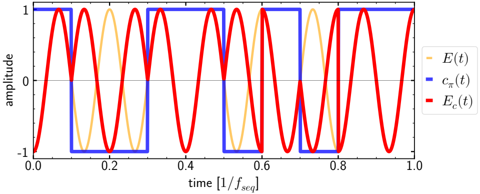
Straylight suppression with tunable coherence in high precision interferometers

GWADW Elba 2023



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23rd May 2023

Universität Hamburg
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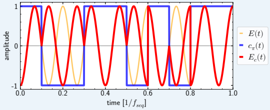
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

GRAVITATIONAL
WAVE DETECTION

Outline

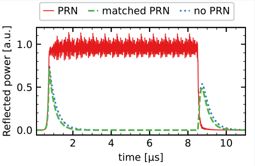
Motivation & Concept



scattered light

- limitations at low frequency
  - characteristics
  - resulting problems
- PRN phase modulation
  - concept
  - expectations

Cavity response

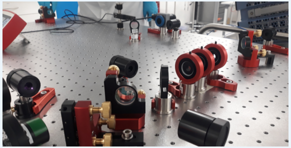


simulation of cavity fields

- lengths matching
- detuning
- power build-up
- locking

related paper in review

Outlook



- time-domain simulation
  - plans for improvement
  - recycling cavities
- experimental setup
  - Michelson interferometer
  - adding cavities

Motivation

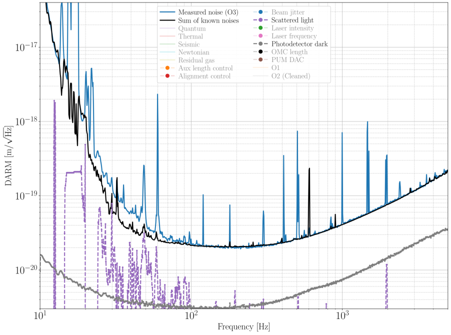


Figure: LIGO Hanford noise budget [1]

- scattered light is major limitation at low frequencies
- *non stationary* noise

Motivation

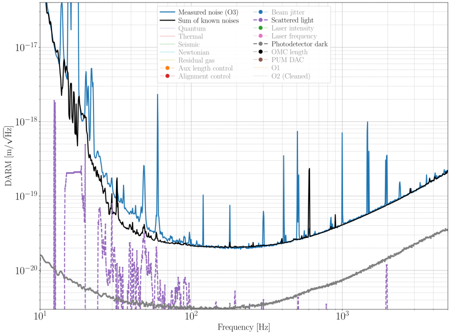
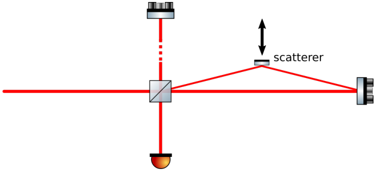
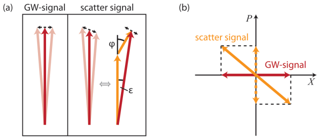


Figure: LIGO Hanford noise budget [1]

- scattered light is major limitation at low frequencies
- *non stationary* noise



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

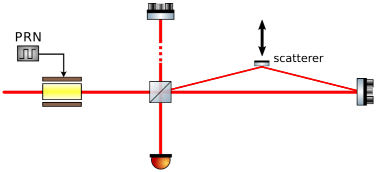


Source: [2]

Concept

Tunable Coherence

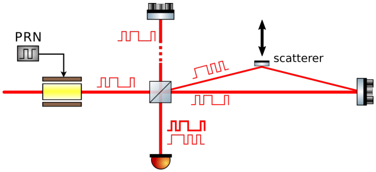
- phase modulation at **GHz**
- *"random"* noise as modulation sequence c_0
  $\longrightarrow$ ***pseudo white-light interferometer***



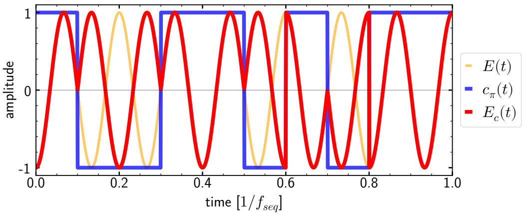
Concept

Tunable Coherence

- phase modulation at **GHz**
- *"random"* noise as modulation sequence c_0
  → ***pseudo white-light interferometer***
- *chips* of c_0 generated as 0 or 1
  → modulation $c_{\pm 1}(t)$ of 0 or π



$$E(t) = E_0 e^{i(\omega t + \varphi + c_0(t)\pi)} = c_{\pm 1}(t) E_0 e^{i(\omega t + \varphi)}$$



Concept

modulation sequence

- pseudo-random-noise (**PRN**) sequence as modulation input c_0
- *m-sequence* of length l_{seq}

$$\ldots\underbrace{1011100}_{\text{"random"}}1011100\,1011100\,\underbrace{1011100}_{l_{seq}}101\ldots$$

Concept

modulation sequence

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- *m-sequence* of length l_{seq}

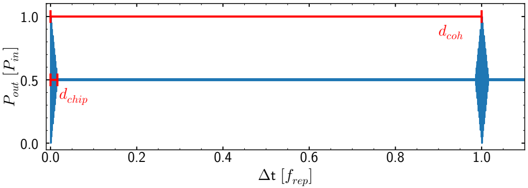
$$\ldots\underbrace{1011100}_{\text{"random"}}\underbrace{1011100}1011100\underbrace{1011100}_{l_{seq}}101\ldots$$

influence on MI output

- small scale dependent on chip length d_{chip}
- large scale dependent on autocorellation of PRN sequence

  → **tunable coherence**

  → ***re-coherence*** length d_{coh}



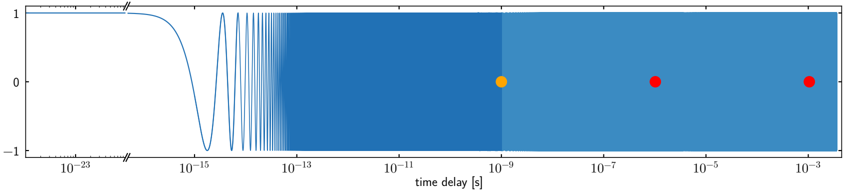
$$d_{coh} = \frac{l_{seq}}{f_{\mathrm{mod}}} \cdot c$$

$$d_{chip} = \frac{c}{f_{\mathrm{mod}}}$$

Concept

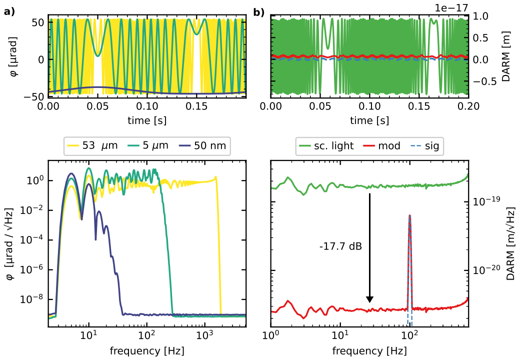
Distance examples

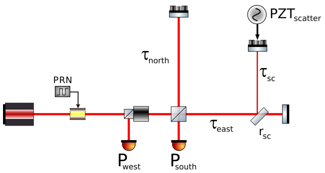
				$f_{\text{mod}} = 1$ GHz		$f_{\text{mod}} = 10$ GHz	
laser frequency		1064 nm	l_{seq}:	31 chips	16 383 chips	31 chips	16 383 chips
🟠 PRN chip	d_{chip}	[cm]		29.9 cm	29.9 cm	2.99 cm	2.99 cm
🔴 PRN sequence	d_{coh}	[m]		9.29 m	4911.50 m	0.93 m	491.15 m



Simulation results

Michelson Interferometer





$$P_S = \frac{P_0}{2}\Big[(1-r_{sc}^2)\,[1-R(\tau)\cos(\omega\tau)] + r_{sc}^2\,[R(\tau+\tau_{sc})\cos(\omega(\tau+\tau_{sc})) - R(\tau_{sc})\cos(\omega\tau_{sc})] + r_{sc}^4\,[1+R(\tau_{sc})\cos(\omega\tau_{sc})]\Big]$$

Simulation results

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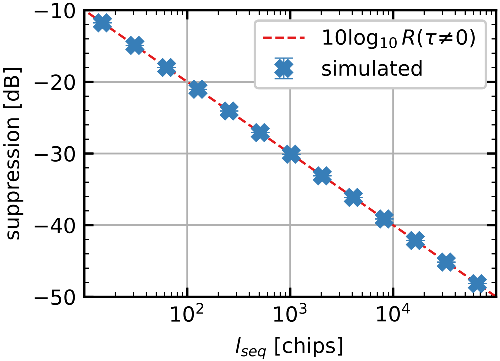

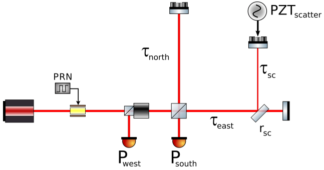

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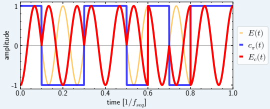

scattered light

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  - characteristics
  - resulting problems
- PRN phase modulation
  - concept
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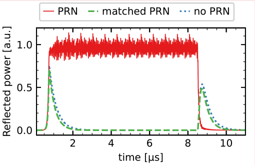
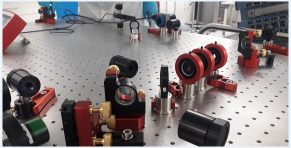
Cavity response



simulation of cavity fields

- lengths matching
- detuning
- power build-up
- locking

Outlook



- time-domain simulation
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  - recycling cavities
- experimental setup
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Cavity response

Equations for fields

modulated input field

$$E_{in}(t) = E_0 e^{i(\omega t+\varphi+c_0(t)\pi)} = c_{\pm 1}(t) E_0 e^{i(\omega t+\varphi)}$$

random behavior for e.g. reflected field

$$E_{\text{refl}}(t) = r_1 E_0 e^{i(\omega t+\varphi)} \Bigg[c_{\pm 1}(t) - \frac{t_1^2}{r_1^2} \sum_{n=1}^{\infty} c_{\pm 1}(t-n\tau) \left(r_1 r_2 e^{-i\omega\tau}\right)^n \Bigg]$$

and equivalently for other fields

Cavity response

Equations for fields

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and equivalently for other fields

recoherence for sequence matching cavity

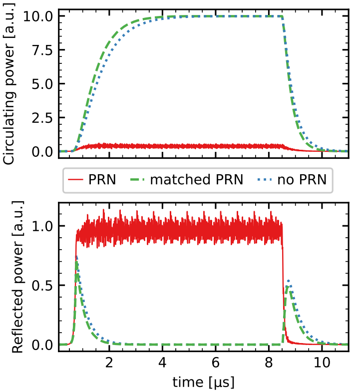
if $c_{\pm 1}(t - n\tau) = c_{\pm 1}(t)\ \forall n, t$:

$$E_{\text{refl}}(t) = r_1 c_{\pm 1}(t) E_0 e^{i(\omega t+\varphi)} \left[1 - \frac{t_1^2}{r_1^2} \sum_{n=1}^{\infty} \left(r_1 r_2 e^{-i\omega\tau}\right)^n \right]$$

$$= c_{\pm 1}(t) E_0 e^{i(\omega t+\varphi)} \left[r_1 - t_1^2 r_2 e^{-i\omega\tau} \sum_{n=0}^{\infty} \left(r_1 r_2 e^{-i\omega\tau}\right)^n \right]$$

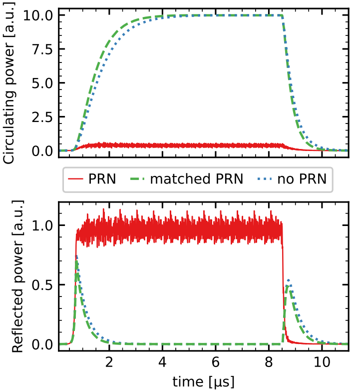
$$= E_{in}(t) \left[r_1 - \frac{r_2 t_1^2 e^{-i\omega\tau}}{1 - r_1 r_2 e^{-i\omega\tau}} \right]$$

Length matching



- random behavior if sequence does not fit
- cavity length locked to recoherence length
- modulation frequency locked to laser frequency

Length matching



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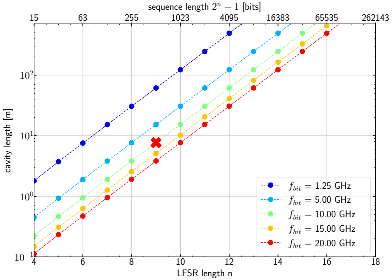
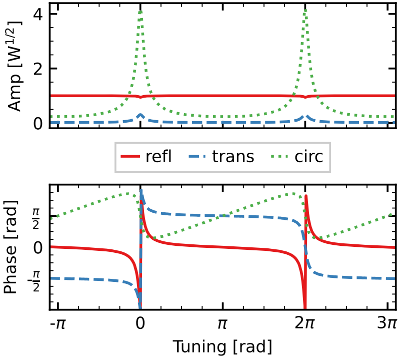
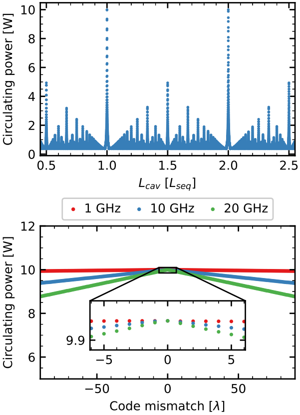


Detuning



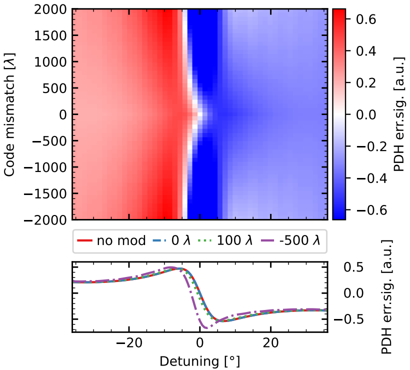
- no difference **if** cavity is locked to sequence length
- shown left: over-coupled
- same for under-coupled & impedance matched
- tuning range limited due to modulation
- modulation frequency should be locked to laser frequency

Power build-up



- full build-up for integer multiple of sequence length
- halved build-up for e.g. 1.5 sequence lengths
- FWHM depending on modulation frequency
  → in µm to mm range
  → e.g. for 10 GHz around 1776 wavelengths
- sensitivity depending on cavity finesse

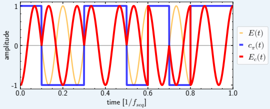
PDH - error signal



- normal error signal for matched cavity
- local oscillator phase not adjusted for each simulation
  → probably cause for observed steeper flanks
- locking might require additional unmodulated laser

Outline

Motivation & Concept



scattered light

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  - characteristics
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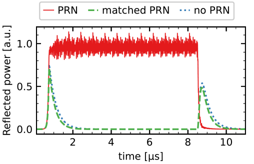
Cavity response



simulation of cavity fields

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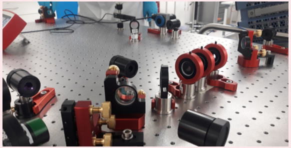
Outlook



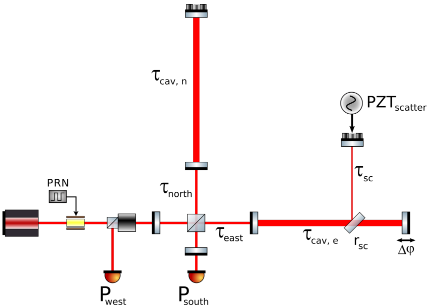
- time-domain simulation
  - plans for improvement
  - recycling cavities
- experimental setup
  - Michelson interferometer
  - adding cavities

Outlook

Simulation

future needs

- recycling cavities & scattered light
- more generalized setup
- higher precision without performance penalty
- performance increase



Outlook

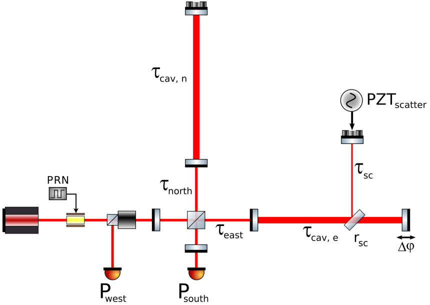
Simulation

future needs

- recycling cavities & scattered light
- more generalized setup
- higher precision without performance penalty
- performance increase

conceptual ideas

- use modular setup
  - → define each optic and its "connections"
  - → iterate through setup and propagate fields in time-steps
- for FINESSE compatibility, use similar input method
  - → run both simulations parallel



Outlook

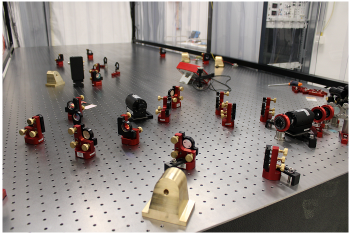
Experiment

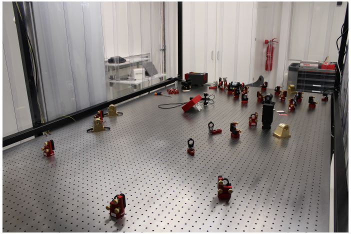
moved into the lab

prepared supporting infrastructure

started setup for testing

adjust interferometer and measure



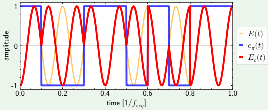


experiments in preparation

tunable coherence & dual-port quadrature read-out

Conclusion

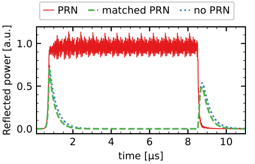
Motivation & Concept



scattered light

- non-stationary noise
  - limiting at low frequency
  - even more problematic in future detectors
- PRN phase modulation
  - GHz modulation
  - high suppression possible
  - length matching crucial

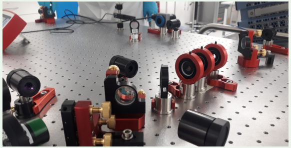
Cavity response



simulation of cavity fields

- lengths matching is crucial
- detuning is possible
- power build-up works normal if lengths match
- locking probably needs an unmodulated laser

Outlook



- time-domain simulation
  - recycling cavities
  - more general setup
  - FINESSE compatibility
- experimental setup
  - moved into lab
  - Michelson interferometer setup in preparation

related paper in review

Bibliography

Craig Cahillane. *https://ccahilla.github.io/*. URL: https://ccahilla.github.io/ (visited on 03/10/2022).

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