodyne signals consists of a carrier and two side carriers with different frequencies. In frequency discrimination circuit, one side carrier was extracted from a carrier and the other side carrier, then converted to the same frequency as an RF master oscillator. The output signals from frequency discrimination circuit were followed to PLL circuit to detect phase error and to feedback to each frequency shifter. Each signal beam was locked to the RF master oscillator. In order to verify the phase locking status, output signals from PLL circuit split and measured using network analyzer. Note that the phase error signals were fed back to each frequency shifter as instantaneous frequency controllers, leading to an endless phase control without any phase slip.



Fig. 2 Snap shot of experimental setup of optical phase controller

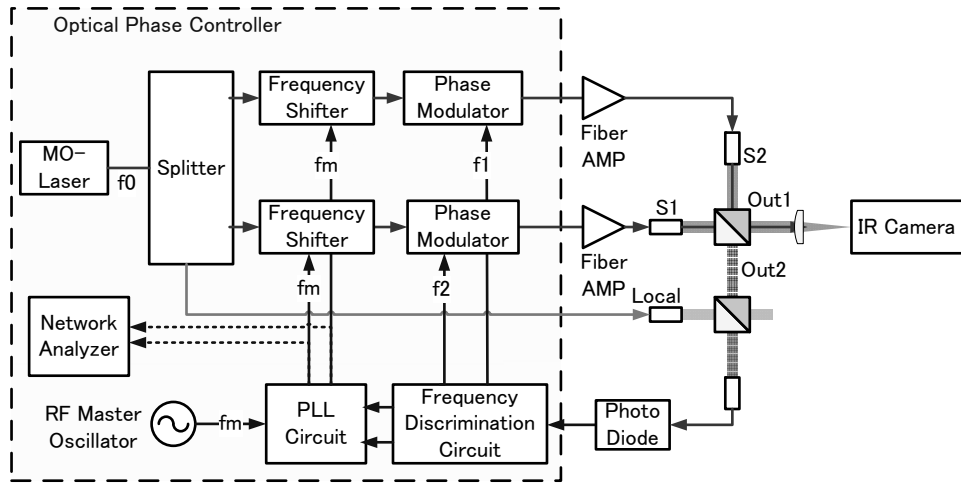


Fig. 3 Block diagram of an experimental Setup

EXPERIMENTAL RESULTS

At first far field pattern has been measured. The beam combination results are shown in Fig.4. Fig. 4 shows the FFP of (a) S1 output beam, (b) S2 output beam, (c) combined beam in PLL turning off and (d) combined beam profile in PLL turning on. The each beam profile is single mode without grating lobes. Fig. 5(a) shows the measured far field pattern of the incoherently added beam (PLL OFF) and the coherently added beam (PLL ON). Fig. 5(b) shows the far field intensity along the x-axis. Comparing the coherently added beam to incoherently added beam, the peak intensity ratio is 1.95, leading to combining efficiency is 95[%]. This measurement result is good agreement with designed combining efficiency of 99[%].

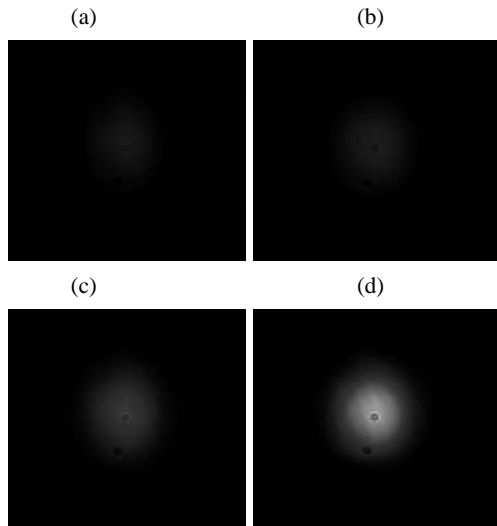


Fig. 4 Far Field Profile (a) S1 output, (b) S2 output, (c) Output(PLL OFF), (d) Output(PLL ON)

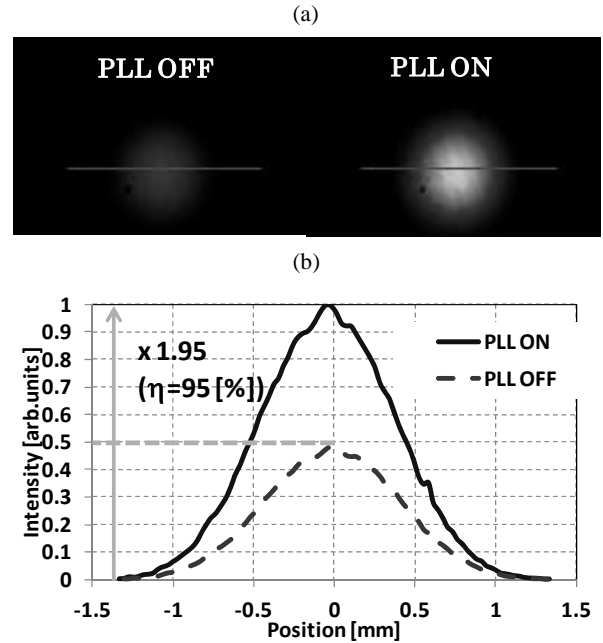


Fig. 5 (a) Far field Pattern in (left) turning off PLL and (right) turning on PLL (b) Far field intensity along the x-axis

Next a performance of phase locked has been tested by measuring output PLL circuits signals where the turning on/off PLL. Fig.6 shows the phase error measured in the network analyzer. It is clearly demonstrated that residual phase error has been decreased less than 0.2[deg.] compared to phase error of 70[deg.] where the turning off PLL. This measurement result of 0.2[deg.] ($\lambda/1800$) is good agreement with designed phase error of 0.3[deg.]

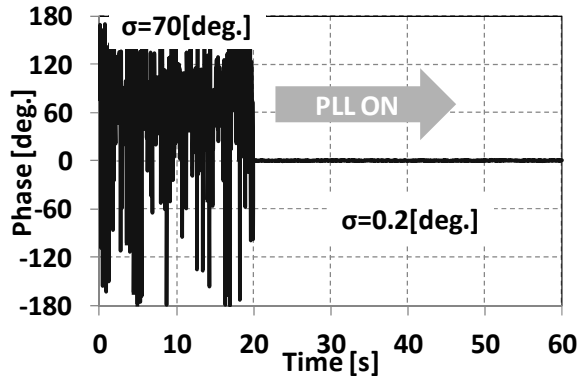


Fig. 6 Measurement of phase error

SUMMARY

We have demonstrated coherent beam combination with multiple phase modulated optical signals. When phase locking was obtained, we ensured combining efficiency and phase error is 95[%] and 0.2[deg.], respectively. This measurement result is good agreement with designed combining efficiency of 99[%] and phase error of 0.3[deg.].

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