Consideration of a phase camera configuration; one-beam scanning and two-beam scanning

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Abstract

There are two candidates of configuration in the phase camera, which is called one-beam scanning and two-beam scanning. In this report, the pros and cons of them are considered quantitatively.

1 Introduction

The phase camera uses heterodyne detection. A frequency shifted laser beam (the reference beam) is combined with the test beam at BS. After the combination, two beams are observed using a photo detector (PD). In order to observe the wavefront, the test beam is scanned by a scanner. This scanner location makes two different configuration. Figure 1 shows

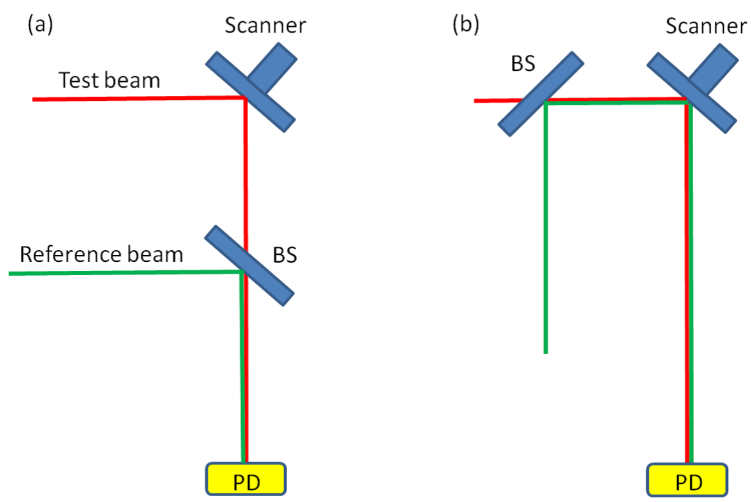

Figure 1: Optical configurations. (a) one-beam scanning, (b) two beam-scanning.

those two configurations. In the case of Figure 1-(a) only the test beam is scanned, while two beams are scanned at the same time in Figure 1-(b). There are merit and demerit in each case. In this report, the pros and cons are summarized to think which configuration is better.

2 Pros and cons

One-beam scanning

Merit

- SNR increase by a higher power detection at the test beam edge

Demerit

- Fringe visibility loss due to dense fringes made by different incident angle
- Amplitude should be corrected including this fringe visibility loss

Solution

- Long distance between PD and scanner (small angle operation of the scanner); longer than 26 cm

Two-beam scanning

Merit

- Cancelling phase shift caused by the scanner and tilt of beams

Demerit

- SNR reduction by a less power detection at the beam edge
- Calibration is necessary for amplitude measurement

Solution

- Sufficient power for the incident beams (above 5 mW for each beam with a modulation depth of 0.1 rad)

Figure 2: Summary of the pros and cons.

Figure 2 shows the summary of the pros and cons of two configurations.

The merit of the one-beam scanning is a high SNR at the beam edge because the reference beam is fixed on the center of the beam where the laser power of the reference beam becomes maximum. The demerit of the one-beam scanning is the fringe visibility loss by a different incident angle between the test beam and reference beam. The difference of the incident angle of two beams makes a spatial fringe pattern, which is dense at a beam edge. A PD has a finite active area where the beam signal is averaged. If the size of the fringe pattern is smaller than that of the active area, the fringe brightness and darkness are canceled, i.e. the fringe visibility is degraded. In order to solve this demerit, the scanner operation angle should be small to keep two beams almost in line. For the small angle operation with keeping a scanning beam area, a long distance between the scanner and PD is necessary. According to the following section, the necessary distance between the scanner and PD is 26 cm to cover the scanning beam area of 5 mm diameter.

While the merit of the two-beam scanning is the cancellation of phase shift by the scanning effect both at the scanner mirror position and at the PD position. This cancellation becomes significant in the case of the absolute phase measurement, but this is less priority because this phase camera employs the relative phase measurement. The demerit of the two-beam scanning is low SNR at the beam edge. The two-beam scanning loses the laser power at the beam edge because the reference beam is also scanned. In order to solve this, a suitable power is necessary to keep sufficient SNR in a measurement region. According to the following section, the necessary power of each beam is 5 mW at the PD position. Also, in order to analyze the amplitude of the test beam, the reference beam should be calibrated although the calibration is easy; just to scan the reference beam without the test beam.

3 Fringe visibility loss by incident angle mismatch

The one-beam scanning configuration scans only the test beam. In such case, the incident angle of the test beam becomes different from the fixed reference beam during scanning. This makes a phase shift at PD position, and then the interference pattern is changed. According to the reference [1], the fringe gap Λ is written as

$$\Lambda = \frac{\lambda}{2\sin\theta}, \tag{1}$$

here λ is the wavelength of the laser, and θ is the incident angle defined in Figure 3.

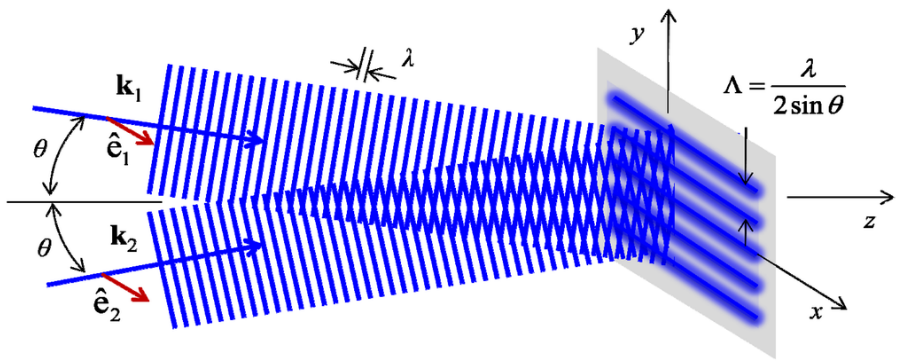

Figure 3: Two-beam interference with different incident angle. This figure is in the reference [2].

The fringe gap should be larger than the active area of a PD. In other words, the spatial fringe pattern should be distinguishable by a PD. By taking the Nyquist theorem into account, the condition of

$$\Lambda > 2d_{\mathrm{PD}} \tag{2}$$

is imposed. d_{PD} is the diameter of the active area of a PD. Note that this condition includes a safety margin by a factor of 2 (the condition to avoid the full cancellation is $\Lambda > d_{\mathrm{PD}}$). From Eq.(1) and Eq.(2),

$$\theta < \frac{\lambda}{4d_{\mathrm{PD}}} \tag{3}$$

is obtained when $\theta \ll 1$. We use a PD with an active area of $55\,\mu$m, and the laser wave length of 1064 nm. The resultant θ is 4.8 mrad, meaning the difference of the incident laser angle (2θ) of 9.7 mrad.

The scanning pattern is the Archimedean spiral with a radius of 2.5 mm at PD position. The scanning angle depends on the distance between the scanner and PD to cover this scanning area. The condition of Eq.(3) is rewritten as

$$r > \frac{2ld_{\mathrm{PD}}}{\lambda} \tag{4}$$

using a relation of $l = r \cdot 2\theta$ where l is the radius of the scanning area and r is the distance between the scanner and PD. By using 2.5 mm of l, $r = 0.26$ is obtained. The necessary distance between the scanner and PD is 26 cm.

Even if the condition of Eq.(3) and Eq.(4) is satisfied, the fringe visibility is degraded by this effect. The loss factor η by averaging fringe pattern is calculated by

$$\eta = \frac{1}{\epsilon}\int_{-\epsilon/2}^{\epsilon/2} \cos x \, dx, \tag{5}$$

here $\epsilon = 2\pi d_{\mathrm{PD}}/\Lambda$. Even when r is 26 cm, η is 0.64 (the signal is down to 64% of the beam center) at the edge of the scanning area. This fringe visibility loss is a demerit of the one-beam scanning.

4 SNR and sensitivity

The two-beam scanning makes a steep power loss at the edge of the combined beams because of the Gaussian power distribution. In order to compare the two configurations, calculations of SNR and sensitivity of the phase camera is straightforward. Figure 4 shows a calculation result of them in the case of PC2, which is planed to set on EPRB with an length of 50 cm distance (assumption) between the scanner and PD. The flat beam is assumed. This calculation includes the visibility loss discussed in the previous section. The expected input power is 12 mW - 17 mW of the test beam (carrier), 0.5% of the carrier for the 6 MHz sideband (USB), and 7 mW of the reference beam (measured), respectively. In this calculation, the worst case about the laser power is assumed.

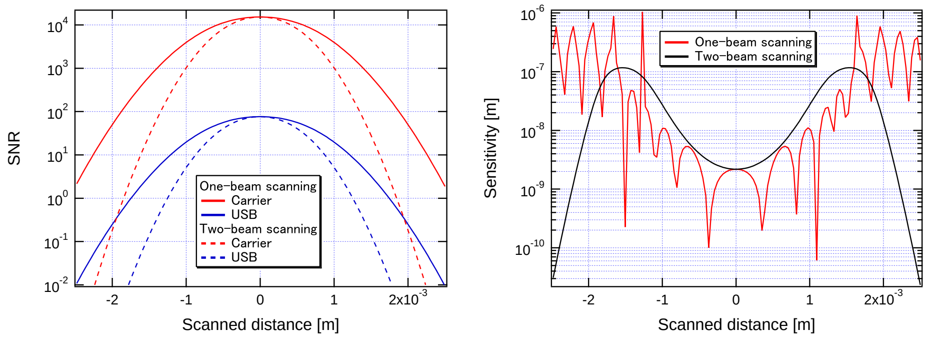

Figure 4: Comparison of SNR and sensitivity between one-beam scanning and two-beam scanning in PC2. Left: signal to noise ratio (SNR). Right: sensitivity (residual phase after phase subtraction between carrier and upper sideband is divided by the wave number). The assumed input power of the reference beam at PD is 7 mW, it of the test beam (carrier) is 12 mW, and it of the sideband (USB of 6 MHz) is 0.06 mW. The scanned distance is ± 2.5 mm. Both beams are flat beam with a radius of 833 μm. The sensitivity of the two-beam scanning (black line) looks better outside of about 1.5 mm because of noise > signal and their common subtraction, but it is meaningless since the SNR is lower than one.

The one-beam scanning has a better SNR widely, in other words, broad observation area. It is a merit of this configuration. Also in the sensitivity, the one-beam scanning configuration is better than the two-beam scanning. The requirement of the sensitivity is 2 nm according to the reference [3]. The current achievable area fitting this requirement is about $\pm 500\,\mu$m by the one-beam scanning. The laser power limitation is more serious than the space limitation in the current situation. So the one-beam scanning configuration is preferable in PC2 (and also PC1, PC3 because the input laser power is expected to be smaller than PC2). Here, I showed only results. The calculation detail will be explained in the other report.

5 discussion

There is a discussion point whether it is real or not the dips of the sensitivity in the one-beam scanning. The dips comes from the wrapped phase (zero/2π-crossing). If we use the unwrapping of the phase with noise in low SNR region, an unexpected phase jump could happen. This might be a possible problem in the aberration map reconstruction from the unwrapped phase. The phase unwrapping for 2D is not so simple [4]. This should be checked. In the case of one-beam scanning, we have to treat this wrapping or unwrapping phase because a lot of phase shift exceed 2π is expected due to the beam tilt.

The power limitation is serious but this calculation results are the worst case scenario. The test beam can be larger than it by 50% at maximum. The reference beam has an unexpected loss now. If this loss is solved, the reference beam power is increased by 50%. We use a bit small output amplifier for AOM, which creates the reference beam. By replacing this amplifier with a high power, the beam power is increased about 20%. The AOM location is the Atrium where the distance from EE-room (the location of RF signal) is 15 m because the AOM and optical fiver junction parts should be housed in a clean environment. This long distance cable for RF signal makes additional loss of 10%. In total, the sensitivity can be improved by a factor of 2-3.

6 Conclusion

There are two possible optical configuration in the phase camera. The one-beam scanning makes a fringe visibility loss by dense fringes due to an incident angle difference between the test beam and reference beam. The solution is to prepare enough space (the distance between the scanner and PD is longer than 26 cm). The two-beam scanning has a steep power loss at the beam edge due to the Gaussian power distribution. The solution is to use enough laser power. According to the SNR calculation, the laser power limitation is more serious than the space limitation in the current situation of PC2. It is better to take the optical configuration of the one-beam scanning for all of PCs (PC1, PC2, and PC3) because PC1 and PC3 is expected to be less power than PC2. Note that the one-beam scanning makes phase jumps by crossing $0/2\pi$ of the phase. We should carefully consider a suitable manner to use the unwrapping of the phase.

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