Nanometer positioning control by a multiple-pass Laser Doppler displacement meter

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Abstract

High accuracy positioning systems in the nanometer range are needed for IC fabrication, research in micro-electro-mechanical systems (MEMS) and nanotechnology. A linear encoder with sub-nanometer resolution is needed for such applications as large field x-ray lithography, large field scanning microscopes, x-ray microscopes, x-ray micromachining, etc. For a conventional laser interferometer the resolution is about $\lambda/64$ or 10 nm. Higher fringe interpolation, may be limited by the optical non-linearity, electronic noises, detector shot noises, and environmental conditions. Furthermore, for nanometer positioning measurement by a laser interferometer in a laboratory environment, the accuracy or resolution is limited by the speed of light changes caused by air circulation or turbulence. To solve these problems, a multiple-pass optical arrangement can be used to increase the resolution and to minimize the effect of air turbulence.

Reported here is a laser Doppler displacement meter with a multiple-pass optical arrangement developed by Optodyne to achieve sub-nanometer resolution with a measuring range of 100 mm and a maximum velocity of 600 mm/sec. The optical setup is compact and easy to align. The performance of the multiple-pass optical arrangement, a comparison with a single-pass laser interferometer, various sources of errors and uncertainties, the test setup and results, will be described.

I. Introduction

High accuracy positioning systems in the nanometer range are needed for IC fabrication such as deep UV lithography, research in micro-electro-mechanical systems (MEMS) and nanotechnology. A linear encoder with sub-nanometer resolution is needed for such applications as large field x-ray lithography, large field scanning microscopes, x-ray microscopes, x-ray micromachining, etc.

For a conventional laser interferometer the resolution is about $\lambda/64$ or 10 nm. With higher fringe interpolation, $\lambda/1024$ or 0.6 nm can be achieved [1]. However, the major uncertainties are the optical non-linearity, electronic noises and detector shot noises [2]. For high resolution and high accuracy measurement in a laboratory environment, the measurement is effected by the environment such as mechanical and acoustic vibrations, thermal expansion, and air turbulence.

Because of the air circulation, or turbulence, the effective laser beam path length (OPD) is fluctuating. This fluctuation limits the accuracy of the laser measurement. Long time-average has been used to minimize the effect of air turbulence. However, too much averaging may cause a time-lag and inconvenience in the measurement. Another method is to control the environment to minimize the air circulation and temperature gradient or to cover the laser beam path completely. However, in a shop environment, both of these are difficult to achieve.

To overcome these difficulties, a laser Doppler displacement meter (LDDM) with a 6-pass optical arrangement is used to achieve sub-nanometer resolution with a measuring range of 100 mm and a maximum velocity of 600 mm/sec. The optical setup is compact and easy to align. As compare with a laser interferometer, the advantages are: higher resolution, less effected by air turbulence, less shot noises, less non-linear phase distortion, and less non-linearity error. The multiple-pass optical arrangement, various sources of errors and uncertainties, the test results and experimental comparison with a single-pass laser interferometer will be described.

II. Laser interferometers in a laboratory environment

There are optical, electrical, and environmental limitations on high fringe interpolation to achieve high resolution in a laboratory environment. The optical non-linearity or non-linear phase distortion is a fundamental limit on the accuracy of the heterodyne Michelson interferometer caused by leakage of the frequency components in the beam splitter [2]. A typical optical non-linearity is 6 nm [4]. For high fringe interpolation, high signal-to-noise ratio (S/N) is important. Reducing the electronic noises in the circuit and the shot noises in the photo-detector will increase the S/N, and also improving the laser alignment will increase the fringe contrast or the S/N.

Usually, the material thermal expansion is the largest source of error in the positioning accuracy. However, with controlled room temperature and using invar material (thermal expansion coefficient is near zero at room temperature), the effect of thermal expansion can be minimized.

Air turbulence or index of refraction fluctuation is the most commonly discussed error source in interferometer accuracy. Small thermal gradients are present in the environment. Because the thermal diffusivity of air is low (0.2 cm^2/sec), the thermal in-homogeneities are mixed by the airflow before they reach equilibrium. In a region 10 cm long, the time scale for thermal equilibrium is 500 sec, while the transit time for a 100 LFM flow is 0.2 sec. Hence the time scale for turbulence is from a few msec up to 200 msec.

Mechanical vibration is another source of errors. These are the vibration of the floor and sonic frequencies transmitted through air and through the supporting structure. A table with good vibration isolation and damping is essential. With proper isolation, damping and acoustic shielding, the effect of thermal heating, mechanical and acoustic vibrations can be minimized.

III. Laser interferometer and Single aperture laser Doppler system

Conventional laser interferometers are based on the Michaelson interferometer. There are two laser beams, the output beam and the return beam, which are parallel but displaced about 25 mm, as shown in the top of Fig. 1. Hence, large optics is required. Also, the alignment is critical, 3 elements have to be aligned co-axially.

The single-aperture LDDM laser system is based on laser Dopplermetry. The laser head is very compact (25 mm x 25 mm x 202 mm) and is completed with stabilization circuits, electro-optics, and photo-detectors. As shown in the bottom of Fig. 1, the output beam and the return beam share the same aperture. Hence large optics is not required. Hence it is more compact and flexible.

The major features of the LDDM single-aperture laser system are compact, small laser head and reflector, high resolution and high accuracy, versatile and flexible. The laser stability is 0.1 ppm, the laser system accuracy is 1 ppm, the resolution is 2 nm, the maximum range is 5 m, and the maximum speed is 5 m/sec.

IV. Multiple-pass optical arrangement

For a typical laser interferometer, the laser beam is reflected by a retroreflector target, and the displacement of the target is determined by measuring the change in the optical path length. A multiple-pass is an optical arrangement, with the laser beam reflected back and forth between the retroreflector target and some mirrors or prisms mounted stationary with the laser head. It has been shown in Ref [3, 4] that multiple-pass optical arrangement can increase the resolution, and reduce the effect of air turbulence.

Conventional multiple-pass optical arrangements using mirrors are rather complex, balky and difficult to align. This is because the conventional laser interferometer uses 2 apertures. A 6-pass optical arrangement developed by Optodyne can easily be achieved by attaching an optical adapter to the single aperture laser head and a 38 mm diameter retroreflector target as shown in Fig. 2. Using the property of a cube corner prism, the incident and reflected laser beam are always parallel. Hence the alignment becomes easy. The number of passes between the optical adapter and the retroreflector is increased by a factor of 6.

In the 6-pass optical arrangement a 1 mm displacement of the retroreflector target becomes a 6 mm increment of the effective optical path length. Hence, the resolution is increased by a factor of 6 and the air turbulence is averaged over the 6 parallel paths. However, the maximum range and the maximum velocity are also reduced by a factor of 6. A factor of 12 is also possible with multiple corner cubes. A schematic of the 12-pass optical arrangement is shown in Fig. 3.

The major advantages of the 6-pass laser system are: higher resolution, less effected by air turbulence, less shot noises, and less non-linear phase distortion. The disadvantages are: shorter range, lower speed, more optical components and less lateral tolerance.

V. Performance test and results

The performance of a laser system with 6-pass optical arrangement was compared with a single-pass laser interferometer. Both laser systems were set up co-axially with both retroreflectors mounted together and with equal distances from the laser heads. A typical result is shown in Fig. 4. The heavy line is the fluctuation in the 6-pass optical arrangement and the light line is the fluctuation in a single-pass optical arrangement. The effect of air circulation or the change in refractive index, is reduced considerably in the 6-pass optical arrangement.

To demonstrate the sub-nanometer resolution in the laboratory environment, a 12-pass optical arrangement with a PZT driver is used to move the stage at an increment of 0.2 nm. As shown in Fig. 5, the 0.2 nm steps are clearly resolved.

VI. Summary and conclusion

In summary, a laser Doppler displacement meter with a multiple-pass optical arrangement has been developed by Optodyne. The performance is sub-nanometer resolution with a measuring range of 100 mm and a maximum velocity of 600 mm/sec. The optical setup is compact and easy to align. It is also less sensitive to the air turbulence.

References

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Figure Captions

1. A comparison of laser interferometer and a single-aperture laser Doppler system.
2. A 6-pass optical arrangement using an optical adaptor and a 38 mm diameter retroreflector target.
3. A schematic of a 12-pass optical arrangement and laser beam path.
4. Effect of air circulation on a 6-pass optical arrangement and on a single pass optical arrangement.
5. Using the 12-pass optical arrangement, 0.2 nm steps are clearly resolved.

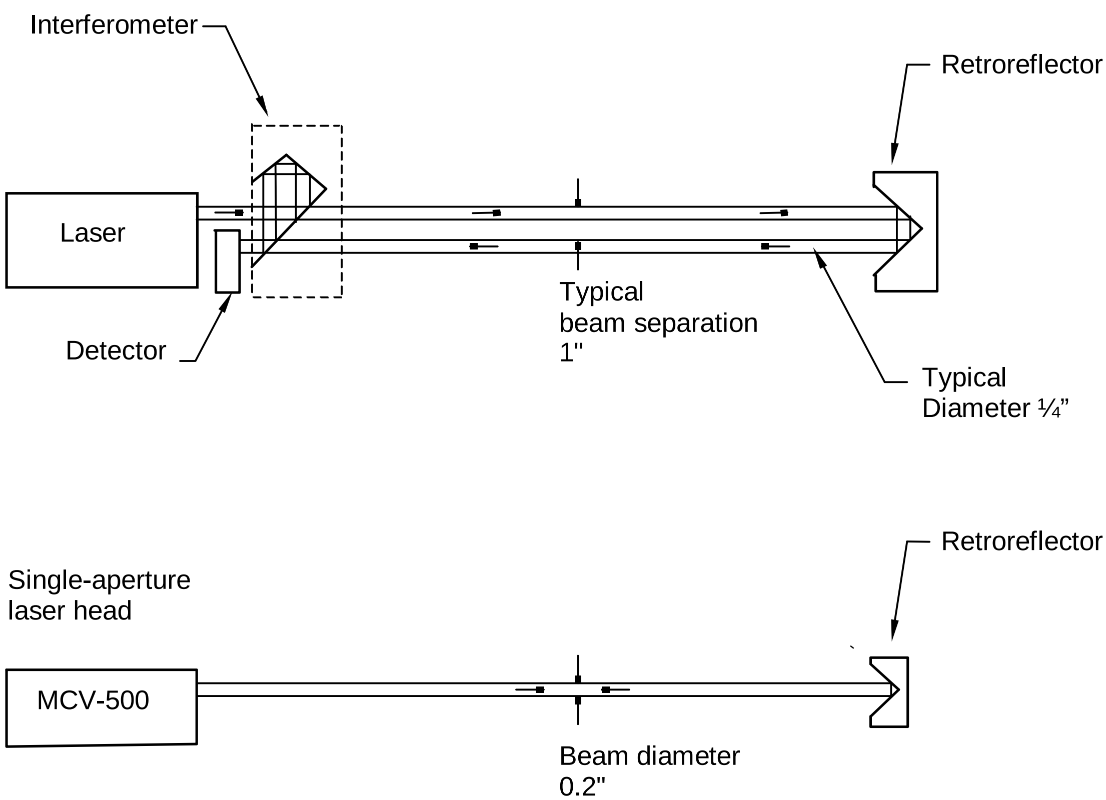

Fig. 1 A comparison of a laser interferometer and a single-aperture Laser Doppler system

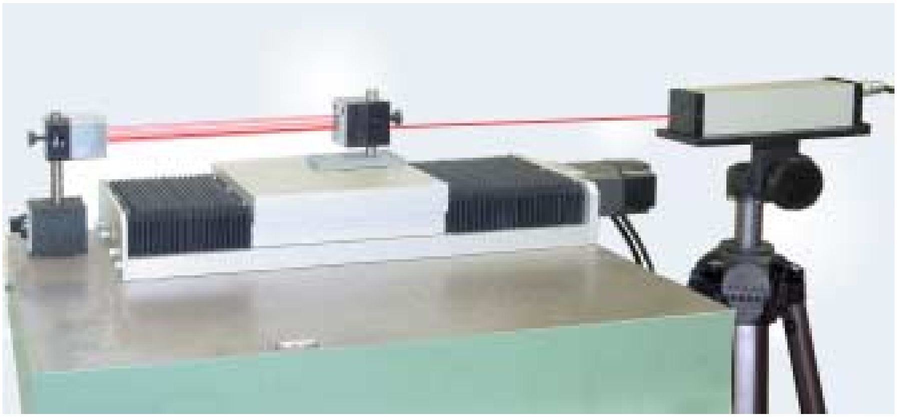

Fig. 2, A 6-pass optical arrangement using an optical adaptor and
a 38 mm diameter retroreflector target.

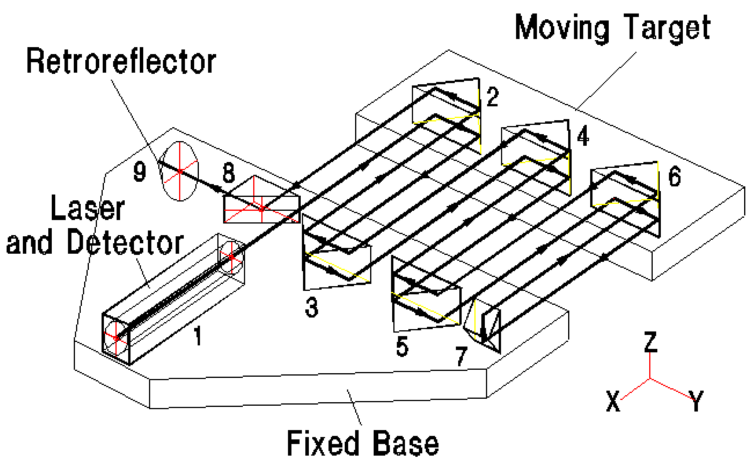

Fig. 3, A schematic of a 12-pass optical arrangement and laser beam path.

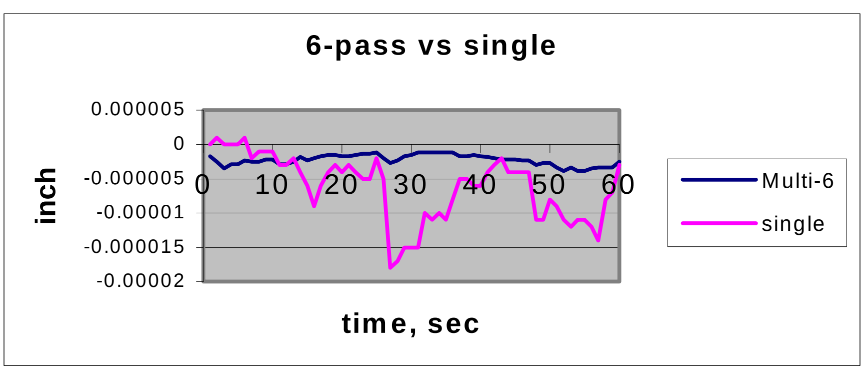

Fig. 4, Effect of air circulation on a 6-pass optical arrangement
and on a single pass optical arrangement.

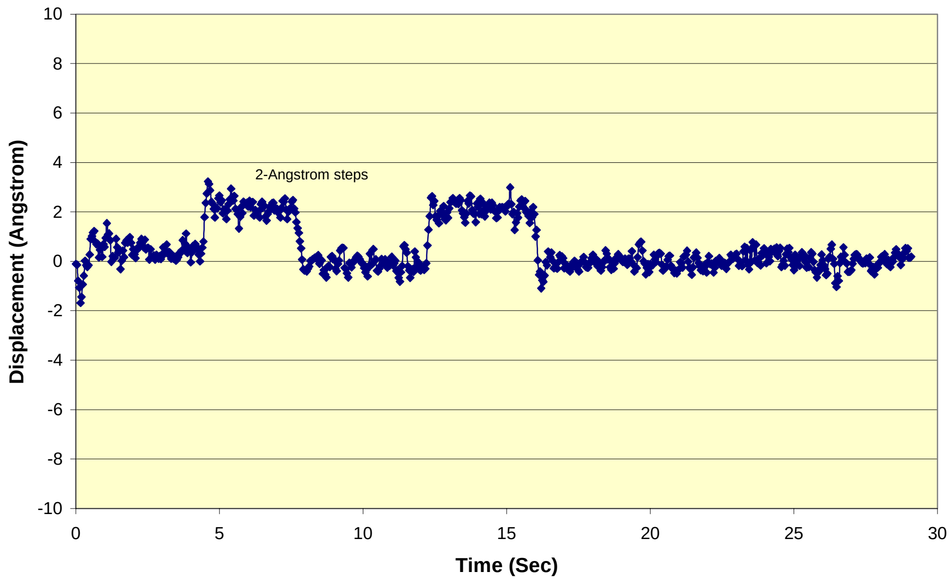

Fig.5, Using the 12-pass optical arrangement, 0.2 nm steps is clearly resolved.