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Displacement measuring grating interferometer: a review

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Key words: Grating interferometer; Optical encoder; Displacement measurement; Precision measurement

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Introduction: precision displacement measurement

- Precision displacement measurement is a key part of the metrology in lithography machine and many other apparatus.

Precision displacement measurement

- **Optical methods**
  - **Laser interferometer**
  - **Grating interferometer**
  - **…**
- **Electrical methods**
  - **Capacitive sensor**
  - **LVDT**
  - **…**

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Electrical methods vs. optical methods

(✓) Advantages (✗) Disadvantages

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Electrical methods

Capacitive sensor:

(✓) Insensibility to air refraction index
(✗) Short range in millimeters
(✗) Influenced by side effects

LVDT:

(✓) Insensibility to temperature
(✗) Lower resolution than other comparable methods
(✗) Restriction from large sized cores and armature

Optical methods

Laser interferometer:

(✓) Extremely large range
(✓) Traceability
(✗) Sensibility to air refraction index

Grating interferometer:

(✓) Ranging from several millimeters to meters
(✓) Resistance to ambient turbulence
(✗) Influence of ruling errors

Laser interferometer vs. grating interferometer (GI)

	Grating interferometer	Laser interferometer
Measuring benchmark	Benchmark: grating pitch; Environmental parameter resistance. Ruling error needs to be calibrated.	Benchmark: wavelength; Environmental parameter sensitive. Traceability.
Length and dimension	Ranges: millimeters to meters; Planar grating is convenient for multi-dimensional measurement.	Ranges: up to kilometers; Complex configurations for multi-dimensional measurement.
Measurement accuracy	Sub-nanometer accuracy from phase subdivision and calibration.	Picometer accuracy from phase subdivision and air refractive index compensation (or vacuum environment).

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Principle and optical structure

- Homodyne grating interferometer (Homodyne GI)
  - Single-frequency laser source and complex quadratic/quadrature detector required.
  - Noise-sensitive homodyne signals.
- Heterodyne grating interferometer (Heterodyne GI)
  - Dual-frequency laser source and simple detectors required.
  - Anti-noise heterodyne signals.
  - Periodic nonlinear errors caused by optical mixing.
- Spatially separated heterodyne grating interferometer (spatially separated heterodyne GI)
  - Periodic nonlinear errors eliminated.
  - Complicated optical structure.

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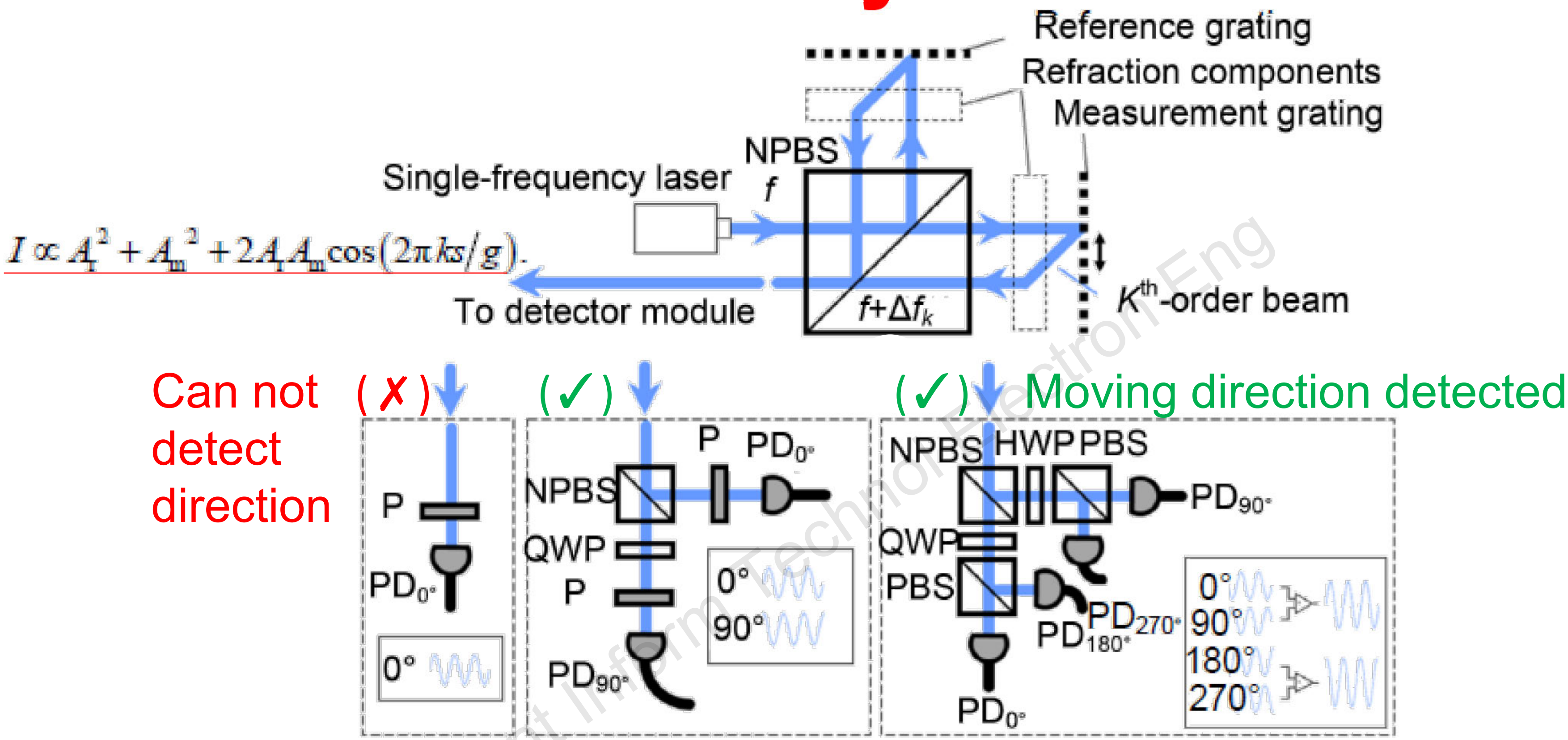
Homodyne GI



A Michelson-type homodyne grating interferometer

- ❑ Several kinds of refraction components available.
- ❑ No need of a reference signal.
- ❑ Quadratic/quadrature detector required for the moving direction.
- ❑ Interference signal is easily affected by noise.

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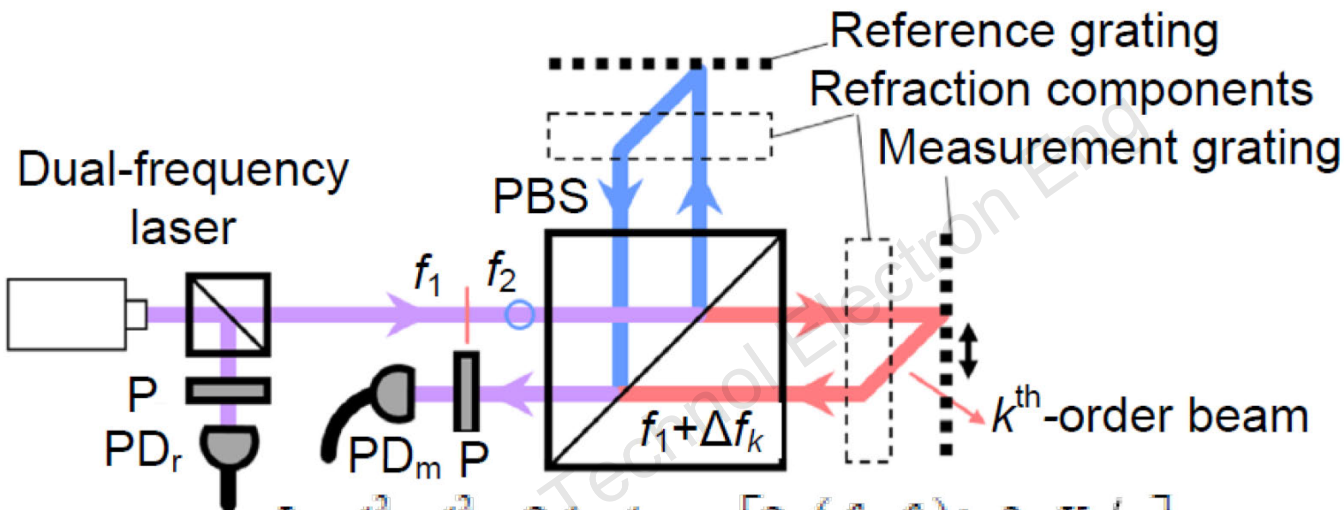
Heterodyne GI (1/2)



$$I_m \propto A_{1m}^2 + A_{2m}^2 + 2A_{1m}A_{2m}\cos\left[2\pi\left(f_1 - f_2\right)t + 2\pi Ks/g\right].$$

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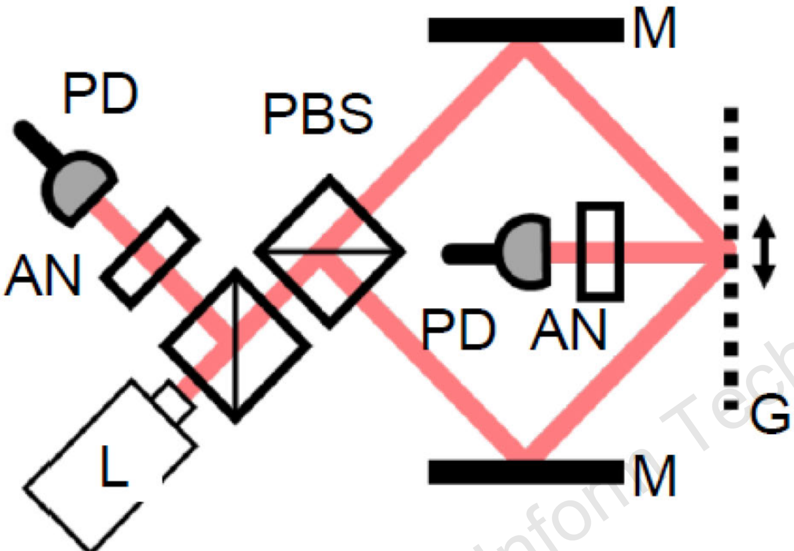
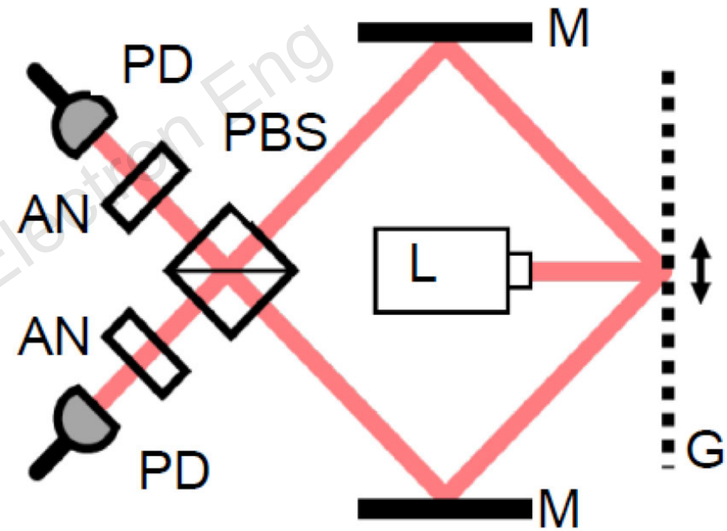
A Michelson-type heterodyne grating interferometer

- ❑ Single detectors for the reference and measurement signals.
- ❑ Simple common-optical-path configuration.
- ❑ Imperfect feature of the PBS will cause optical mixing, leading to periodic nonlinear errors.

Heterodyne GI (2/2)



Symmetrical oblique incident beams



Vertical incident beam

Single-grating-type heterodyne grating interferometers

- ❑ The left structure generates a reference and a measurement beam, while the right one provides two differential beams.
- ❑ The single-grating-type doubles the optical fold factor.

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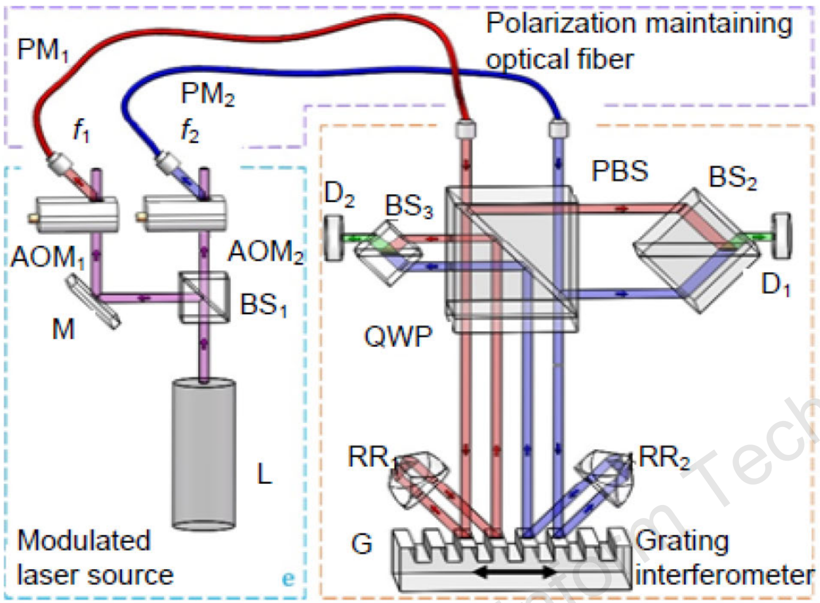
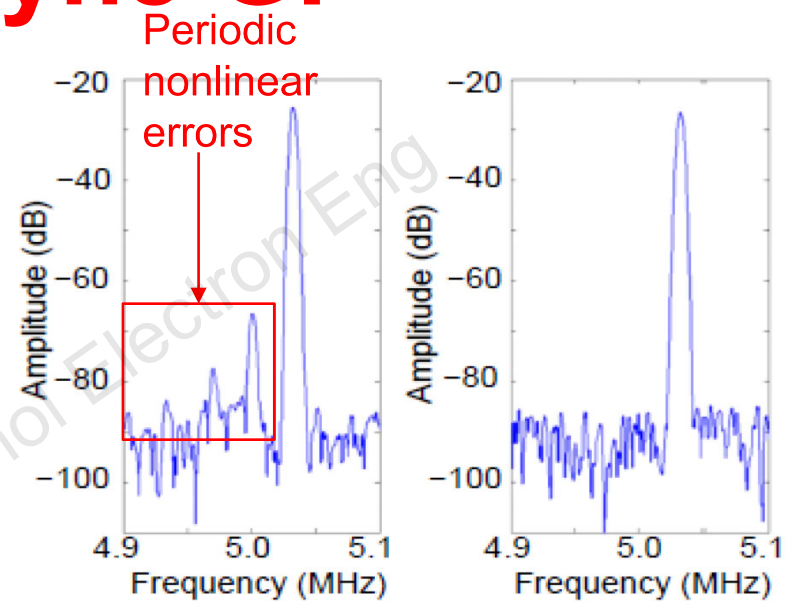
Spatially separated heterodyne GI



Double-diffracted optical structure*



COP configuration Spatially separated

Comparison of frequency spectrums*

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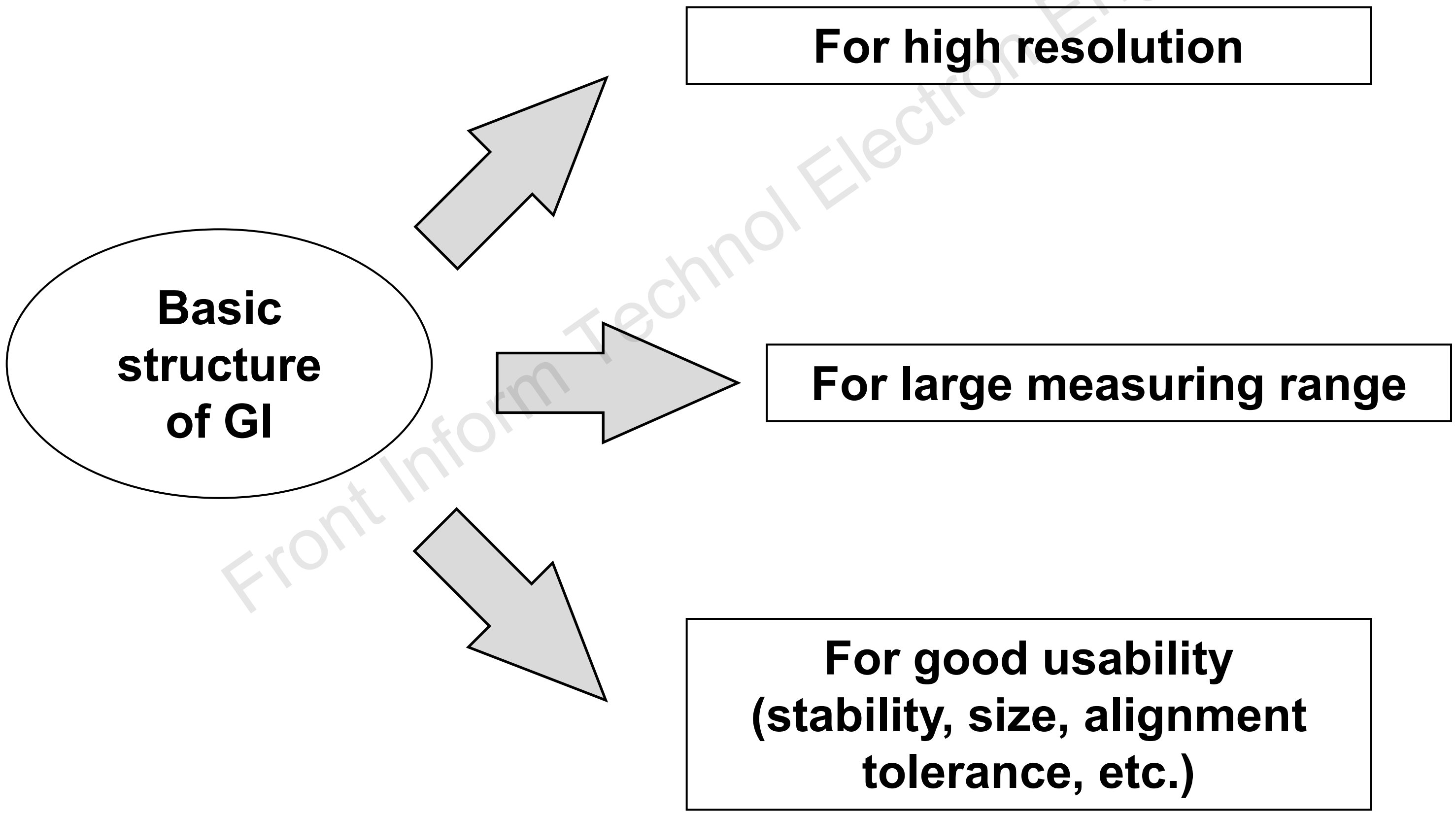
Single-grating-type heterodyne grating interferometers

- ❑ Spatially separated requires a more complex structure.
- ❑ Frequency spectrum of the spatially separated one eliminates peaks of periodic nonlinear errors.

*Xing X, Chang D, Hu P, Tan J, 2017. Spatially separated heterodyne grating interferometer for eliminating periodic nonlinear errors. Opt Expr, 25(25):31384-31393. https://doi.org/10.1364/OE.25.031384

Optical & opto-mechanical structures for good performance



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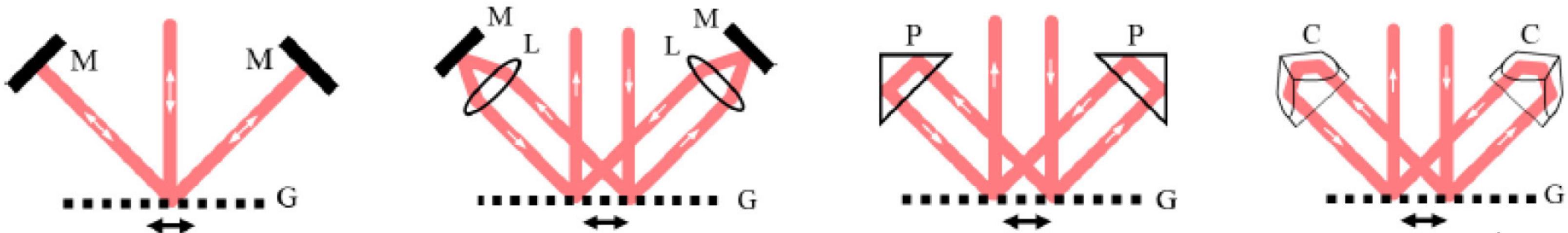
For high resolution

Grating pitch / (fold factor × electrical interpolation factor)

- Smaller grating pitch leads to higher resolution, but it is restricted by manufacturing and the grating formula.
- Larger fold factor supports higher resolution. However, in grating interferometer, low diffraction efficiency is the main problem in improving the fold factor.
- The fold factor of 4 is commonly implemented by a double-diffracted optical configuration. Some of the structures are depicted below.
- The electrical interpolation factor is also important for improving the resolution. Currently, it ranges from 4096 to 65 536.



Mirror | Lens + Mirror | Prism mirror | Corner-cube retro-reflector

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For large measuring ranges

- Large measuring ranges requires large ruling area, which is extremely expensive with a small grating pitch. The out-of-flatness error of a large grating is also a problem.
- <u>Mosaic grating</u> is an effective alternation of large-range grating, but it needs <u>two or more probes</u> for continuous measurement.
- The mosaic grating could be placed on one large base, or several small bases.

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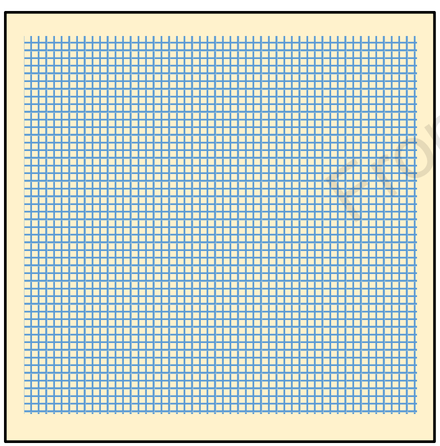
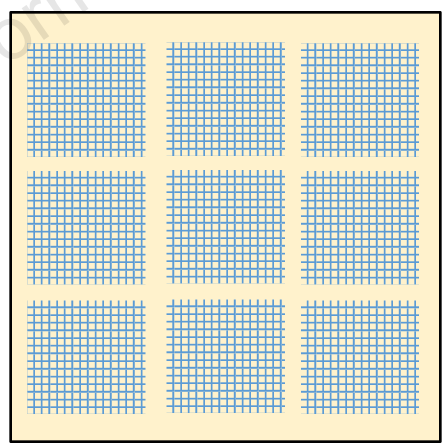
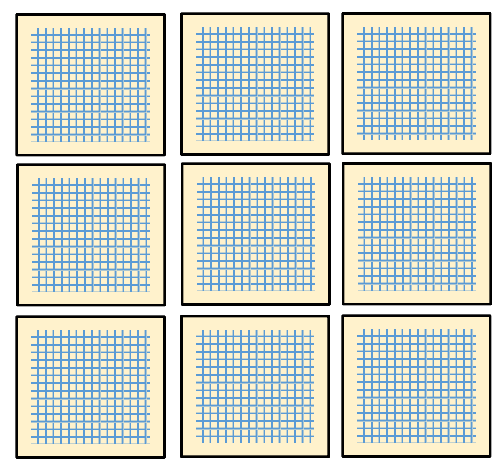


A large-range planar grating



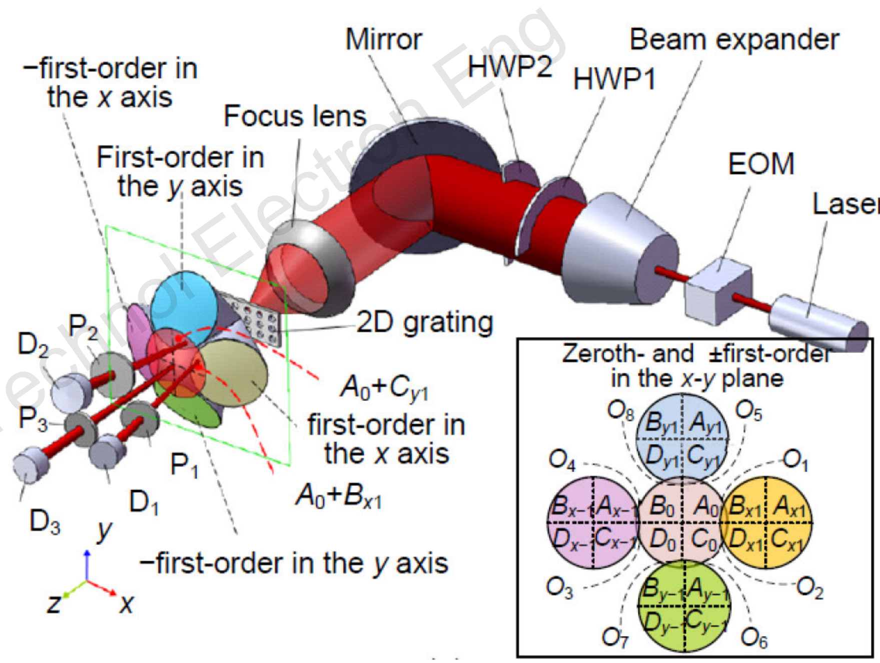
Mosaic grating in one base



Mosaic grating in several bases

For good usability (1/3)

- Combination of grating interferometer and shearing interferometer is a special method for stability and alignment tolerance due to its cone diffraction beams.
- The cost is the loss of laser intensity.



Two-DOF grating shearing interferometers*

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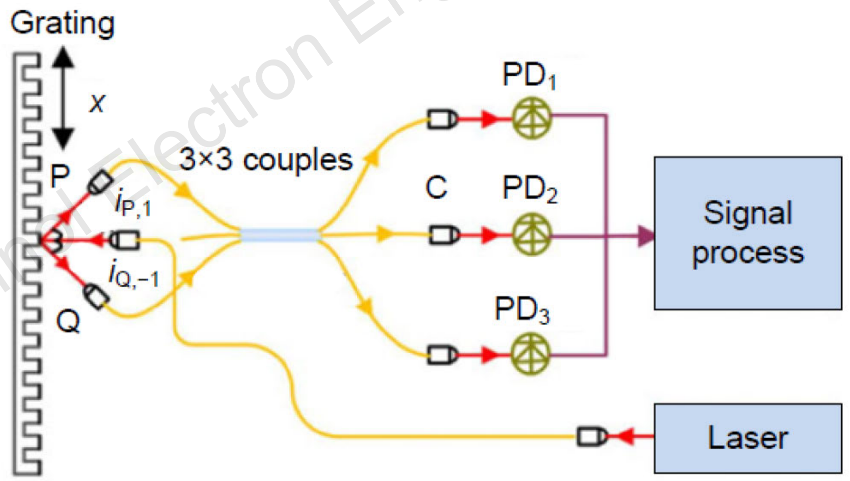
*Hsieh HL, Chen JC, Lerondel G, et al., 2011. Two-dimensional displacement measurement by quasi-common-optical-path heterodyne grating interferometer. Opt Expr, 19(10):9770-9782. https://doi.org/10.1364/OE.19.009770

For good usability (2/3)

- ❑ Fiber-delivered structure is easy to adjust, leading to a high alignment tolerance. The size of fiber structure could be small and flexible.
- ❑ The intensity transmission efficiency of optical fibers and the influence of fibers and couplers on the interference signal phase still require further study.



All-fiber grating interferometers*

*Wei CH, Yan SH, Lin CB, et al., 2015a. Compact grating displacement measurement system with a 3×3 coupler. Chin Opt Lett, 13(5):051301. https://doi.org/10.3788/COL201513.051301

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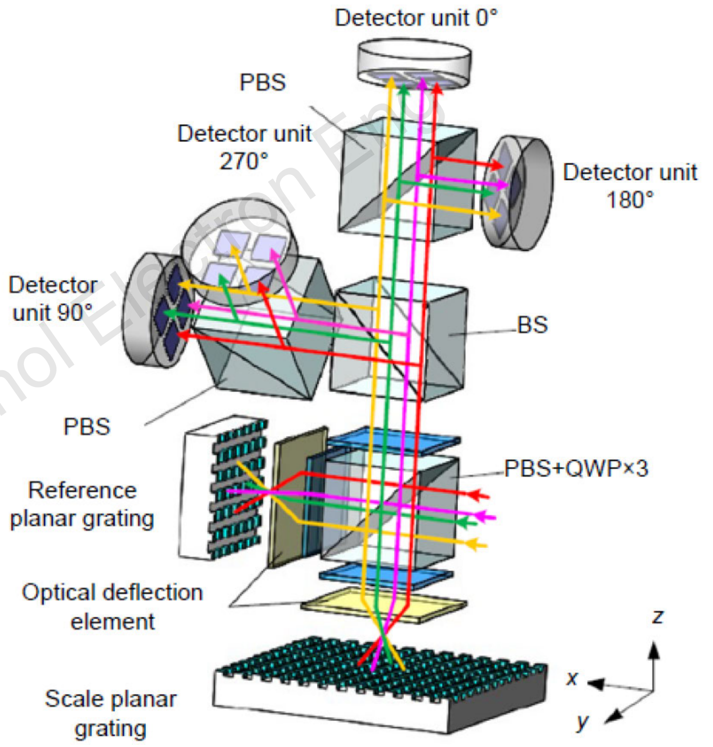
For good usability (3/3)

- ❑ Littrow configuration is widely used for its self-collimation feature.
- ❑ A Littrow-type structure is insensitive to the vertical offset in the *z* direction.
- ❑ In addition, it is easy to adjust and miniature.



Three-DOF Littrow-type homodyne grating interferometer*

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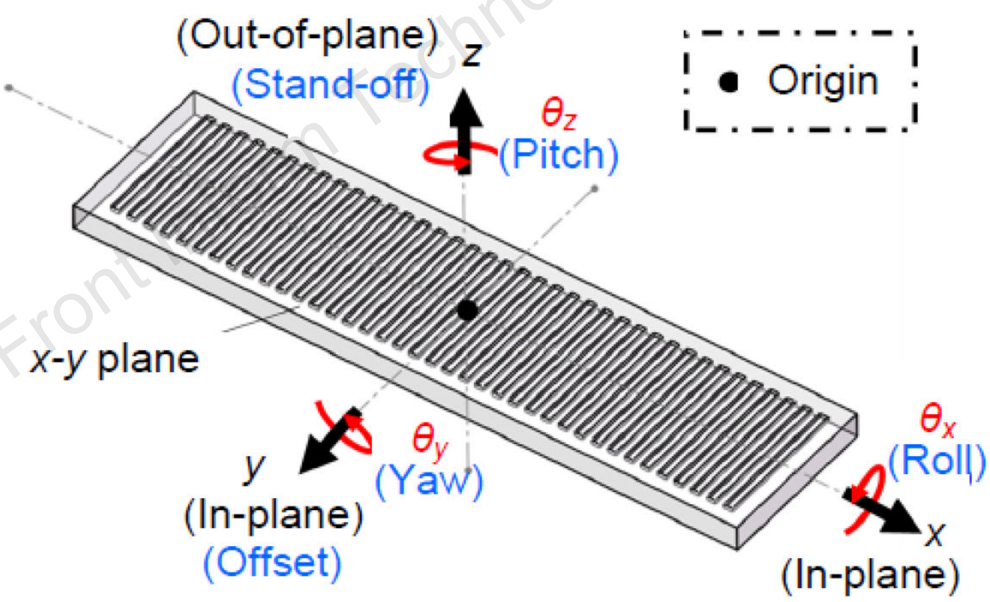
*Lin J, Guan J, Wen F, et al., 2015. Grating encoder for wide range three-axis displacement measurement. 9th Int Symp on Precision Engineering Measurement and Instrumentation, No. 944602. https://doi.org/10.1117/12.2082475

Multi-DOF measurement

- The six degrees of freedom (DOFs) of a grating could be classified as in-plane, out-of-plane, and rotational DOFs.
- Obviously, these six DOFs are coupled together. Thus, they can also be classified as measured DOFs and the error ones.



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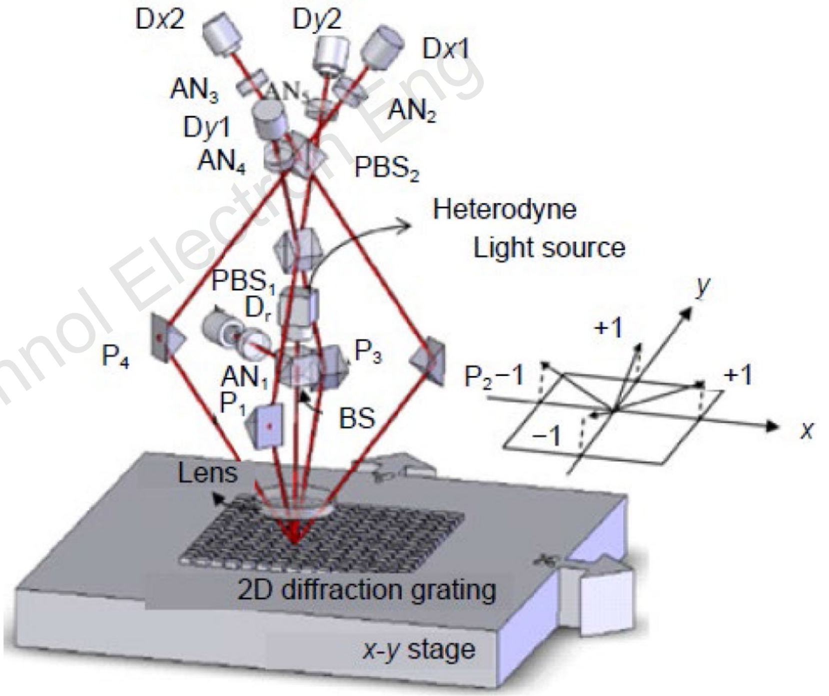
In-plane displacement

- The word “in-plane” indicates the *x*-*y* plane.
- Planar grating is the most commonly used component to measure in-plane displacement.



Planar grating for two-DOF in-plane displacement measurement*

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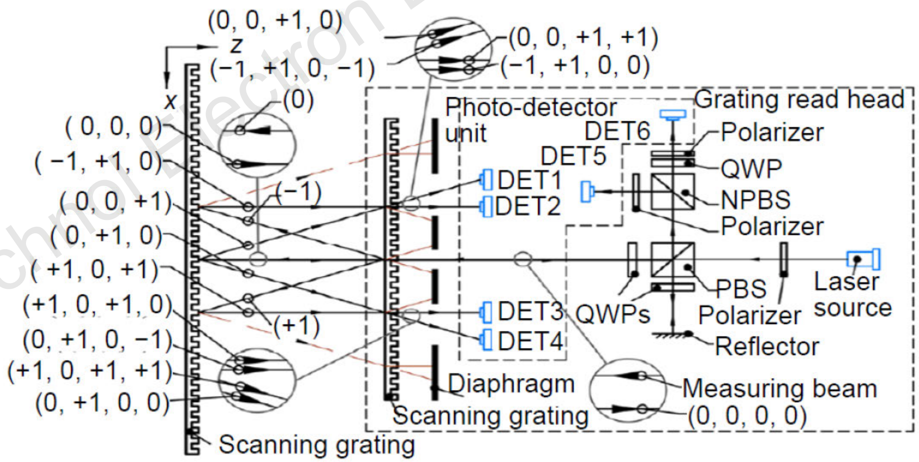
*Hsu CC, Wu CC, Lee JY, et al., 2008. Reflection type heterodyne grating interferometry for in-plane displacement measurement. Opt Commun, 281(9):2582-2589. https://doi.org/10.1016/j.optcom.2007.12.098

Out-of-plane displacement

- The word "out-of-plane" indicates the *z* direction.
- Generally, displacement in the *z* direction could be measured by a combined laser interferometer or phases in differential signals.
- The Littrow configuration could increase the measuring range in the *z* direction.



Combined laser interferometer for measuring out-of-plane displacement*

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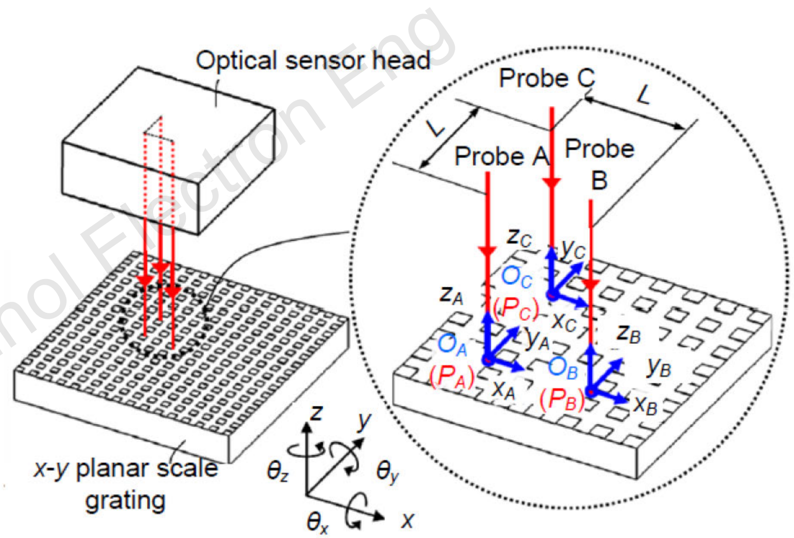
*Lu ZG, Wei PP, Wang CQ, et al., 2016. Two-degree-of-freedom displacement measurement system based on double diffraction gratings. Meas Sci Technol, 27(7):074012. https://doi.org/10.1088/0957-0233/27/7/074012

Rotational measurement

- The roll, yaw, and pitch angles could be measured by a multi-probe planar grating interferometer.
- Compared with the angle sensor, the multi-probe method is traceable.



Multi-probe all-grating-interferometer-based method for 6-DOF measurement*

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*Li XH, Shimizu Y, Ito T, et al., 2014. Measurement of six-degree-of-freedom planar motions by using a multiprobe surface encoder. Opt Eng, 53(12):122405.
https://doi.org/DOI: 10.1117/1.OE.53.12.122405

Error analysis

❑ Benchmark errors

- Including the errors in the grating itself, such as the ruling error, thermal expansion coefficients of the grating pitch, non-orthogonality of the planar grating, and an out-of-flatness error.

❑ Geometric errors

- Geometric errors can be static assembly errors (systematical) and dynamic movement errors (random).

❑ Errors in signals and signal processing

- A real photodetector's performance is far from ideal, suffering from noises. In addition to noise, there are many types of signal errors, such as unequal amplitude, DC bias, non-orthogonality of a quadrature signal, and periodic nonlinear errors.
- The quantitation error and data delay in signal processing should also be considered.

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Summary

In this review, the development of GI from homodyne, heterodyne, and spatially separated heterodyne principles is compared and analyzed. Typical optical structures for high resolution, large range, good usability, and multi-DOF measurement are classified and reviewed. Besides, the error analysis of GI is briefly introduced.

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