NON-DESTRUCTIVE TESTING: SAGNAC AND LDV

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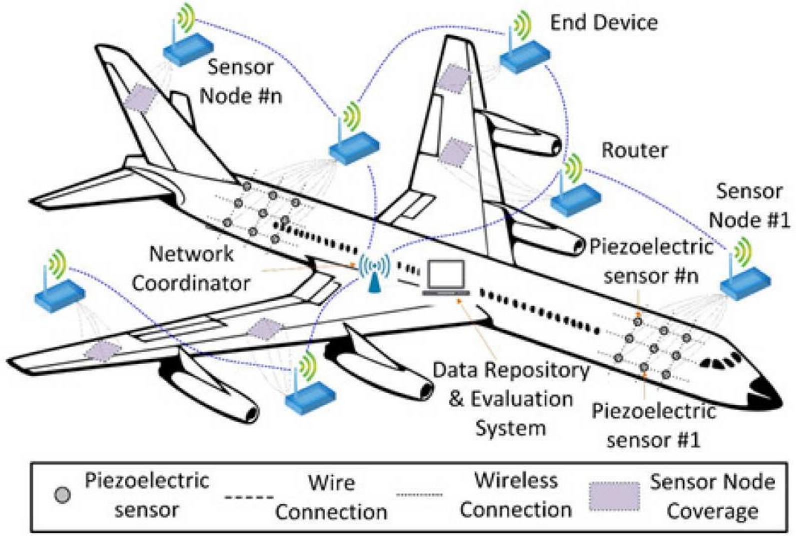
OUTLINE

1. Optical methods for non-destructive testing
2. Motivation to study Sagnac and Mach-Zehnder interferometer-based vibrometries
3. Theoretical comparison of the two vibrometers
4. Conclusions and discussions

Optical methods for NDT

- *Non-destructive testing (NDT):*
  - Applications in automotive/Aerospace/Power/Oil and gas/Building industries
  - Includes: acoustic emission, electromagnetic testing, guided wave testing, thermal testing, ultrasonic testing ...

- *Optical methods for ultrasound detection*
  - Optical methods for ultrasound measurement is interesting: contactless measurement is great
  - Typical solution: Laser Doppler vibrometry (LDV) - based on Mach-Zehnder Interferometry



https://www.imperial.ac.uk/structural-integrity-health-monitoring/research/structural-health-monitoring-/

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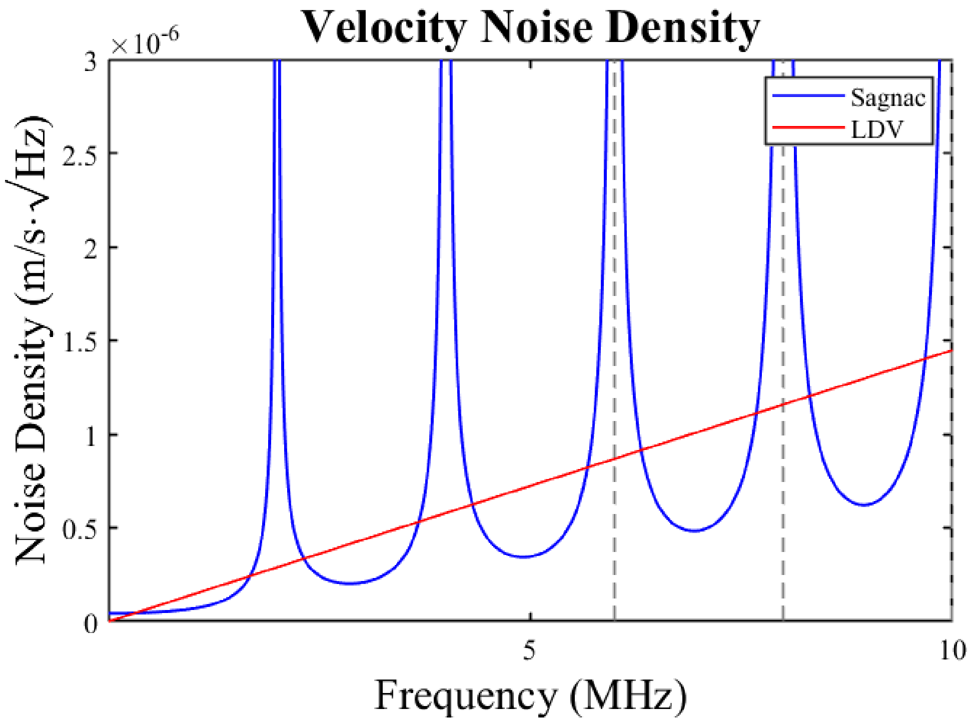
Motivation of the study: Challenges with LDV

- The velocity noise of Mach-Zehnder (MZ) interferometer-based vibrometry (Laser Doppler vibrometry, LDV) increases with frequency.
- Signal-to-noise ratio (SNR) is usually very low for ultrasound.

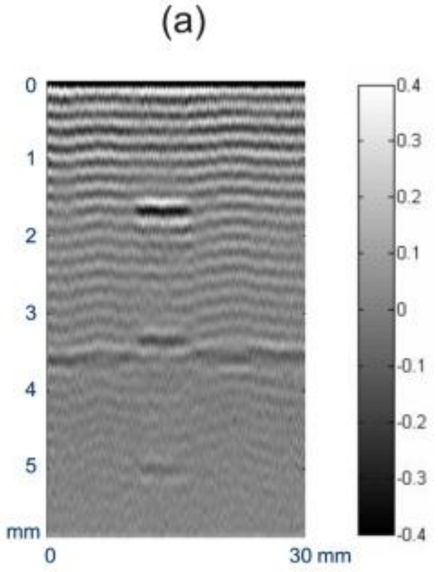


Displacement noise and velocity noise: Sagnac and LDV

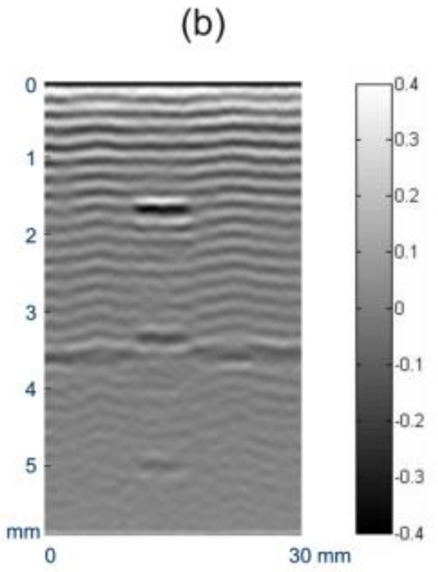
Motivation of the study: Sagnac vibrometer

- A very nice detection has been demonstrated with a Sagnac interferometry
  - Result is similar to those obtained from the contact methods

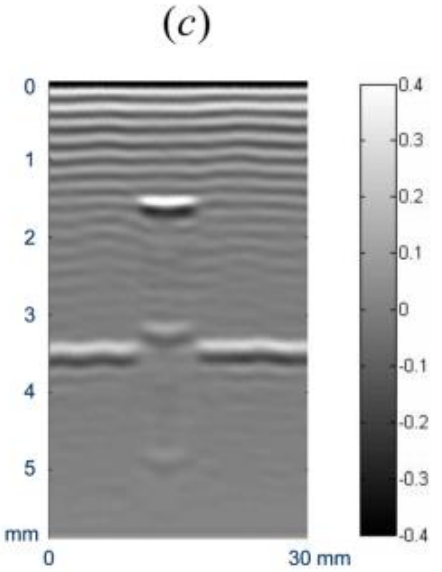
- Key information of the demonstration
  - Sagnac based measuring range: 1-10 MHz. The measured noise equivalent pressure is about 10 Pa over the operating band.
  - ~100ps to ~100ns laser pulse can generate pressure amplitudes achieving 10s or one hundred of Mpa.



Sagnac-based detector, single shot



Sagnac-based detector, 10 moving averages



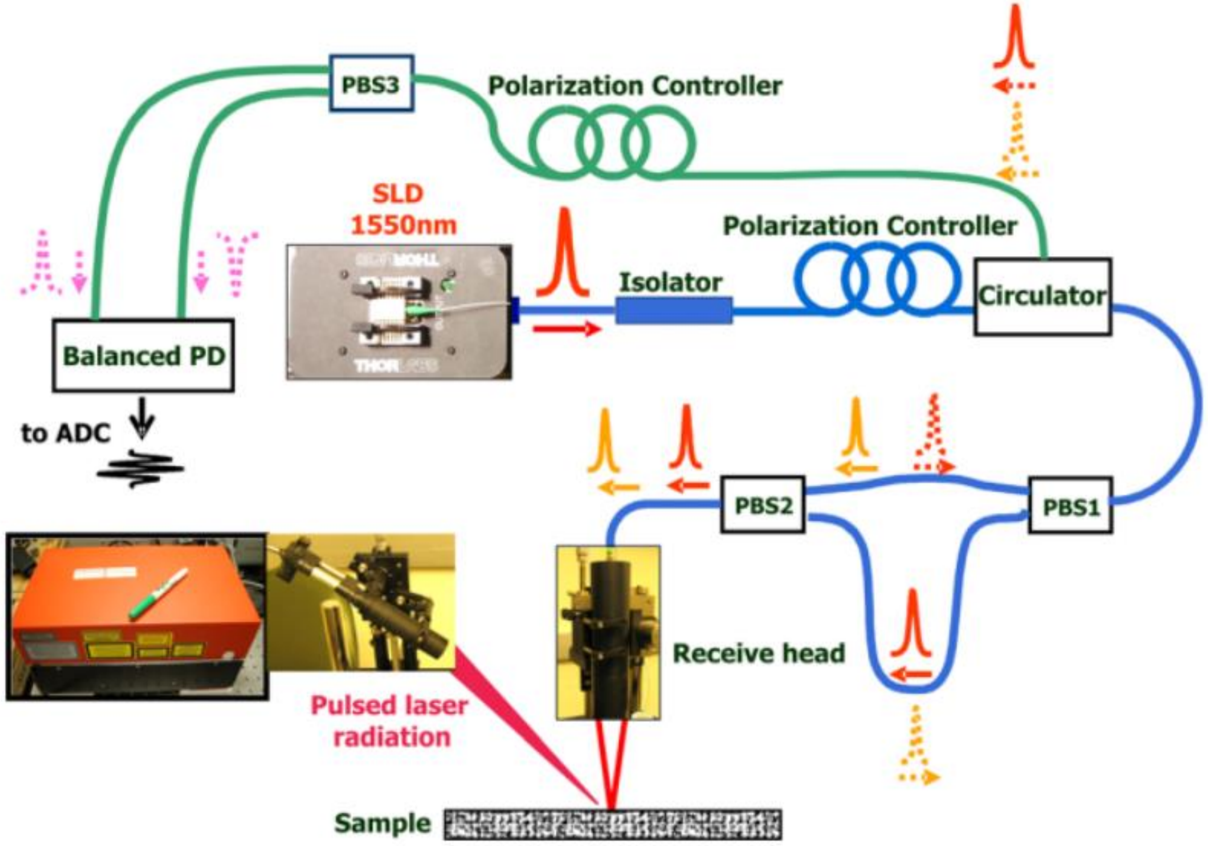
Polyvinylidene Fluoride (PVDF) films Detector
(Conventional method)

Ultrasound echo reconstruction using the Sagnac method

Pelivanov, Ivan, et al. "A new fiber-optic non-contact compact laser-ultrasound scanner for fast non-destructive testing and evaluation of aircraft composites." Journal of Applied Physics 115.11 (2014): 113105.

Motivation of the study

- Understand the limit of the Sagnac vibrometry.
- Check if we can realize similar techniques in **integrated photonics.**



The demonstrated Sagnac vibrometer

WORKING PRINCIPLE: MACH-ZEHNDER VIBROMETER (HOMODYNE LDV)

Blue: reference light $r(t) = a$

Red: measurement light $m(t) = b \cdot \exp(i\theta(t))$

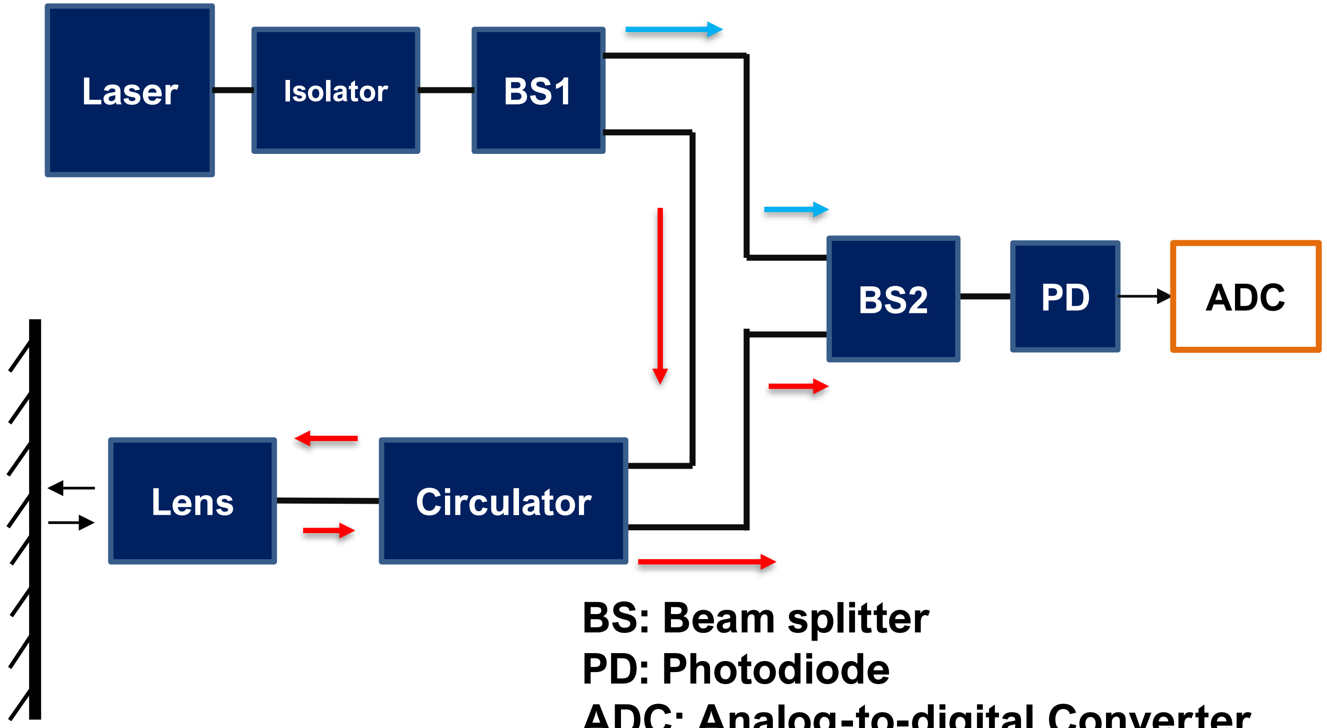
Photocurrent:

$$I(t) = |m(t) + r(t)|^2$$
$$= dc + 2|ab|\cos(\theta(t))$$

Output signal $s(t) = \theta(t)$

Retrieved signal s(t) is proportional to target displacement (Doppler effect)

$$s(t) = \frac{4\pi}{\lambda} d(t)$$



Moving target
$d(t)$

BS: Beam splitter
PD: Photodiode
ADC: Analog-to-digital Converter

WORKING PRINCIPLE: SAGNAC VIBROMETRY

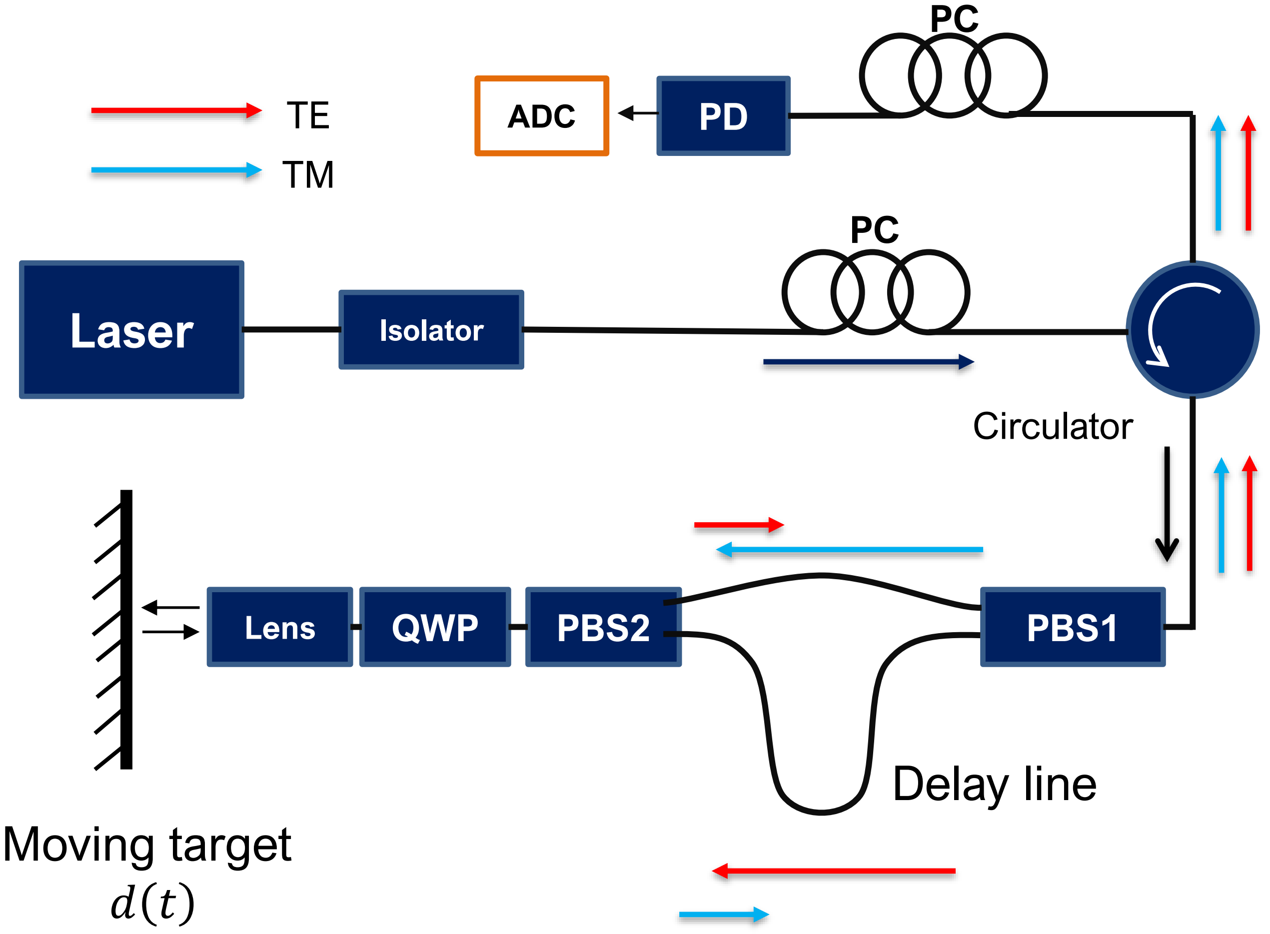
Blue: CCW path; the target first, then the delay line;

$ccw(t) = a \cdot \exp(i\theta(t))$

Red: CW path; delay line first, then the target;

$cw(t) = b \cdot \exp(i\theta(t - \Delta T))$

ΔT is the time delay brought by the delay line.



Photocurrent:

$$I(t) = dc + 2|ab|\cos(\theta(t) - \theta(t - \Delta T))$$

Output signal $s(t) = \theta(t) - \theta(t - \Delta T)$

QWP: Quarter wave plate, PBS: Polarization beam splitter

Working Principle: Sagnac vibrometry

Blue: $ccw(t) = a \cdot \exp(i\theta(t))$

Red: $cw(t) = b \cdot \exp(i\theta(t - \Delta T))$

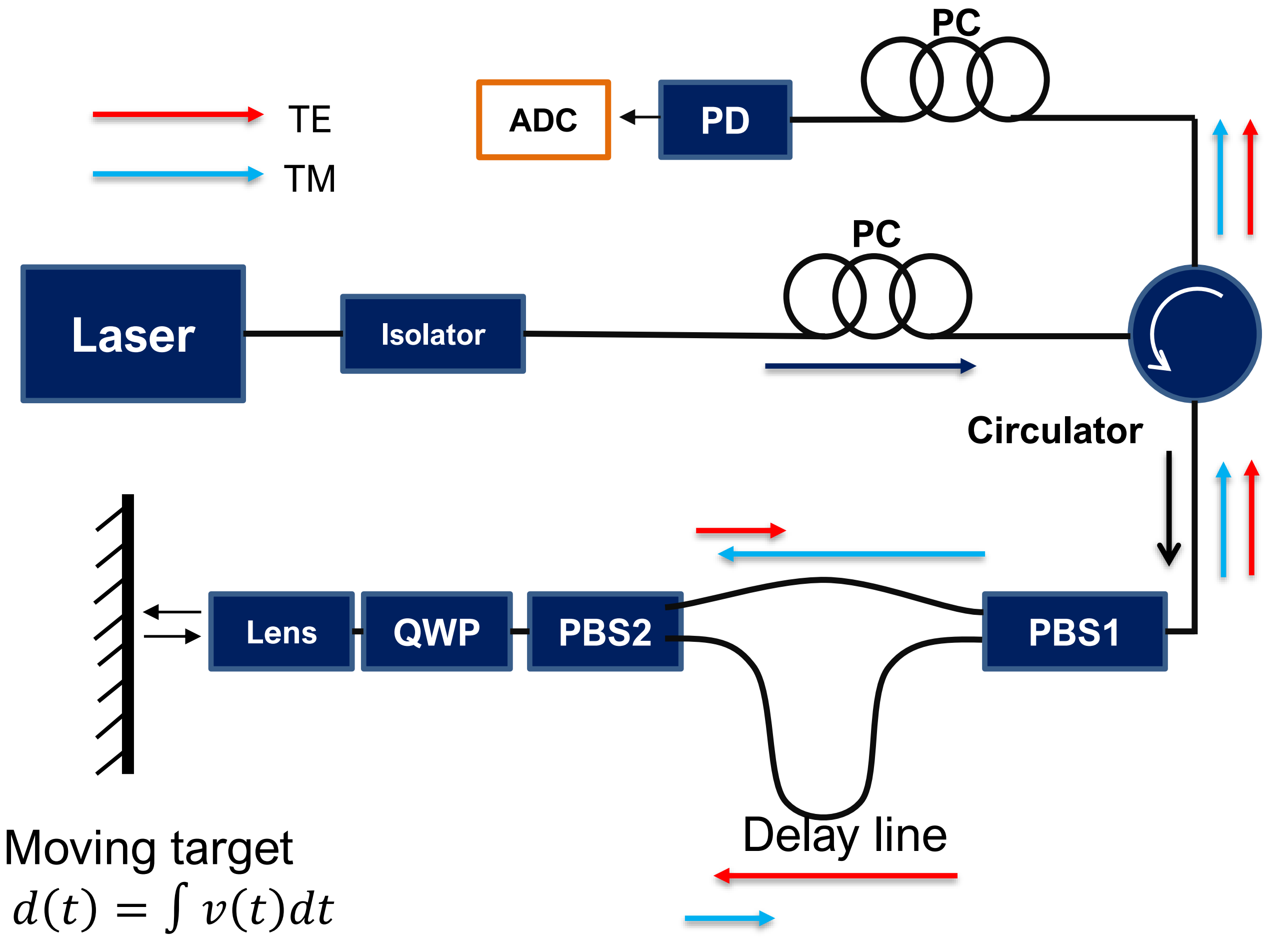
From the retrieved signal $s(t)$, we can obtain the target velocity:

$$s(t)$$

$$= \frac{4\pi}{\lambda} \times \left(d(t) - d(t - \Delta T)\right)$$

$$\approx \frac{4\pi}{\lambda} v(t)\Delta T$$

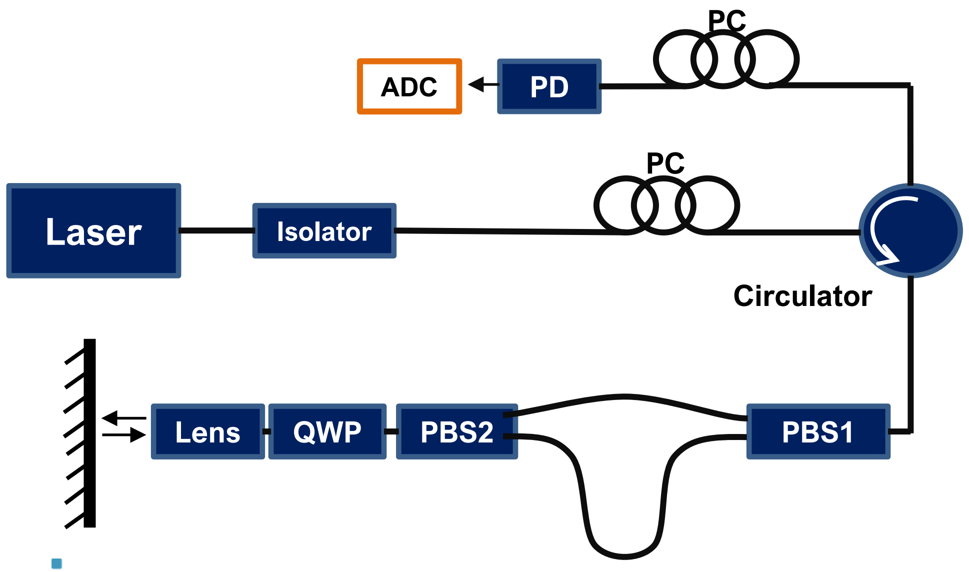
Retrieved signal $s(t)$ is proportional to the target velocity $v(t)$

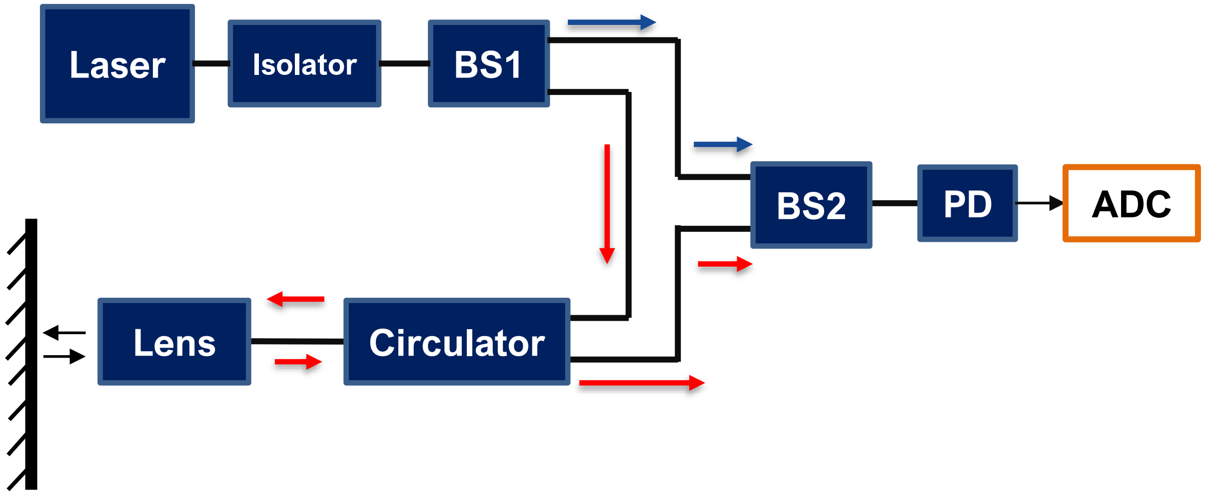


QWP: Quarter wave plate, PBS: Polarization beam splitter

COMPARISON SAGNAC & MACH-ZEHNDER VIBROMETERS

Sagnac vibrometer	Mach-Zehnder vibrometer
Coherent/Incoherent light	Coherent light
Get velocity	Get displacement first
Requires delay line (meters long)	Not requires delay line
Bulky	Can be miniatured on a chip
Resistant to disturbance lights or scatters	Sensitive to disturbance lights





SENSITIVITY IN SHOT-NOISE LIMIT

- Assumption taken before
  - In **shot-noise limited** system.
  - Assuming the **power of the sensing light beam** is the same.

- Retrieving phase signal
  - In MZ vibrometry, the retrieved phase signal is $s(t) = \frac{4\pi}{\lambda} d(\mathrm{t}) \Leftrightarrow \frac{4\pi}{\lambda} D^F(\omega)$
    - Flat over the spectrum.
  - In Sagnac vibrometry, $s(t) = \frac{4\pi}{\lambda}(d(t) - d(t - \Delta T)) \Leftrightarrow \left(1 - e^{-j\omega\Delta T}\right) \cdot \frac{4\pi}{\lambda} D^F(\omega)$
    - Not flat because of filter $\left(1 - e^{-j\omega\Delta T}\right)$. At some frequency points, no signal $s(t)$ is obtained.

Effective Noise density of Sagnac and MZ

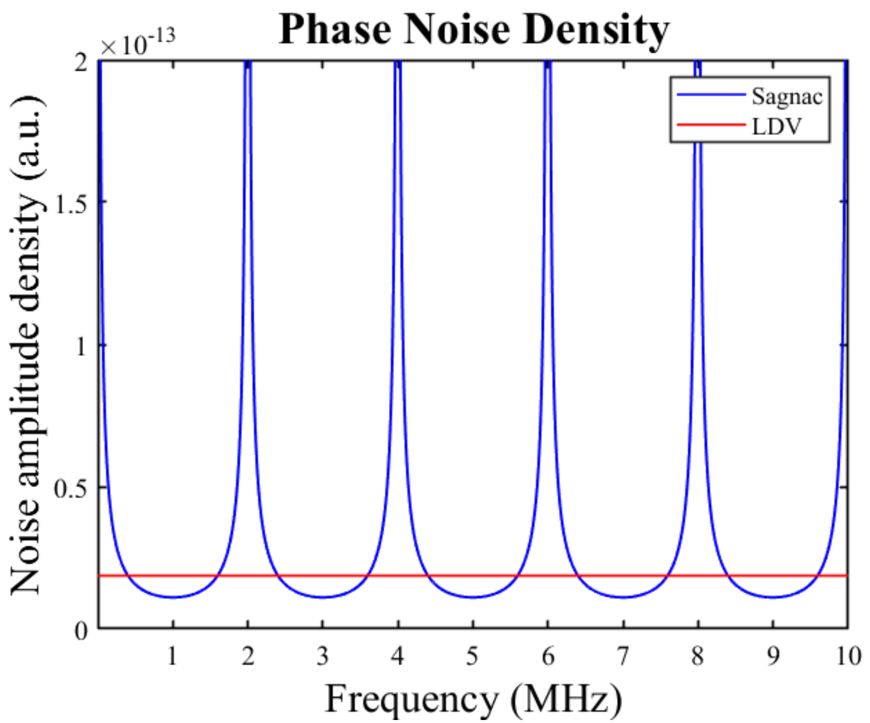
- Sagnac vibrometry:

  The noise density is not uniform. The noise level is a function of delay line length.

- MZ vibrometry:

  Noise density is uniform.

- **Sagnac is not always better than MZ vibrometer with the same sensing power.**



- The sudden increase in phase noise of Sagnac at frequencies such as 2 MHz, 4 MHz and 6 MHz does not imply an actual increase in noise, but rather an absence of signal.
- When the vibration period of the object being measured coincides with the delay time of the delay line, the Sagnac interferometer is unable to detect a signal, that is $\theta(t) = \theta(t - \Delta T)$, and then $s(t) = 0$
- Consequently, the phase noise appears to be effectively infinite.

Discussion

- Why is Sagnac better than conventional LDV in the reported implementation?
  - Use very high optical power: up to 40 mW.
    - Eye safety limits to 1mW for visible light, 10mW for 1550 nm.
  - Great lens system, with N.A. = 0.5, capturing much reflection light.
    - The depth of focus will therefore be limited.
- Sagnac still has advantages in using broadband and low-coherent light sources and avoids unwanted reflection.
  - MZ-based method (not LDV) can also utilize similar method by using a long reference arm.
- Possible to implement Sagnac in a chip?
  - Not easy, because it needs long delay line (>10 m). Or work for very high frequency vibrations (GHz?).

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