Universität Hamburg
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GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

TUNABLE COHERENCE FOR STRAYLIGHT SUPPRESSION IN HIGH PRECISION INTERFEROMETERS

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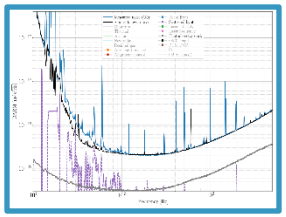
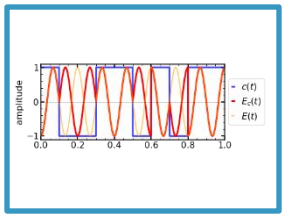
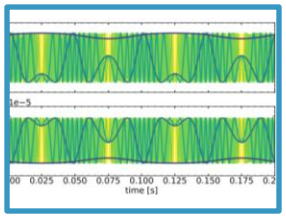


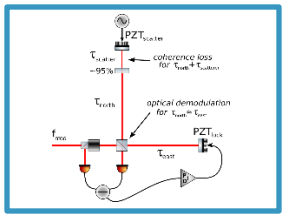
Motivation



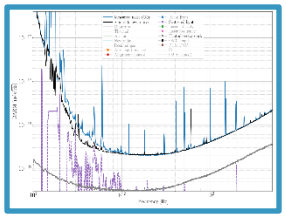
PRN modulation for tunable coherence



Time-domain simulation



Outlook



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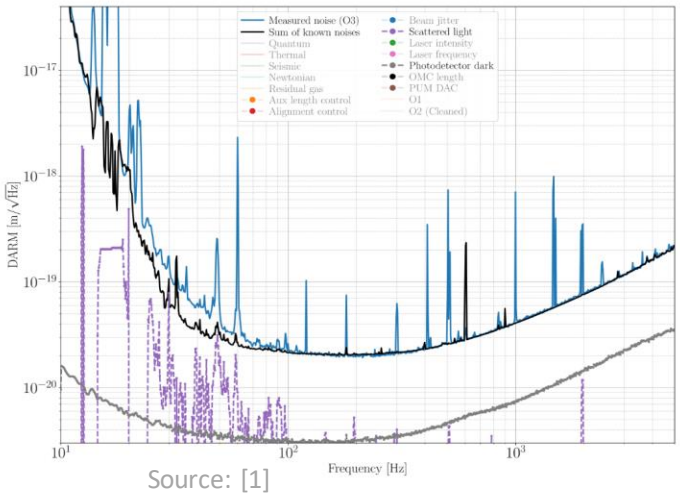

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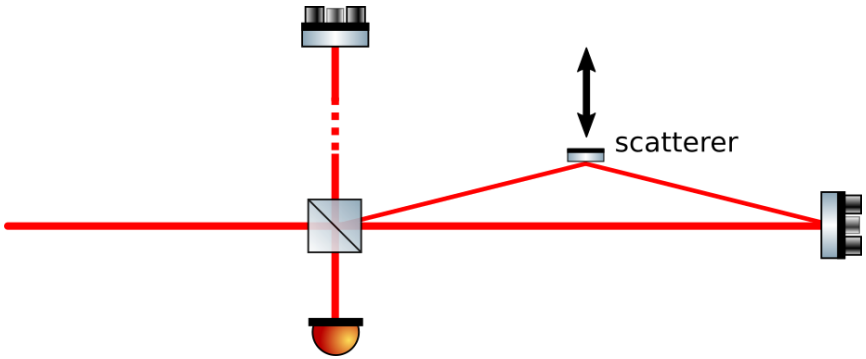
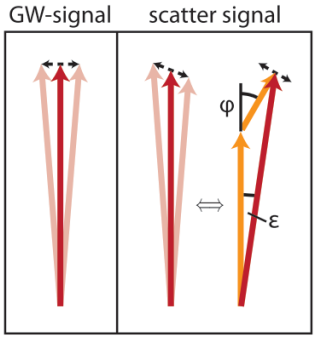
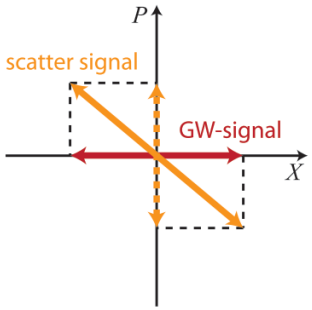


- ***non-linear*** coupling
- frequency ***up-conversion***
- amplitude- ***and*** phase- modulation

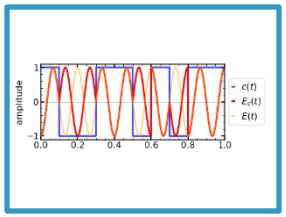
- sensitivity limited in low frequency range
- scattered light is major factor here
- *non-stationary* noise





Source: [2]

Motivation



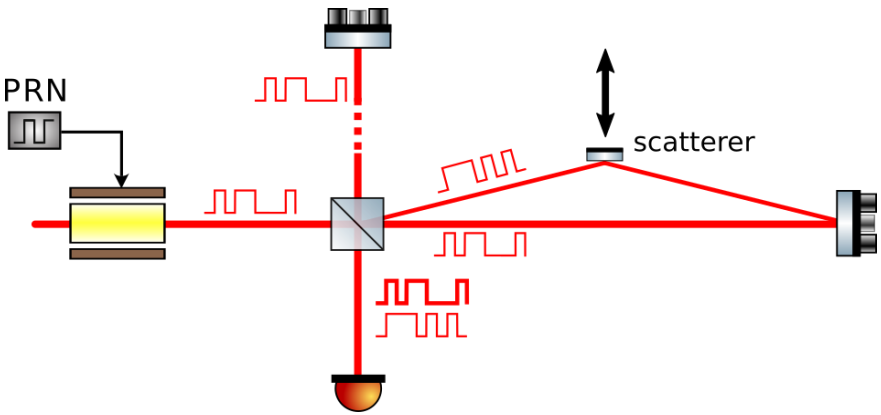
PRN modulation for tunable coherence

Time-domain simulation

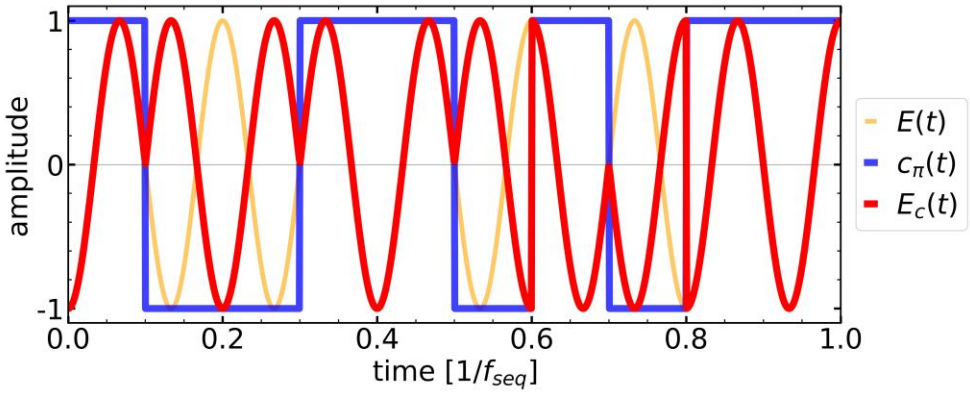
Outlook

Concept

- phase modulation at **GHz**
- *"random"* noise as modulation sequence
  - → ***pseudo white-light-interferometer***
- *chips* of sequence c_1 generated as 0 or 1
  - → modulation of 0 or π



$$\mathrm{E}_i(t) = \mathrm{E}_0 e^{i(\omega t_i + c_1(t_i)\pi)} = c_\pi(t_i)\mathrm{E}_0 e^{i\omega t_i}$$



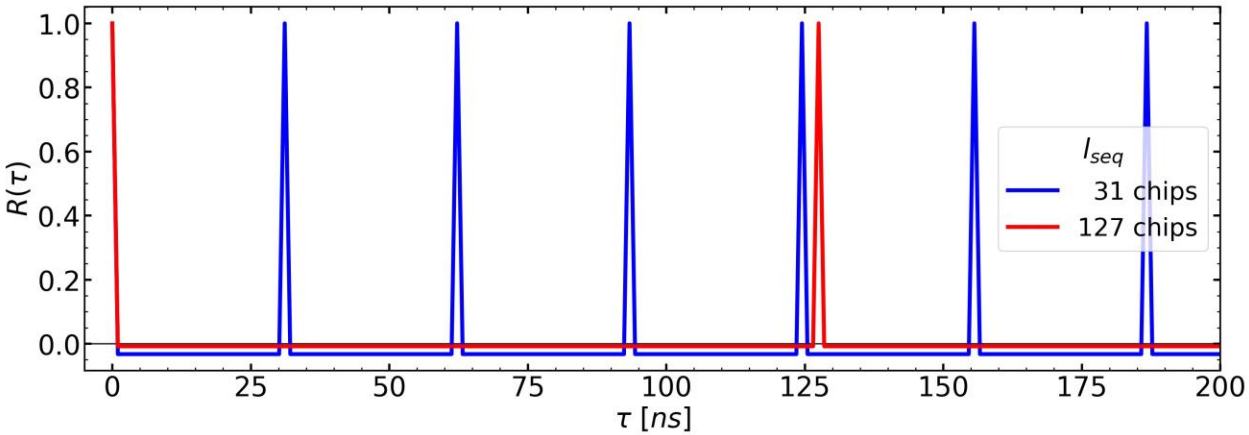
Concept

- pseudo-random-noise (**PRN**) sequence as input c_1
- *m – sequence* of length l_{seq}

  ...1011100101110010111001011100101...

  "random"
- *ideal two-level* autocorrelation function $R(\tau)$

$$R(\tau) = \begin{cases} 1 & \text{if } \tau = 0 \pmod{t_{seq}} \\ -\frac{1}{l_{seq}} & \text{if } \tau \neq 0 \pmod{t_{seq}} \end{cases}$$



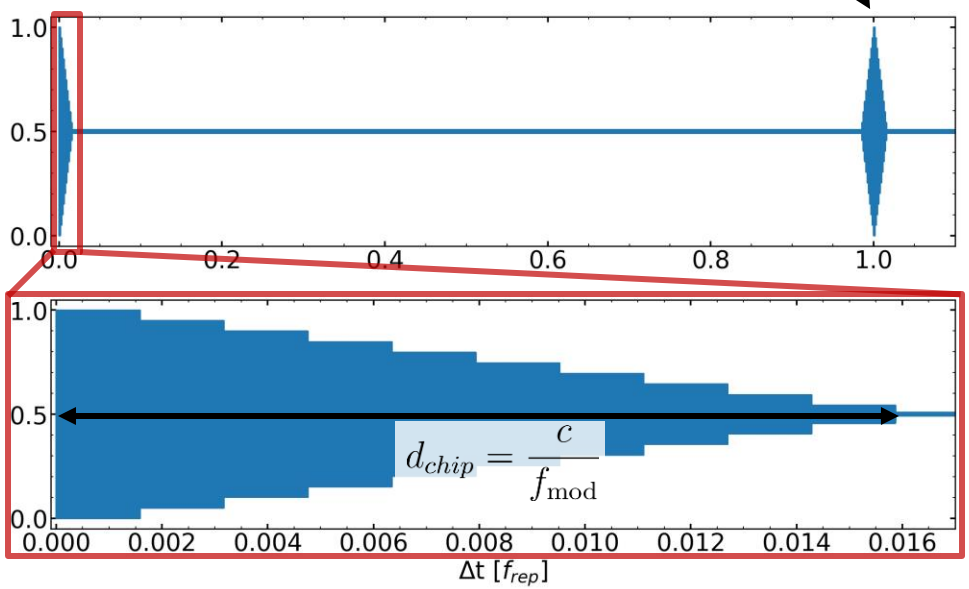
Concept

Influence on the Michelson Output:

- *small- and large*-scale dependencies
- large scale dependent on autocorrelation of PRN sequence

→ ***tunable coherence***

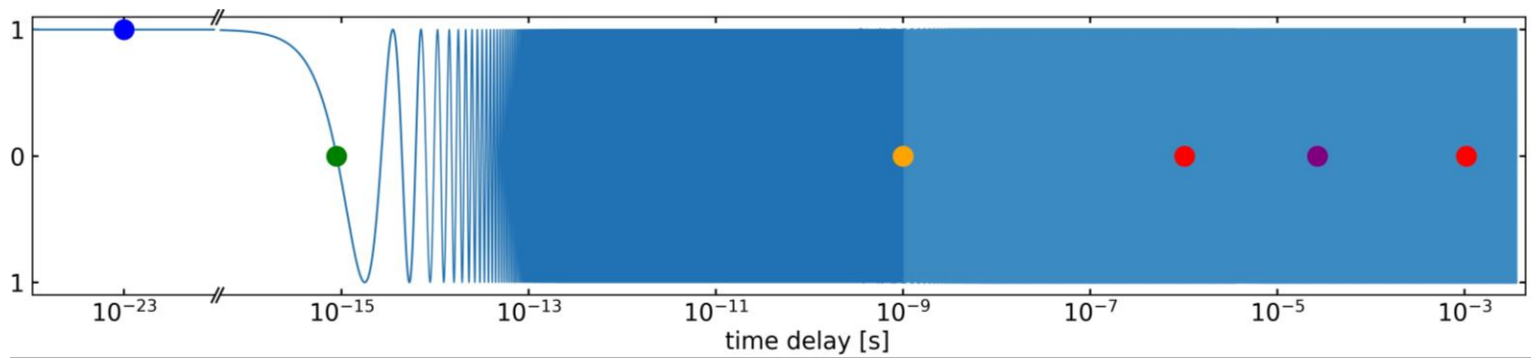
$$d_{coh} = \frac{l_{seq}}{f_{\mathrm{mod}}} \cdot c$$



$$P_{out} \propto \frac{1}{2} \cdot (1 + R(\tau)\cos(\omega\tau))$$

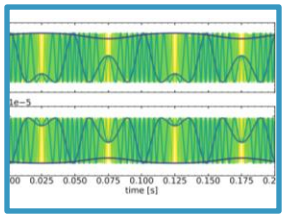
Concept

				f_{mod} = 1 GHz		f_{mod} = 10 GHz	
laser frequency		1064 nm	l_{seq}	31 chips	16 383 chips	31 chips	16 383 chips
PRN chip	d_{chip}	[cm]		29.9 cm	29.9 cm	2.99 cm	2.99 cm
PRN sequence	d_{coh}	[m]		9.29 m	4 911.50 m	0.93 m	491.15 m



Motivation

PRN modulation for tunable coherence

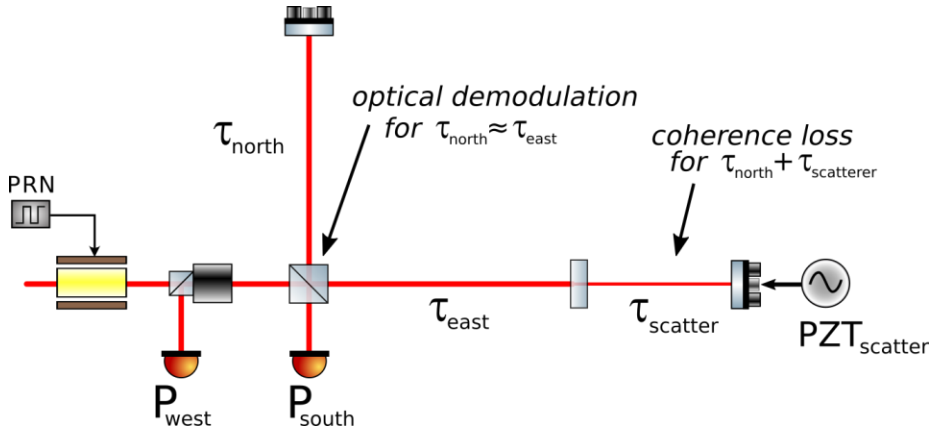


Time-domain simulation

Outlook

Simulation

Setup

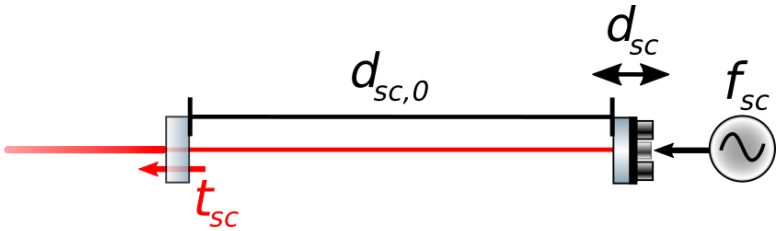


- analytical expression for both output ports
  - with and without **modulation**
- modulation following the m-sequence of an n-bit LFSR
  - $l_{seq}(n) = 2^n - 1$
- *DC-readout* for phase extraction

Simulation

- Model for scattered light delay:

$$t_{sc} = \frac{d_{sc,0} + d_{sc} \cdot \sin(2\pi f_{sc} t)}{c}$$



- Analytical solutions for power at *southport* of IFO
  - without modulation:

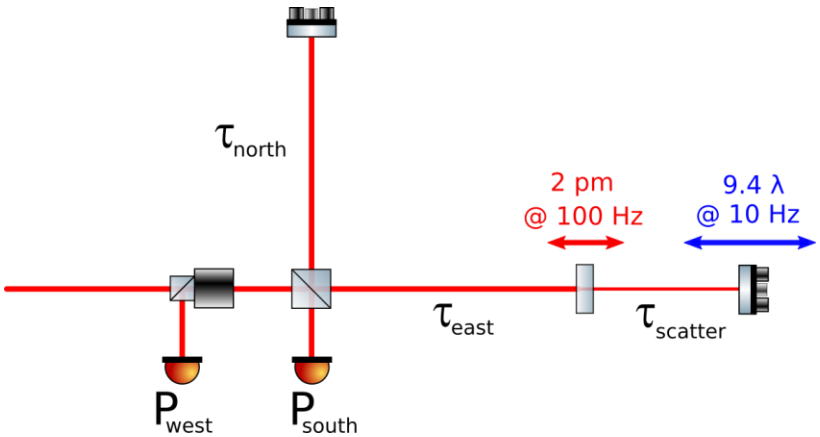
$$P_{south} = \frac{P_{in}}{2}\left[(1-b)[1+\cos(2\omega\Delta t)] + b\,[\cos(\omega t_{sc}) + \cos(\omega(2\Delta t + t_{sc}))] + b^2\,[1-\cos(\omega t_{sc})]\right]$$

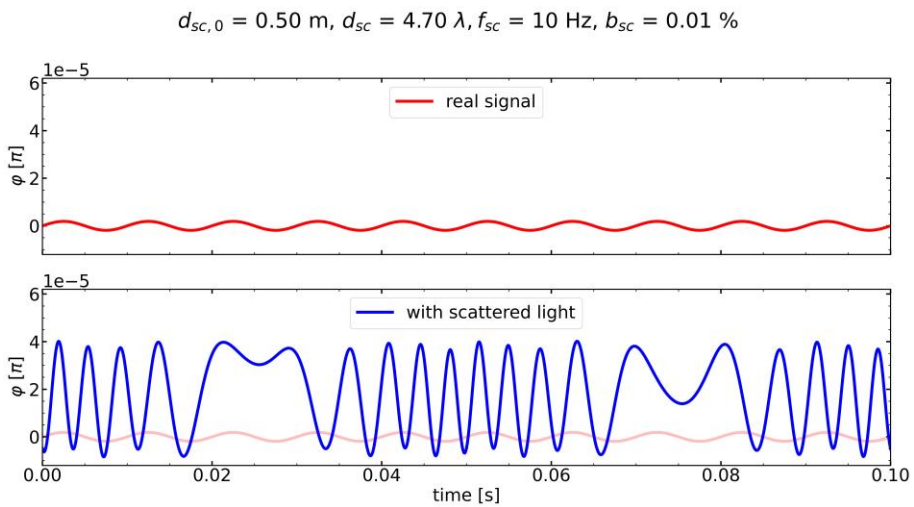
  - with modulation:

$$\boxed{P_{S,mod} \approx \frac{P_{in}}{2}\left[(1-b)[1+\cos(2\omega\Delta t)] + b^2\right]}$$

Simulation

Simple example

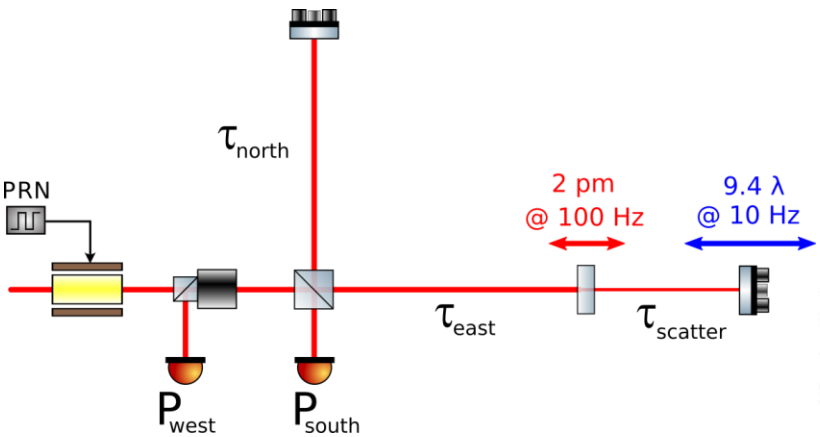


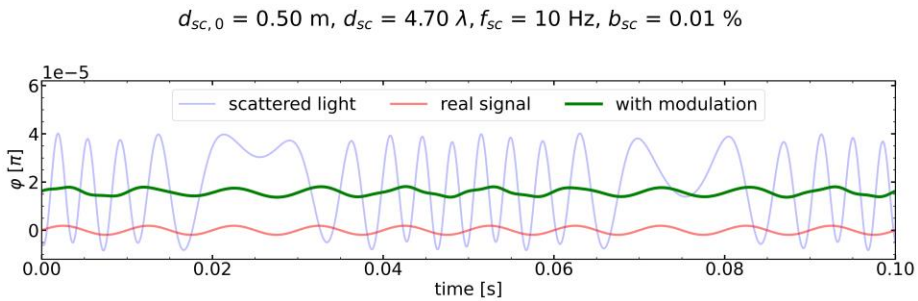


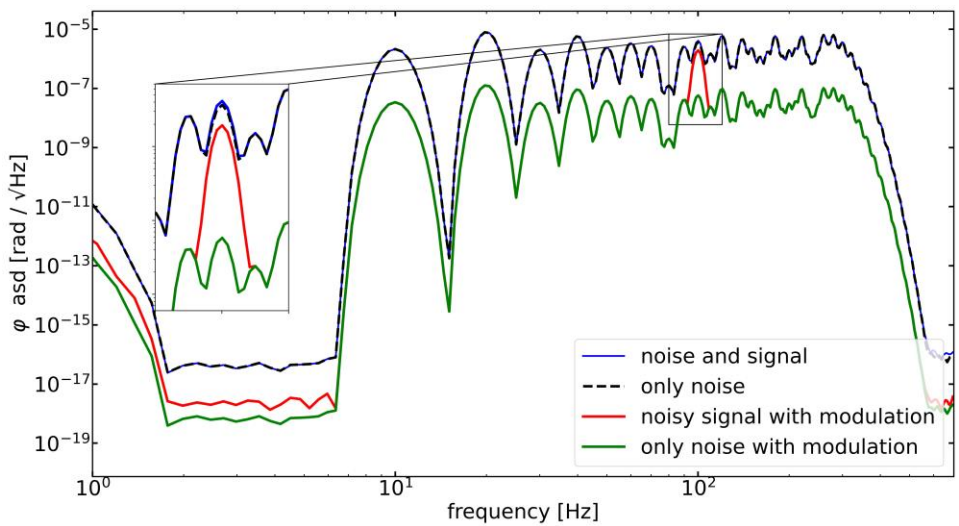
Simulation

Turning on modulation

63 chips sequence at 1 GHz



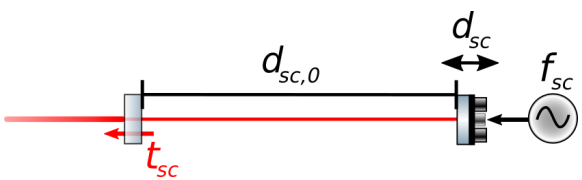


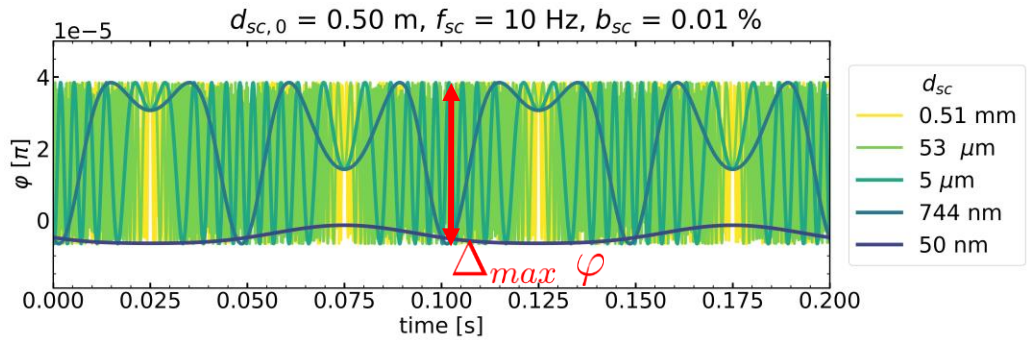


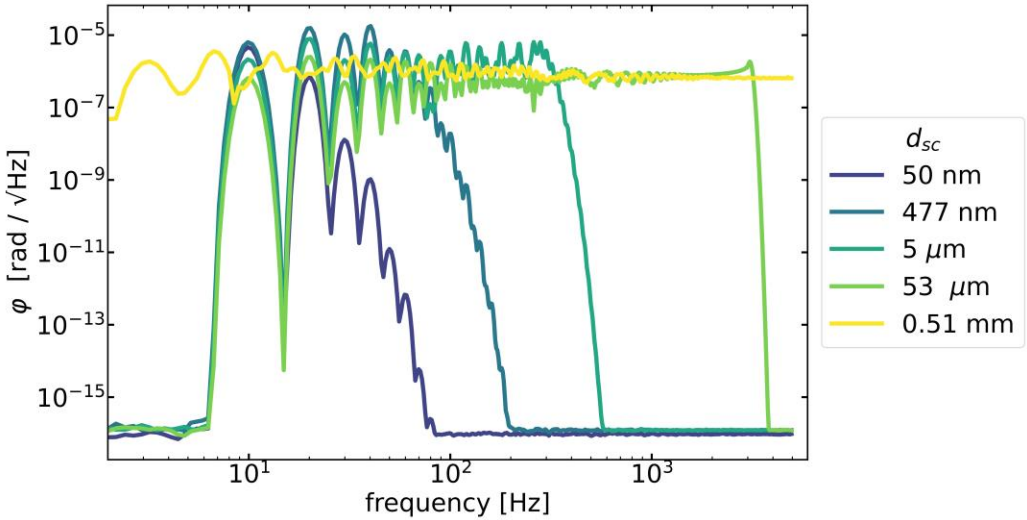
Simulation

Parameter

- scattered light parameter:
  - scattered light amplitude b_{sc}
  - offset $d_{sc,0}$
  - movement range d_{sc}
  - frequency f_{sc}

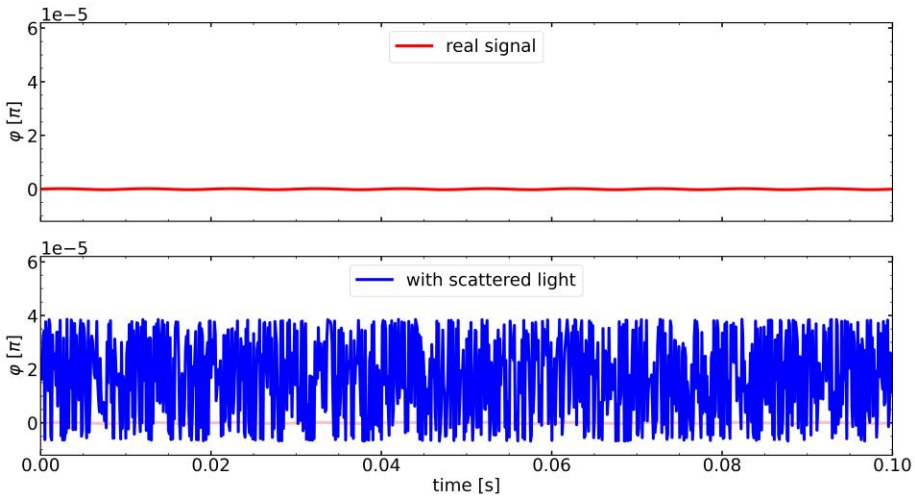


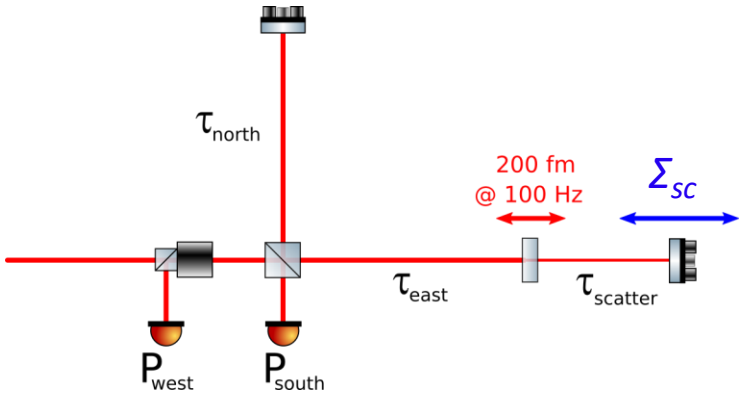




Simulation

More complex example



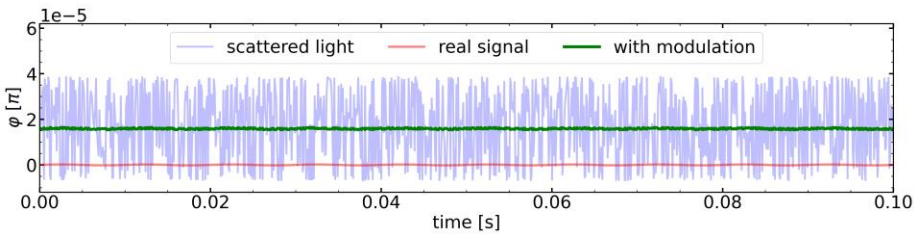


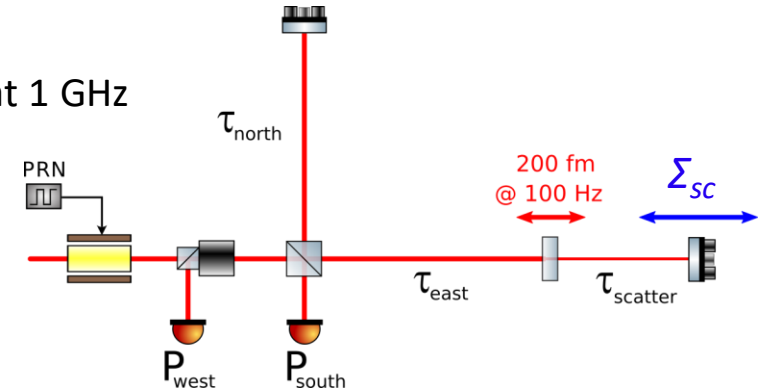
f_{sc} [Hz]	88.98	48.03	42.07	63.0	6.0
$d_{sc,0}$ [cm]	53.6				
d_{sc} [λ]	190.3	154.7	70.2	4.08	182.06
b_{sc}	0.01%				

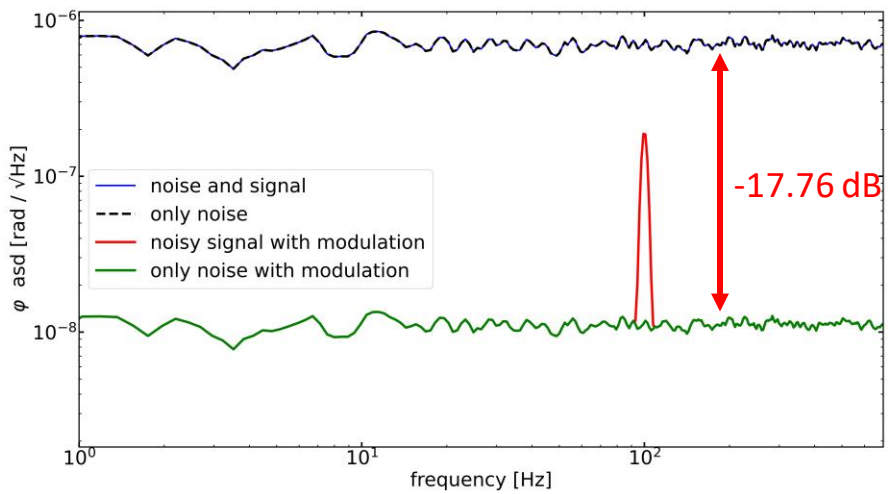
Simulation

More complex example

63 chips sequence at 1 GHz







f_{sc} [Hz]	88.98	48.03	42.07	63.0	6.0
$d_{sc,0}$ [cm]	53.6				
d_{sc} [λ]	190.3	154.7	70.2	4.08	182.06
b_{sc}	0.01%				

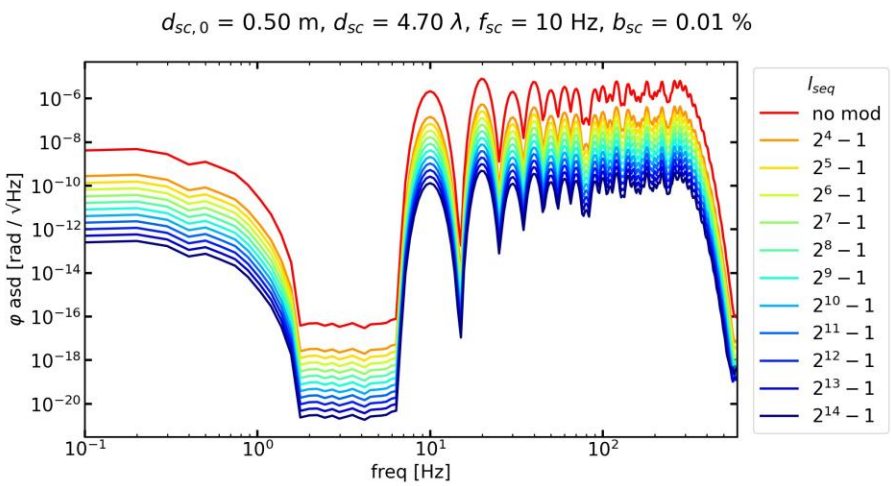
Simulation

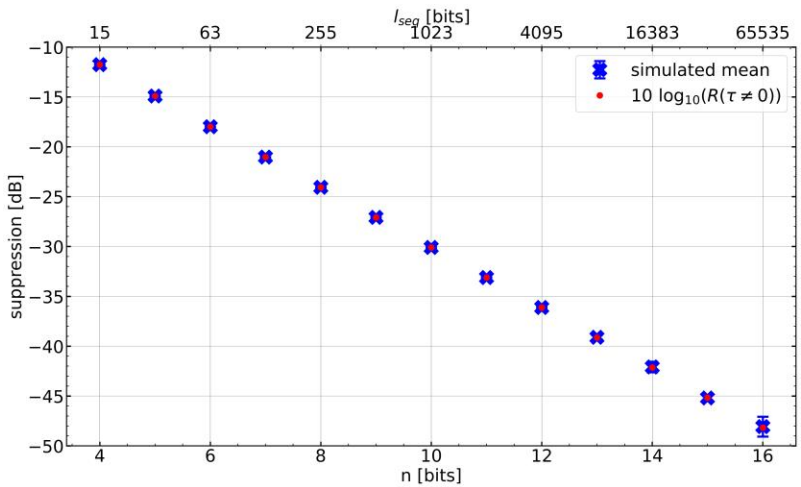
Achievable suppression

$$\Delta P_{S,mod} = \frac{P_{in}}{2}\left[R(\tau \neq 0)\, b\,\left[\cos(\omega t_{sc}) + \cos(\omega(2\Delta t + t_{sc})) + b\cos(\omega t_{sc})\right] - b\,\left[R(2\Delta t)\cos(2\omega\Delta t) + 1\right] + b^2\right]$$

→ realistically in *tabletop experiment*: *1 023 chips* → **-30 dB**

→ realistically in *GW - detector*: *65 535 chips* → **-48 dB**

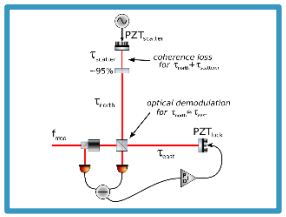




Motivation

PRN modulation for tunable coherence

Time-domain simulation

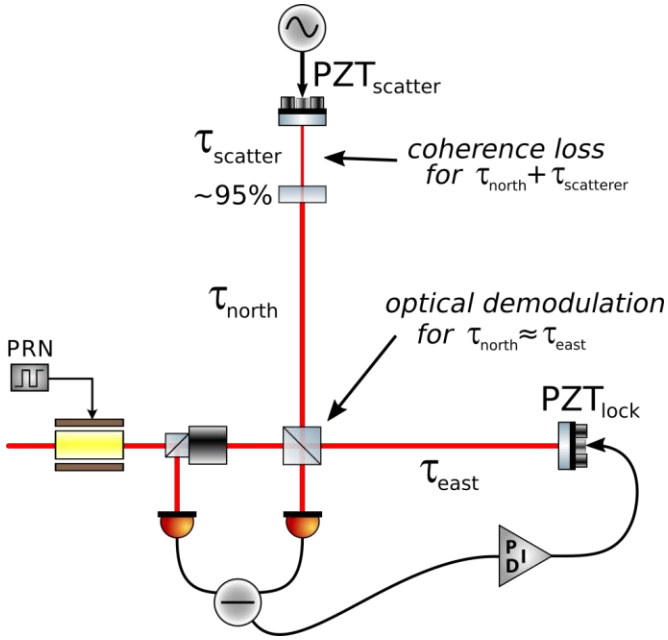


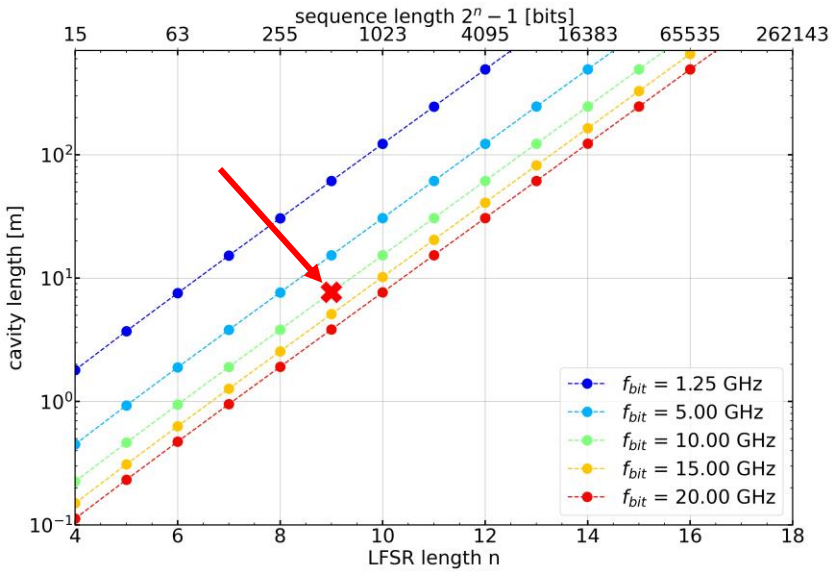
Outlook

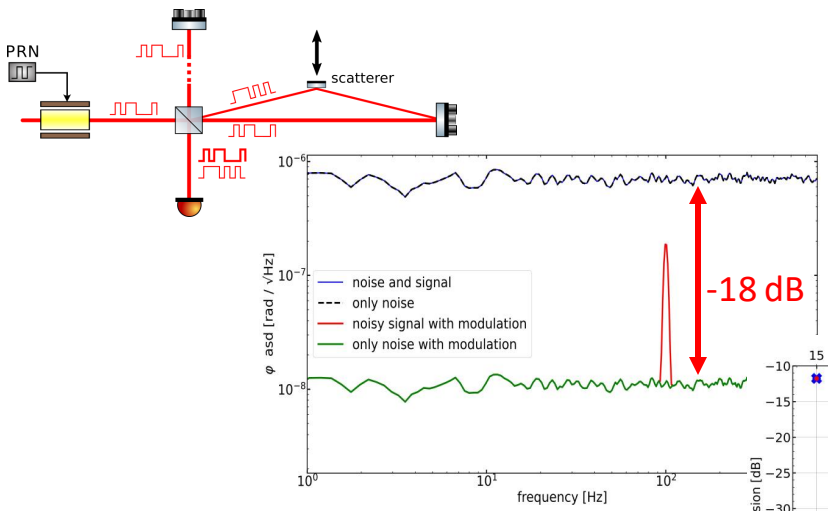
Outlook

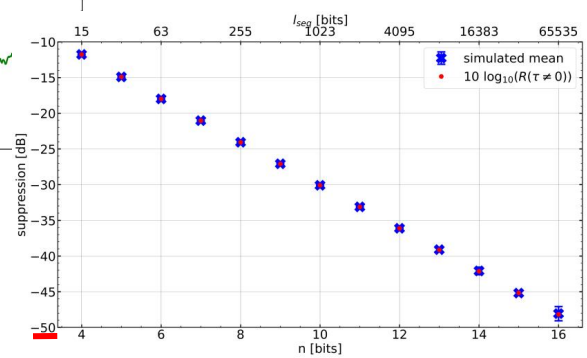
Experimental implementation

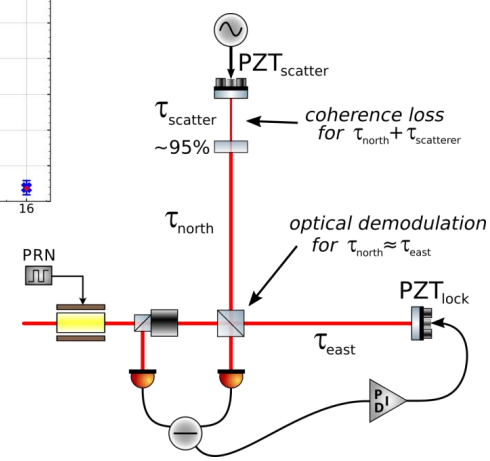
- tabletop setup of simple Michelson interferometer
- add cavities → step by step towards *dual-recycled enhanced Michelson interferometer*











Thank you for your attention!

Sources:

[1] Craig Cahillane; https://ccahilla.github.io/; visited: 10.03.2022
[2] Melanie Ast; Quantum-dense metrology for subtraction of back-scatter disturbances in gravitational-wave detection; 2017