Surpassing the Heisenberg Uncertainty Principle

The world's first Sagnac speed-meter

Interferometry at the Quantum Limit

From the very first Michelson Interferometer invented over 100 years ago to today's kilometre-scale gravitational wave detectors the sensitivity of interferometric length measurements has been improved by about 10 orders of magnitude and is now limited by the so-called Standard Quantum Limit (SQL), a manifestation of Heisenberg's Uncertainty Principle (HUP). The SQL is comprised of the inevitable combination of sensing noise (photon shot noise) and back action noise (photon radiation pressure noise) when repeatedly measuring the position of a test mass. However, by measuring a different variable, i.e. the test mass velocity (speed-meter) instead of its position (position-meter), it is possible to evade back action noise. The momentum of a free test mass can be measured continuously to arbitrary accuracy without being limited by the SQL. Since a Sagnac interferometer is sensitive only to the time-dependent part of the arm-length difference it is automatically a speed-meter and therefore brings measurements beyond the SQL into our reach. Theoretical analyses have shown that the speed-meter approach is the most promising track towards wide-band sub-SQL measurements. An experimental test of this technique is urgently required!

Speed-meter versus position-meter

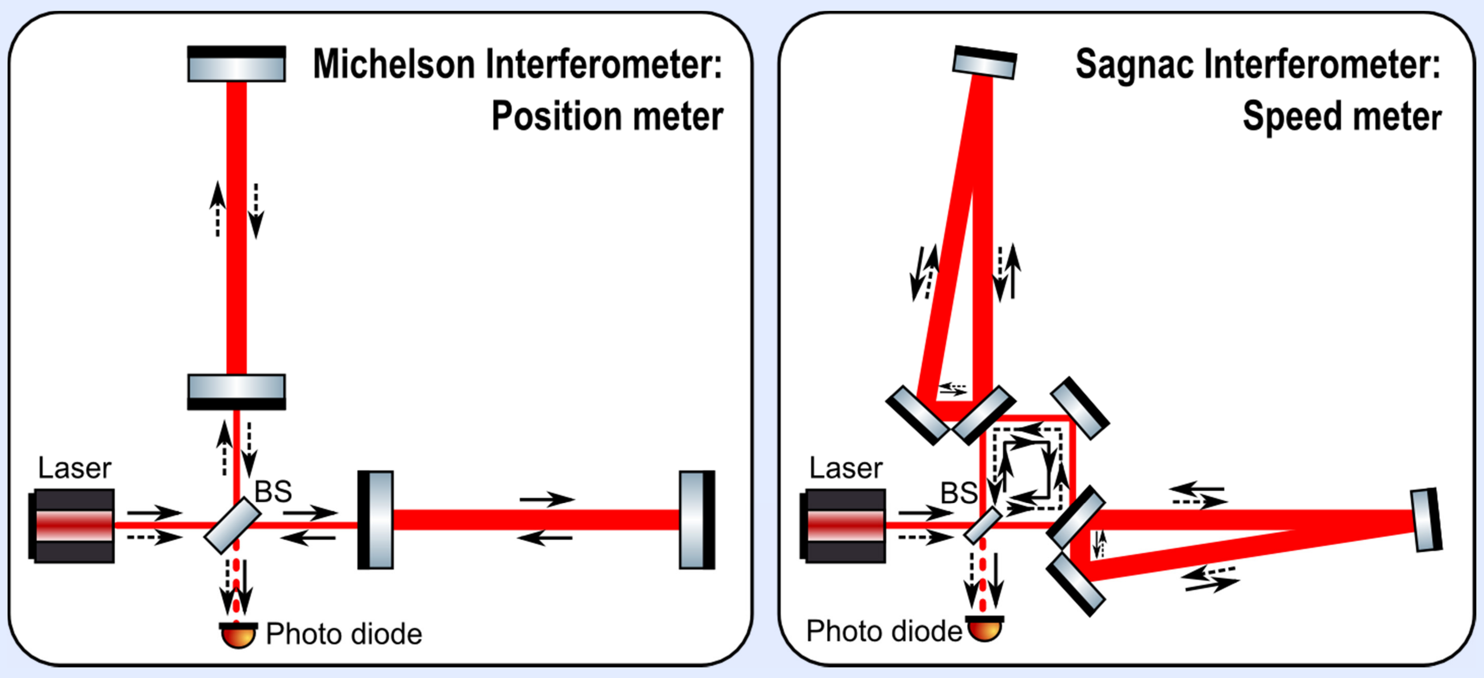

Figure 1: Simplified layouts of a Michelson interferometer with arm cavities (left), which measures the position of the mirrors and a Sagnac speed-meter (right), which measures the momentum of the test masses. In the Sagnac interferometer all mirrors are sensed one time by the light being transmitted through the BS and then a second time (either shortly before or after) by the light reflected from the BS.

The HUP prohibits us from measuring position and momentum of a test mass to infinite accuracy:

$$[\hat{x}(t), \hat{p}(t)] \neq 0$$

Also, measuring continuously the position of test masses in a Michelson is limited by the HUP:

$$[\hat{x}(t), \hat{x}(t')] \neq 0$$

However, the speed or momentum of a test mass can be measured continuously without being limited by the HUP:

$$[\hat{p}(t), \hat{p}(t')] = 0$$

Realisation of a speed-meter testbed

We are currently setting up a proof-of-principle experiment for a speed-meter, aiming to demonstrate that a Sagnac interferometer can outperform a Michelson interferometer with similar design parameters (such as mirror mass and optical power).

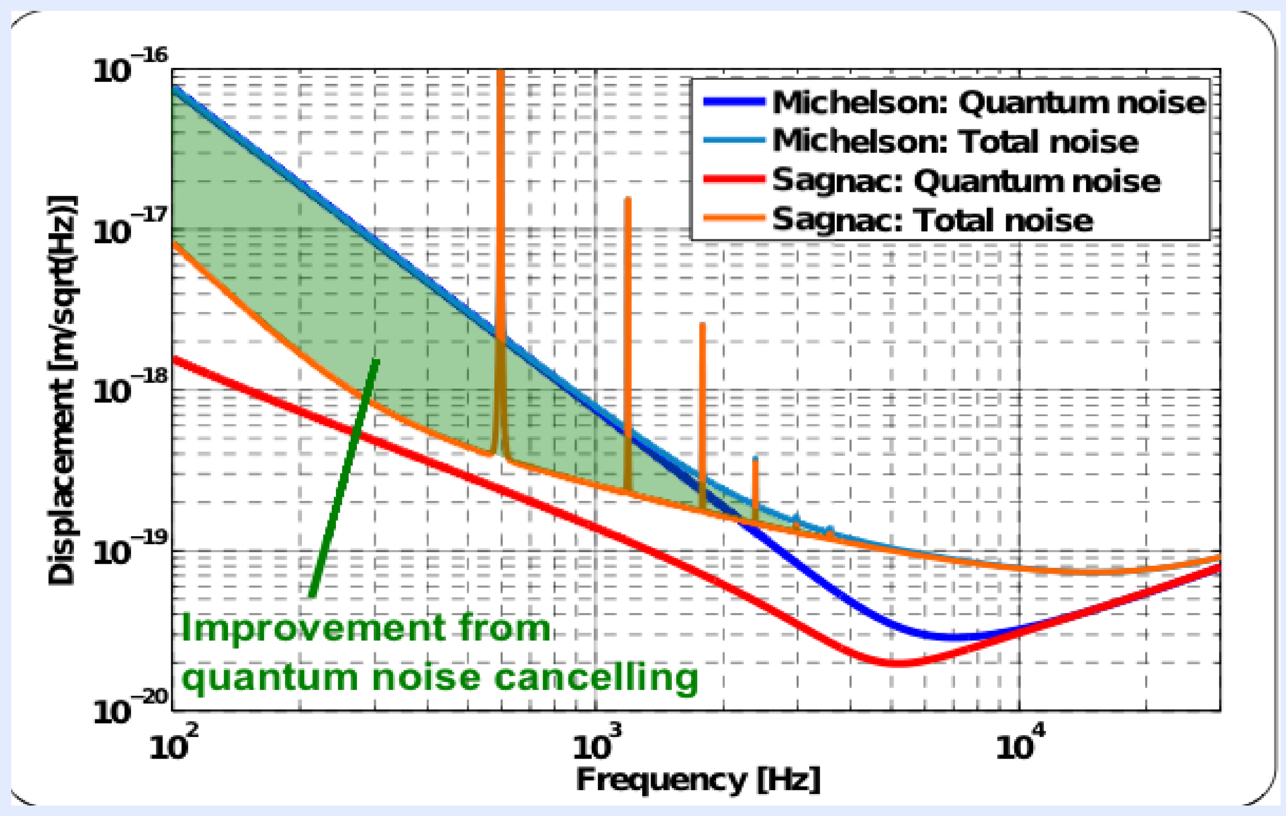

Figure 2: Noise budgets of a Michelson and a comparable Sagnac interferometer (left), both featuring 1gram test masses, arm cavities and a circulating optical power of 1kW. The plot illustrates the improvement in overall sensitivity (green area) that can be achieved by the Sagnac speed-meter over a Michelson interferometer with comparable parameters.

Parameter	Value
Interferometer configuration	Zero-area Sagnac with high-finesse arm cavities
Light source	2W Nd:YAG laser (1064nm)
Mirrors	1 gram fused silica mirrors of 1.04cm diameter
Arm length	1 meter
Optical power	0.3W input, 1kW inside arms
Arm cavity incoupler	500 parts per million transmission (arm cavity finesse ~10000)
Mirror suspension	Double pendulum with blade springs with fused silica fibres as lower stage
Beam radius at mirrors	1mm
Optical losses inside arm cavities	100 parts per million (per round-trip)
Fused silica fibres	20um diameter, 5cm length
Thermo-elastic peak frequency	18kHz
Pendulum Q	2 x 10^6
Suspension control	Passive (eddy-current damping) plus active (coil-magnet) actuators
Dielectric mirror coatings	Titanium-doped tantala and silica
Vacuum	< 4 x 10^{-5} mbar
Optical readout	Tunable homodyne readout
Temperature	Room temperature
Improvement over Michelson	About a factor 10 at a few hundred Hz

Table 1: Key-design parameters of the speed-meter test bed.

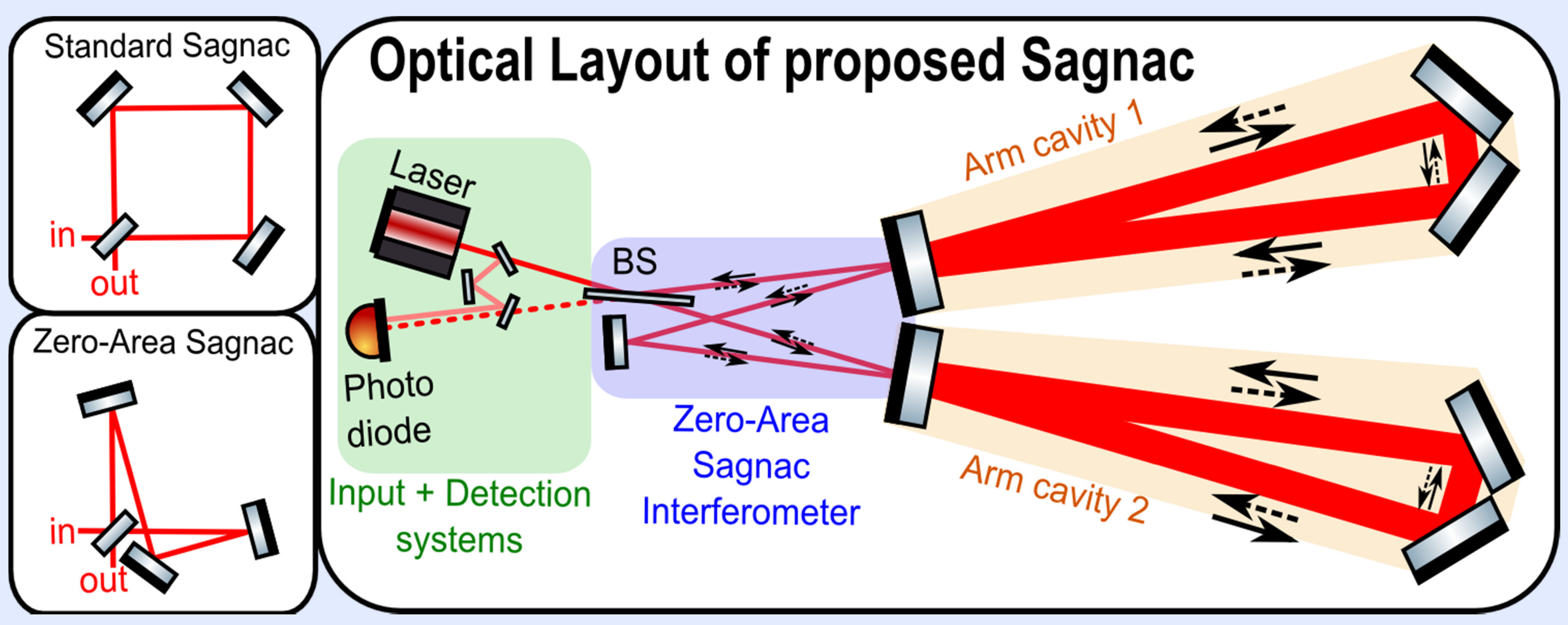

Figure 3: Optical layout of the Sagnac interferometer, which consists of three main building blocks: The input and detection optics including homodyne detection (green), a central Sagnac interferometer (blue) and two high-finesse arm cavities (orange).

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