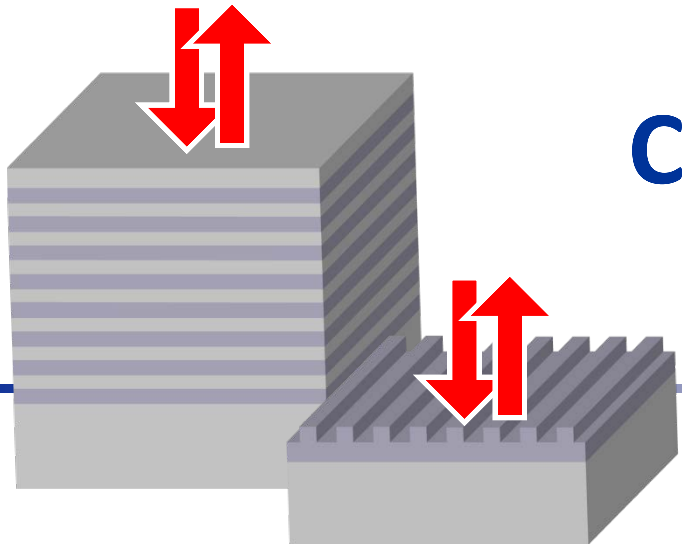
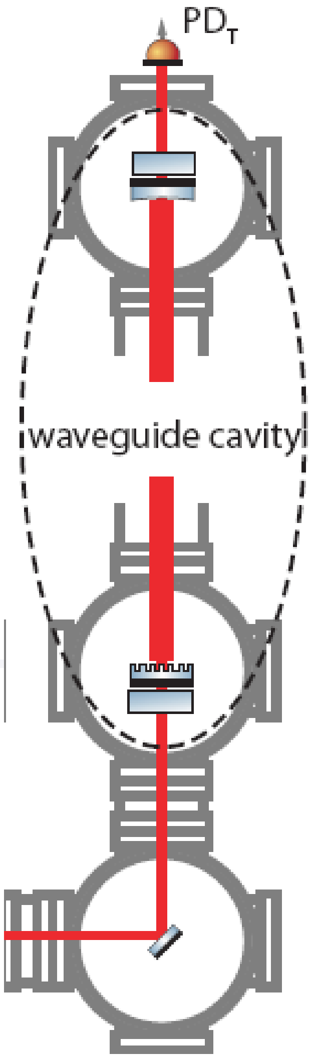
Waveguide Gratings as Cavity Mirrors





Daniel Friedrich

Student seminar, 20th of Jan. 2012

ICRR Institute for Cosmic Ray Research University of Tokyo

Gravitational Wave Group

Hannover, Germany → 東京, 日本

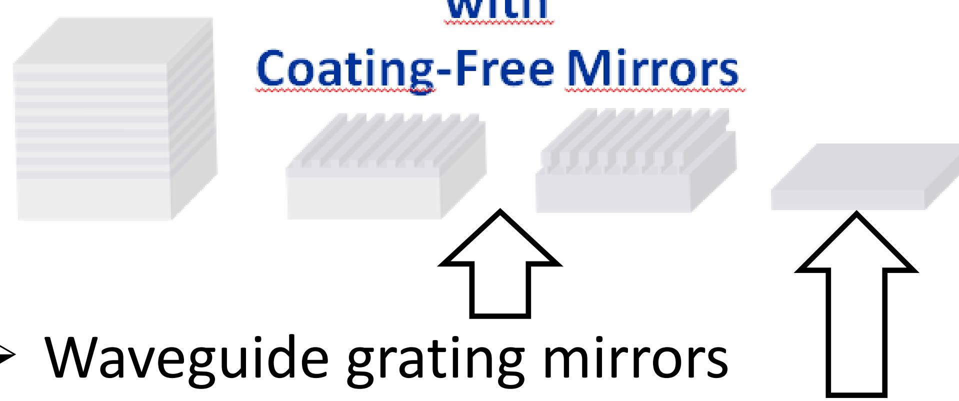
- Since Nov. 2011:
  JSPS research fellow @
  with Prof. Kawamura

ICRR
Institute for Cosmic Ray Research
University of Tokyo

- Nov. 2011:
  PhD thesis @

Albert-Einstein-Institut
Hannover

Laser Interferometry
with
Coating-Free Mirrors



- ➢ Waveguide grating mirrors
- ➢ Opto-mechanics with thin membranes

Outline of this talk

- AEI Hannover
- Introduction
- Resonant waveguide gratings (WGG)
- WGG @ 1064nm
- WGG @ 1550nm
- Summary

AEI Hannover

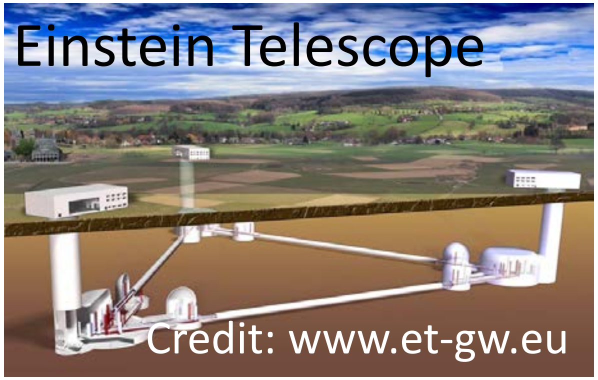
Albert-Einstein-Institut
Hannover

MAX-PLANCK-GESELLSCHAFT

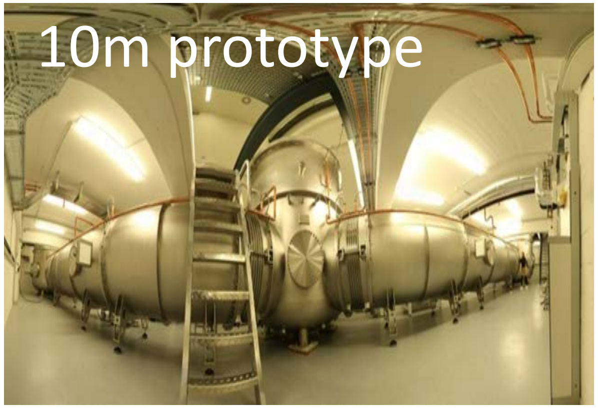
Leibniz
Universität
Hannover

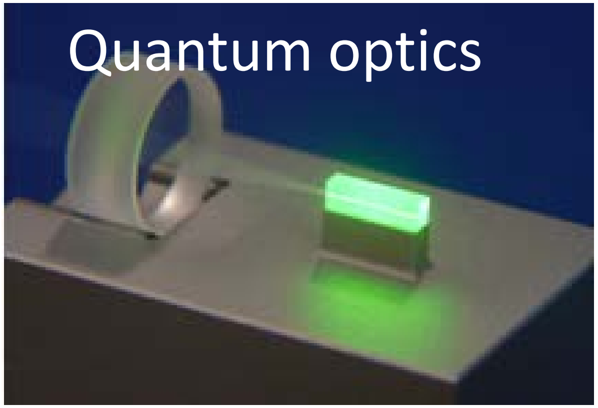
Research @ AEI Hannover

Albert-Einstein-Institut
Hannover



Credits: www.aei-hannover.de





- Data analysis
- Laser development
- Optical components

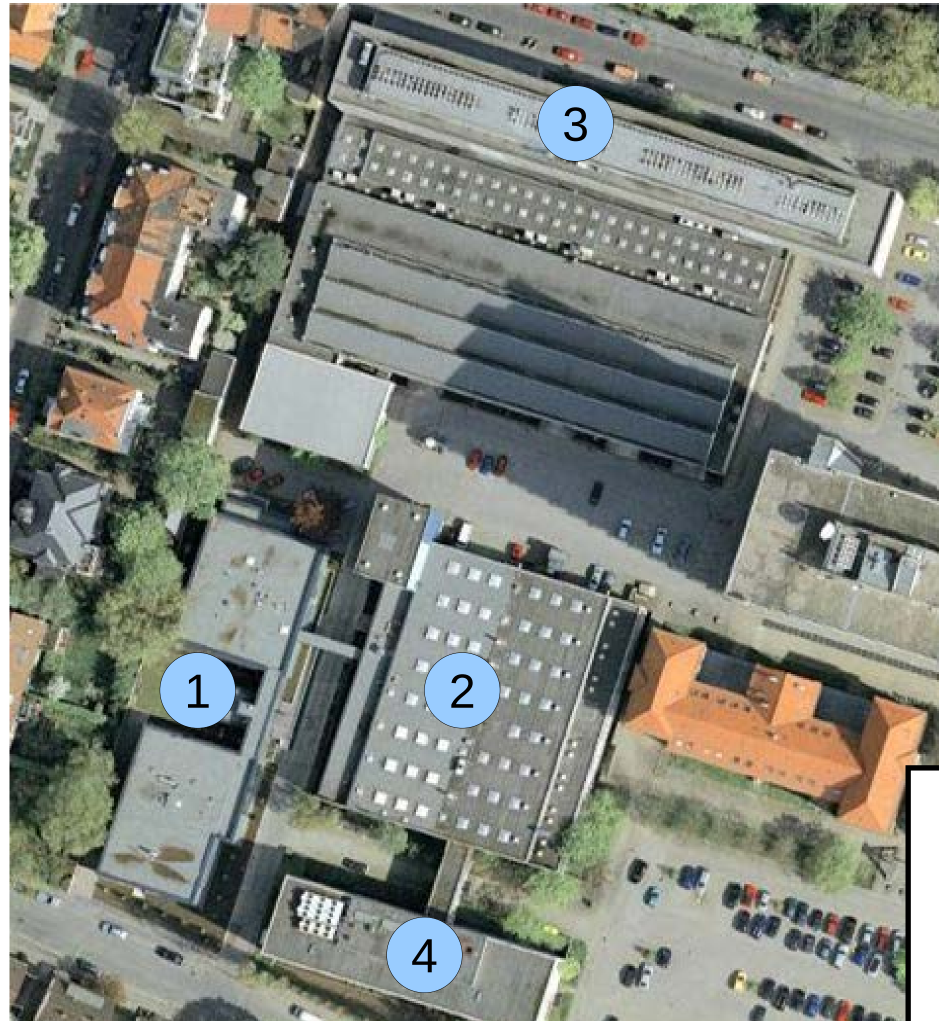
- See also: *www.dfg-science-tv.de/en/projects/the-wave-hunters/2009-06-09*

AEI Hannover

Albert-Einstein-Institut
Hannover

Directors:
Prof. Danzmann
Prof. Allen

Scientific staff: ~80
PhD students: ~50
Master students: ~10



1-4: offices/labs

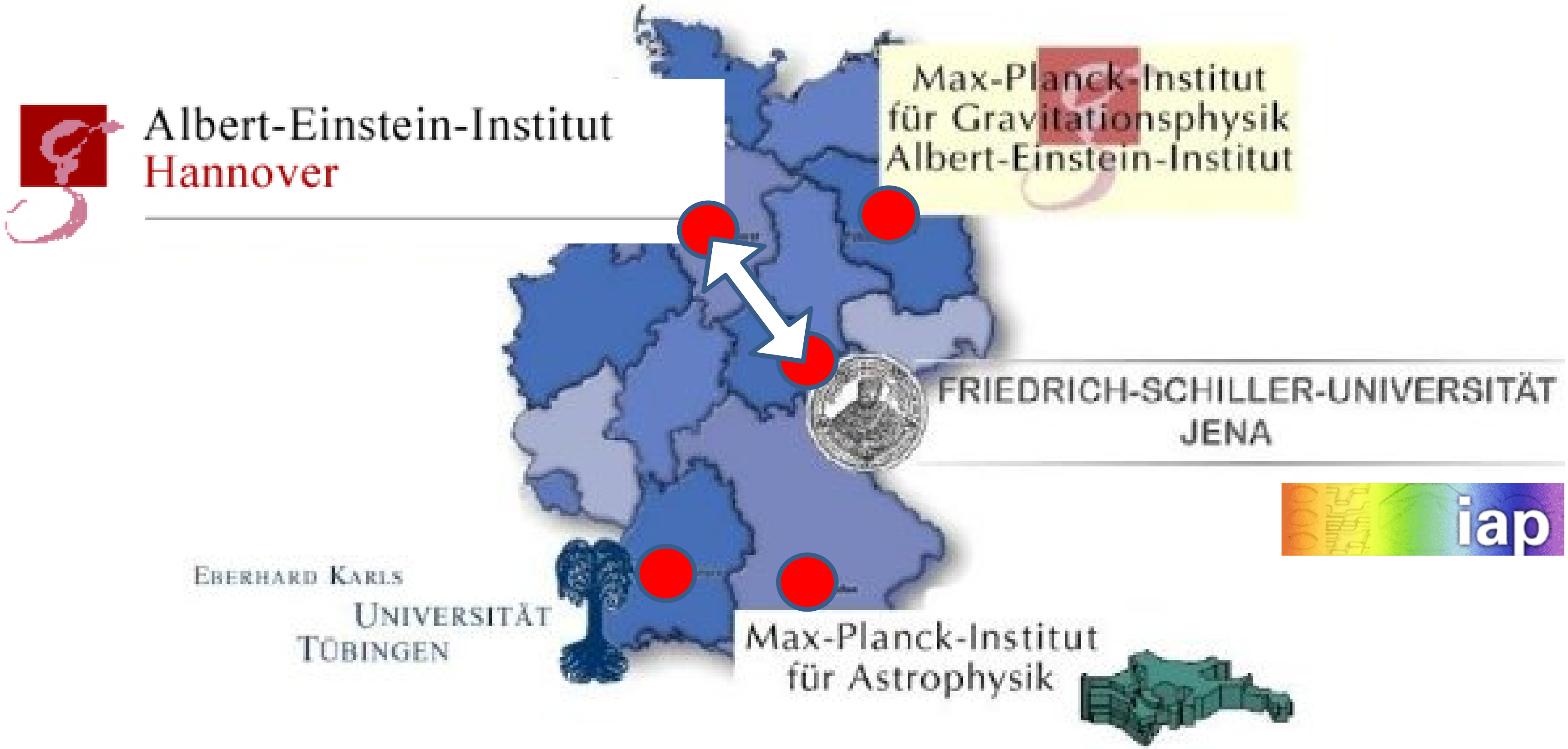
GEO600

High-Reflection Waveguide Coatings…

- Project within the SFB/TR7:
- Started in 2007
- Collaboration: Hannover - Jena

Gravitational wave astronomy

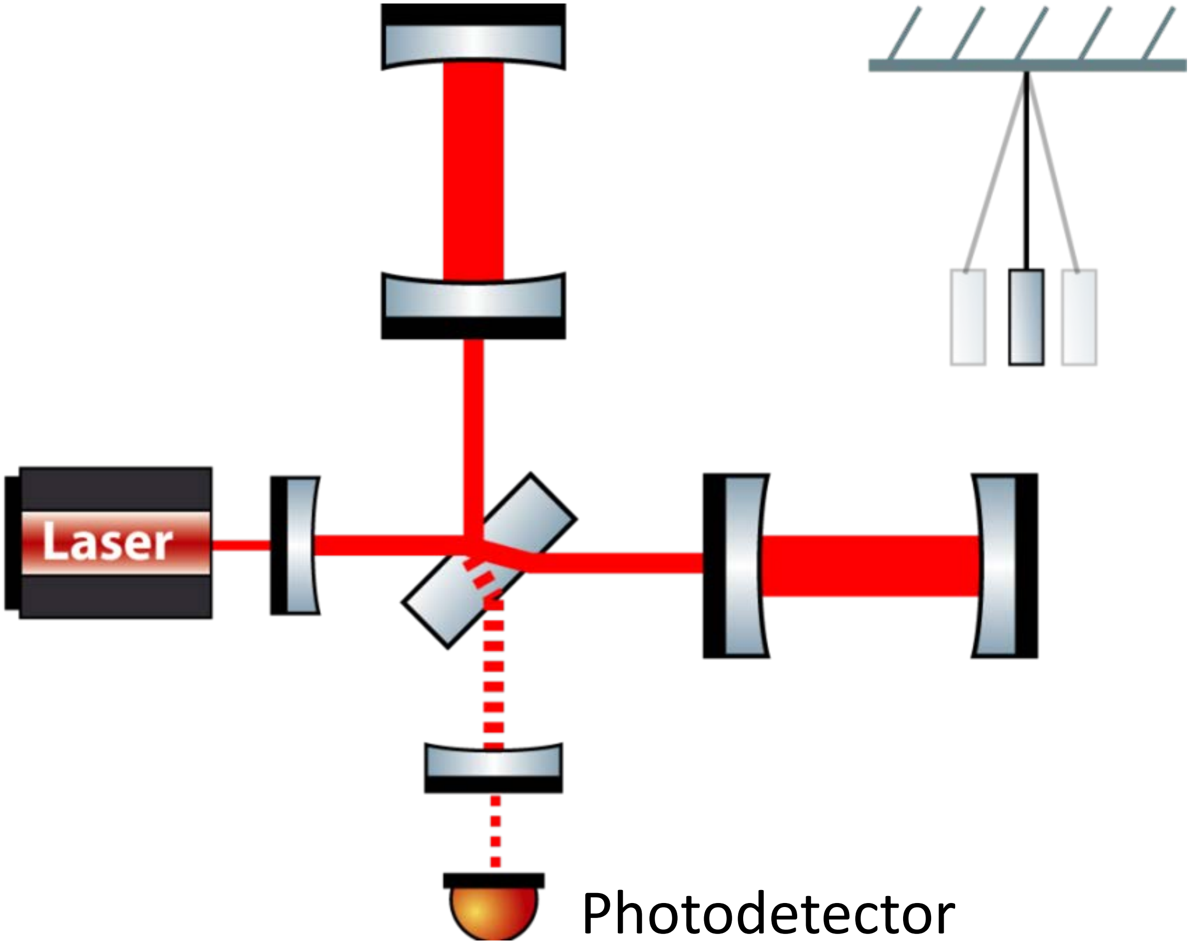
Methods – Sources - Observation



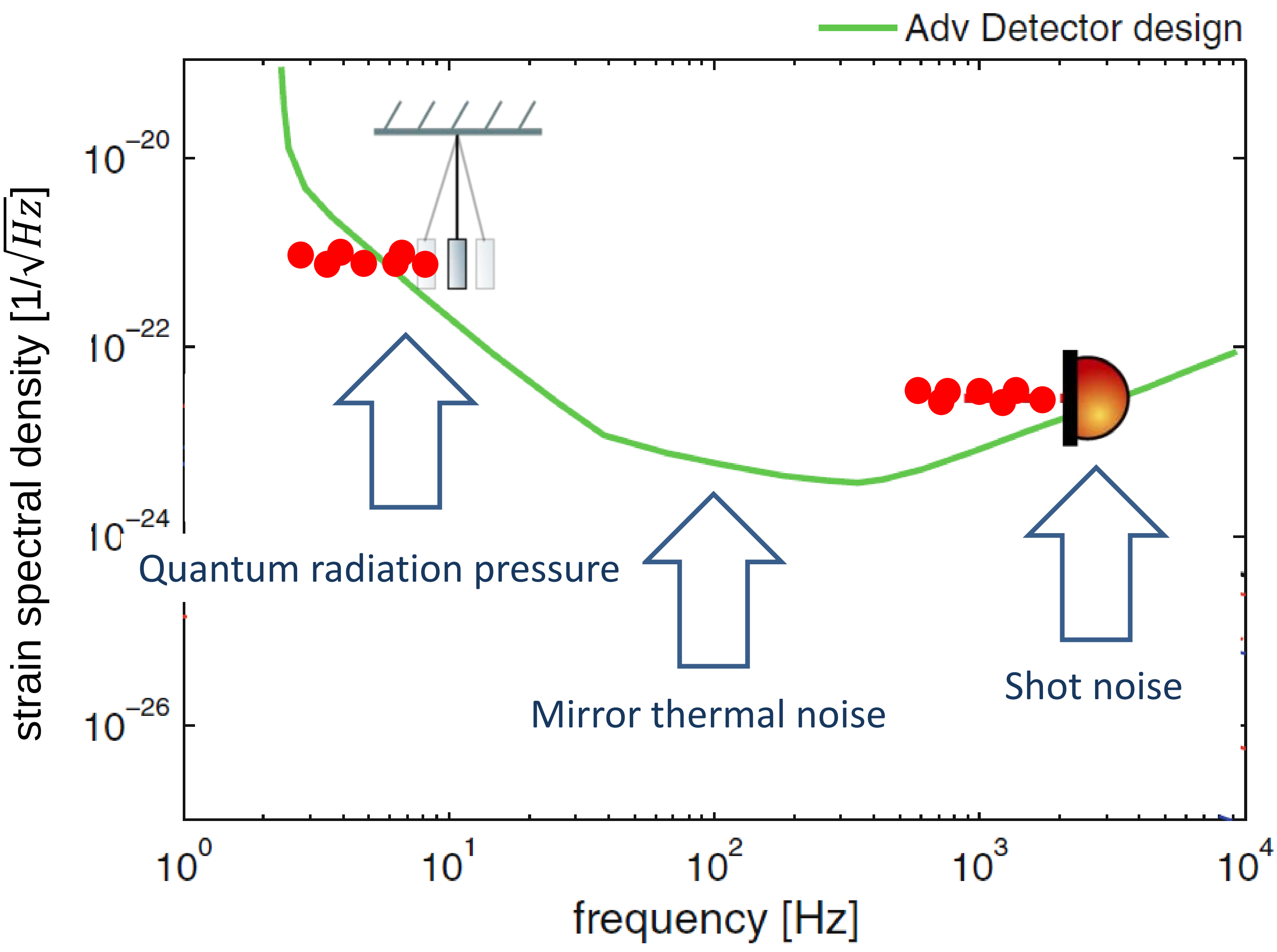
Outline of this talk

- AEI Hannover
- **Introduction**
- Resonant waveguide gratings (WGG)
- WGG @ 1064nm
- WGG @ 1550nm
- Summary

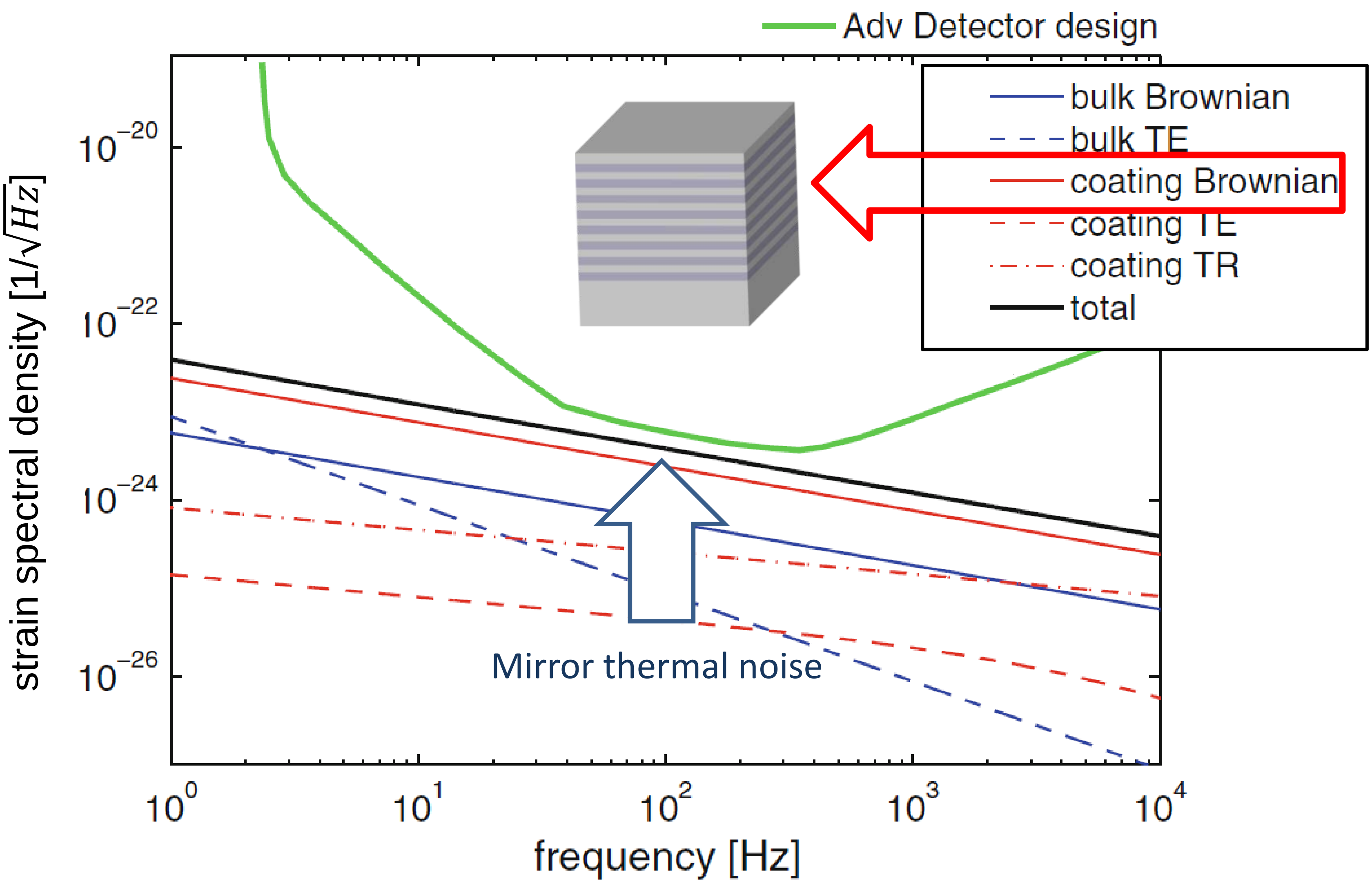
Advanced GW Detectors



3 Main Noise Sources



Mirror Thermal Noise

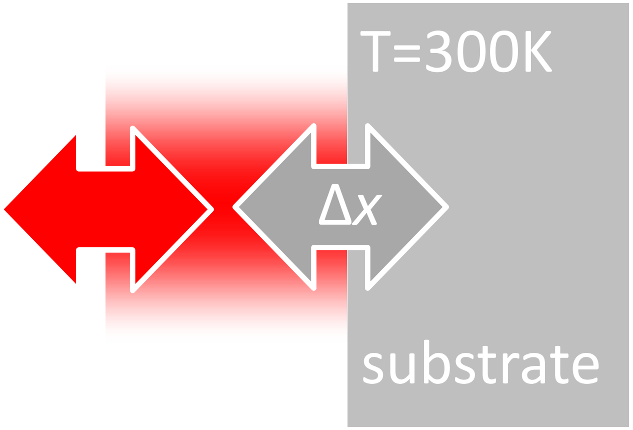


[R. Nawrodt et al. Gen Relat Gravit 43, 593 (2011)]

Brownian Thermal Noise

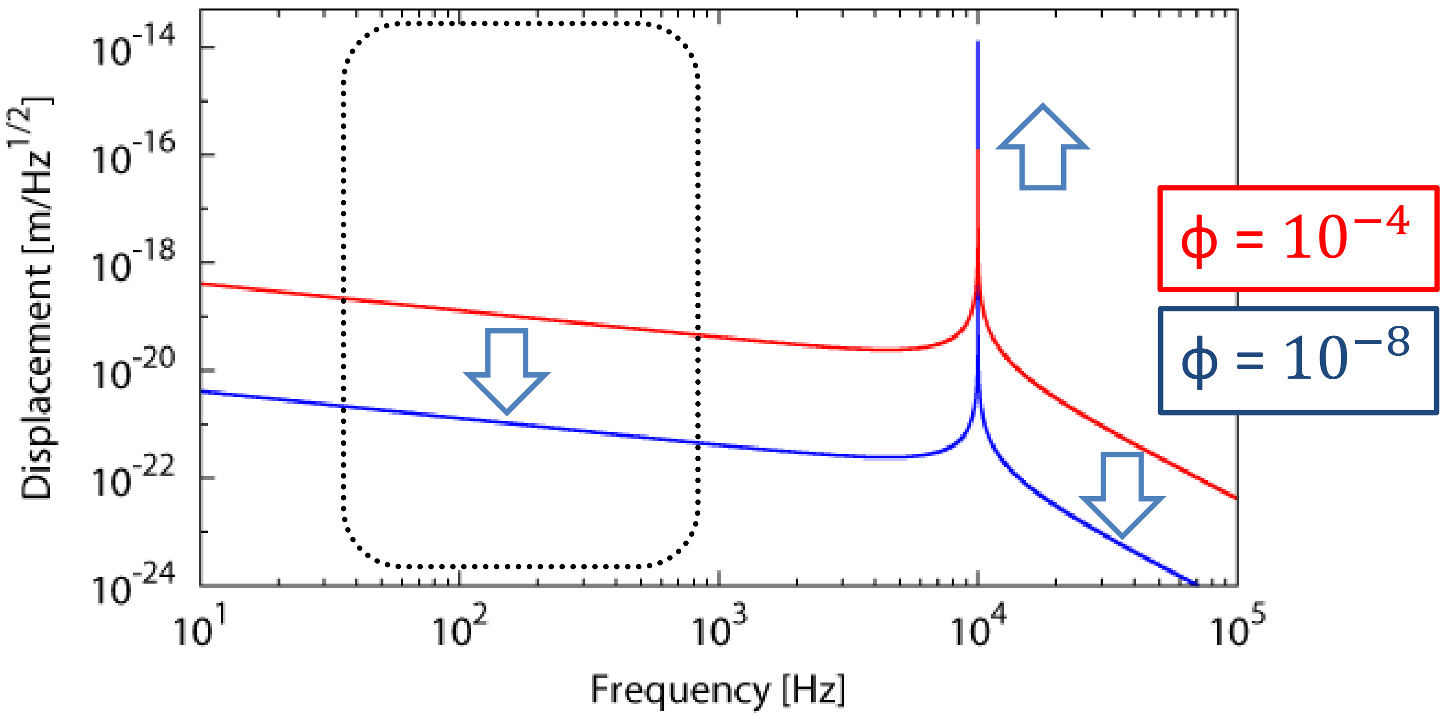
- Temperature driven eigenmotion
- Sensed by the laser beam
- Fluctuations $\Delta x \leftrightarrow$ Dissipation ϕ

H.B. Callen and R..F. Greene, Phys. Rev. ***86****, 702, 1952 v*



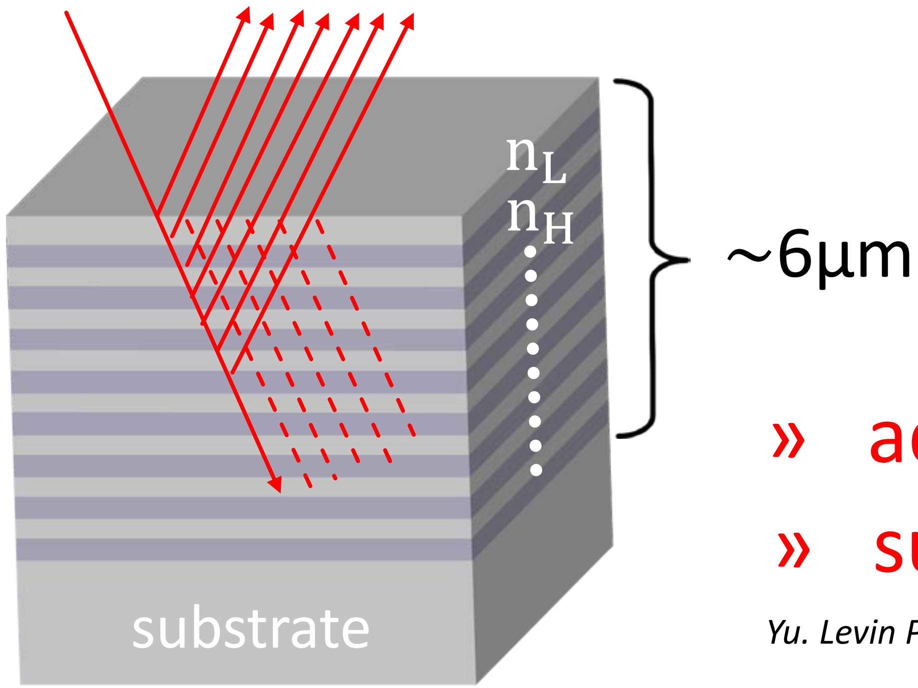
Mechanical Oscillator

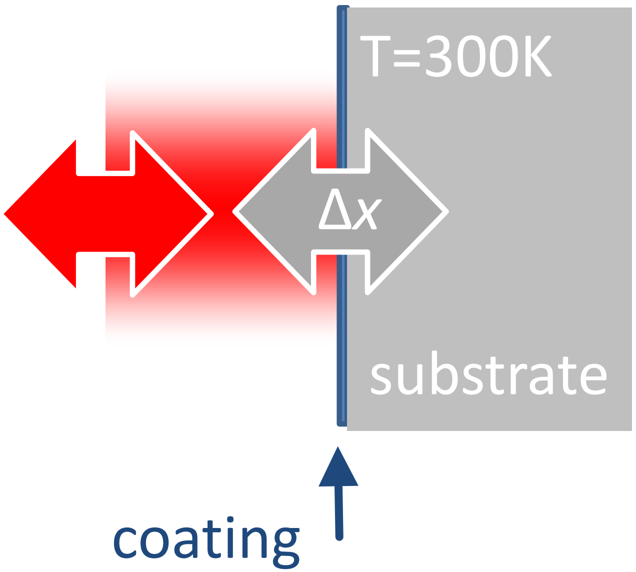
Detection band ↓ ↓ Eigenfrequency



Multilayer Coatings

✓ High reflectivity





» add mechanical loss

» surface loss is crucial

Yu. Levin Phys. Rev. D ***57****, 659 (1998)*

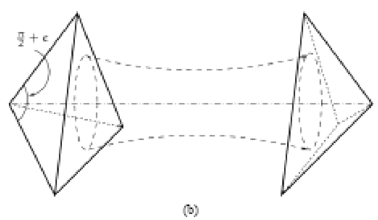
How to Cope with TN

$$S_{\mathrm{x}}^2 = \frac{2k_{\mathrm{b}}T}{\pi^{3/2} f} \frac{1}{Y r_0} \left[\underbrace{\phi_{\mathrm{sub}}}_{\text{substrate}} + \underbrace{\frac{h}{\sqrt{\pi} r_0} \left(\frac{Y'}{Y} \phi_{||} + \frac{Y}{Y'} \phi_{\perp} \right)}_{\text{coating}} \right]$$

- Material research
- Cryogenic Temperature T
- Larger beam radii r_0
- Reduction of coating thickness h

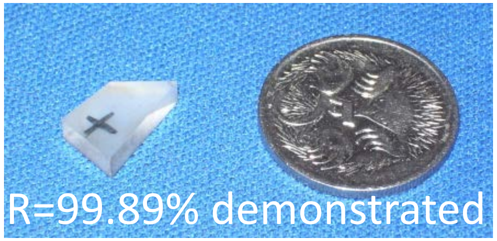
G.M. Harry et al. CQG **19**, 897 (2002)

Coating Reduced/Free Concepts



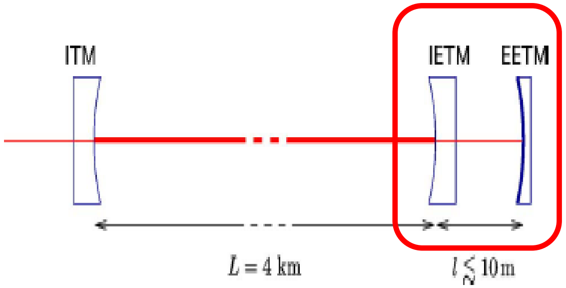
- Corner reflectors

  *V.B. Braginsky et al. Phys . Lett. A **324**, 345 (2004)*



- Coating free retroreflector

  *S. Goßler et al. Phys Rev A **76**, 053810 (2007)*



- Anti-resonant cavities

  *F. Ya. Khalili Phys. Lett. A **334**, 67 (2005)*

Outline of this talk

- AEI Hannover
- Introduction
- **Resonant waveguide gratings (WGG)**
- WGG @ 1064nm
- WGG @ 1550nm
- Summary

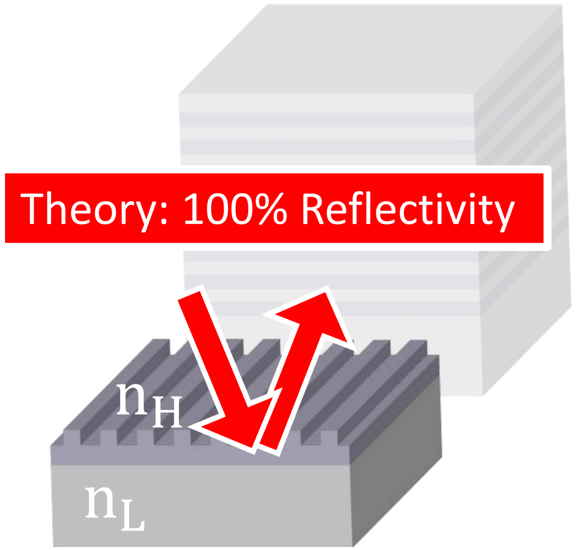
Waveguide Gratings (WGGs)

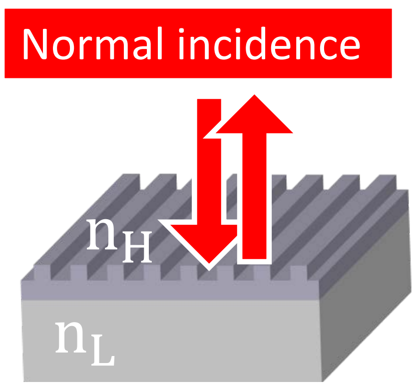
- Structured surfaces
- Indices of refraction ($n_H > n_L$)
- Resonant excitation of light

A. Hessel et al. Appl. Opt. ***4****, 1275 (1965)*

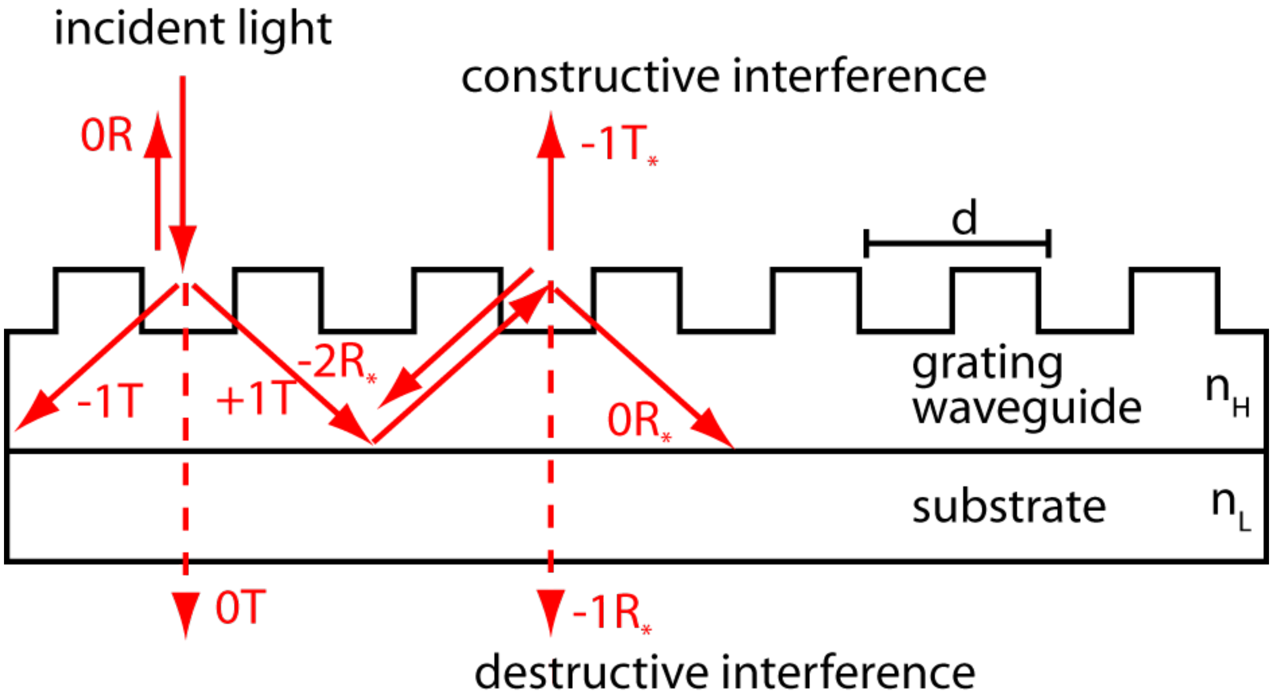
- 98.5% demonstrated @ 1550nm

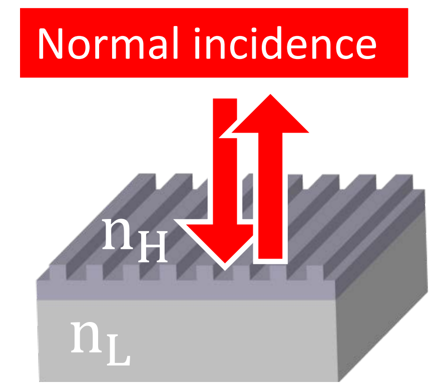
C.F.R. Mateus et al. IEEE Phot. Tech. Lett. ***16****, 1676 (2004)*





Ray Picture





- Existence and direction of diffraction orders *m*

$$n_b \sin(\beta_m) = n_a \sin(\alpha) + \frac{m\lambda}{d}$$

- Restrict diffraction orders

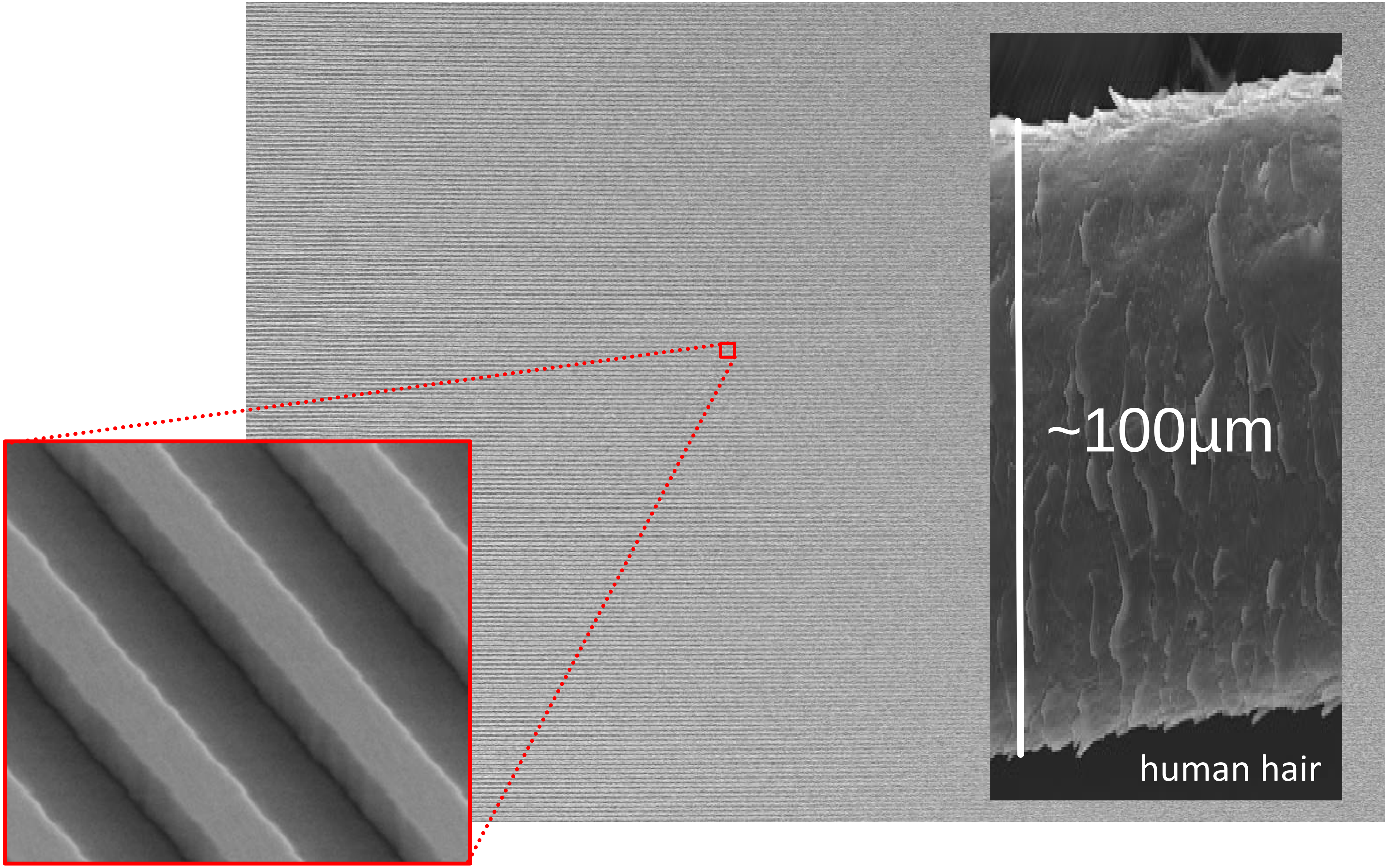
Only 0th order in air $d \leq \lambda$

±1st orders in waveguide $\lambda/n_H \leq d \leq 2\lambda/n_H$

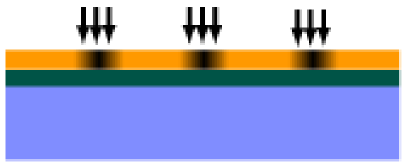
Only 0th order in substrate $d \leq \lambda/n_L$

D. Rosenblatt et al. Journal of Quantum electronics ***33****, 2038 (1997)*

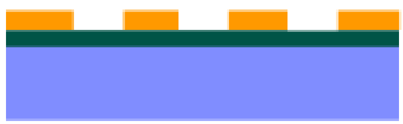
Subwavelength Structures



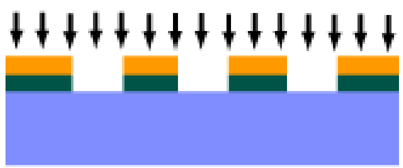
Grating Fabrication



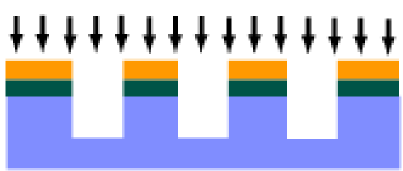
① Electron-beam-lithography



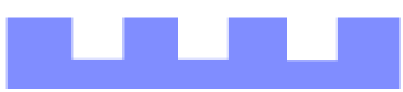
② Resist-removal



③ Etching of the mask



④ Anisotropic etching

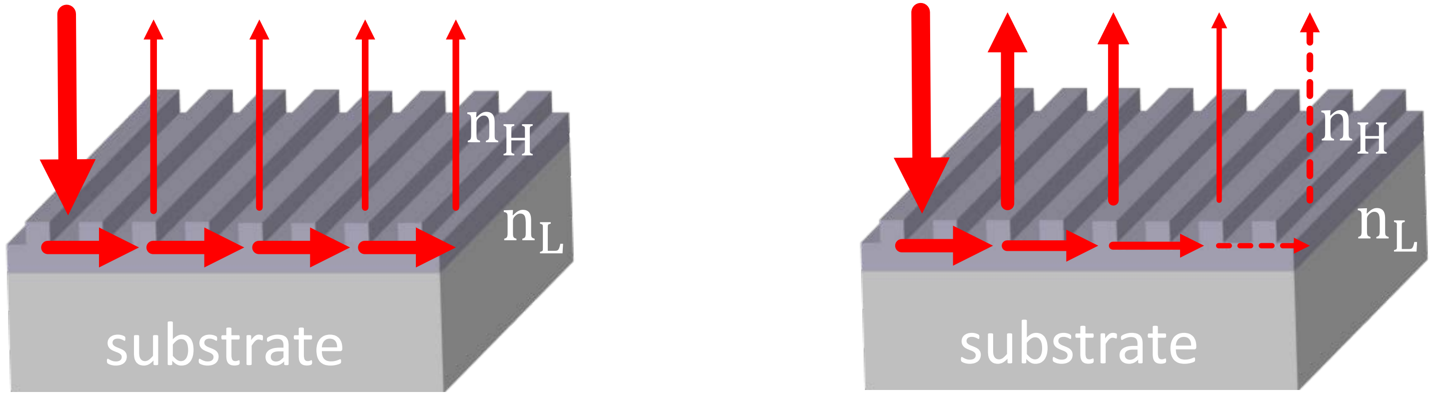


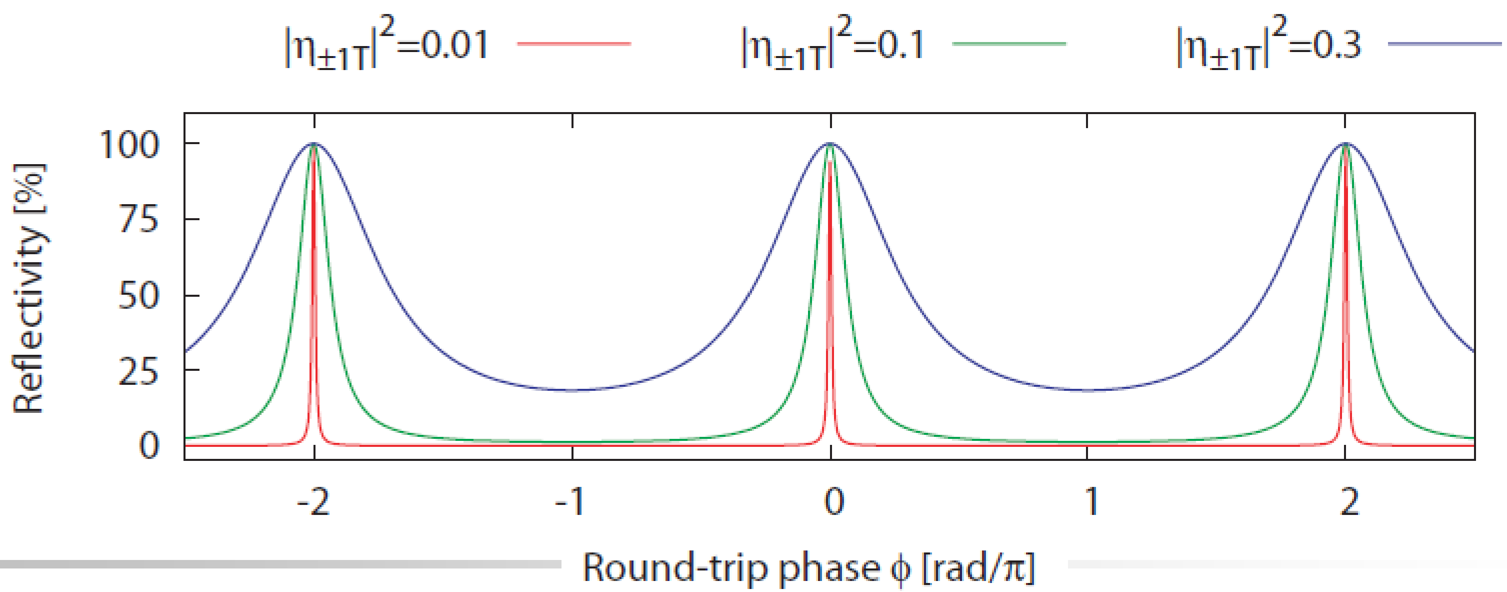
⑤ Cleaning

Resonant Excitation

- Small coupling
→ Long storage time

- Strong coupling
→ Short storage time



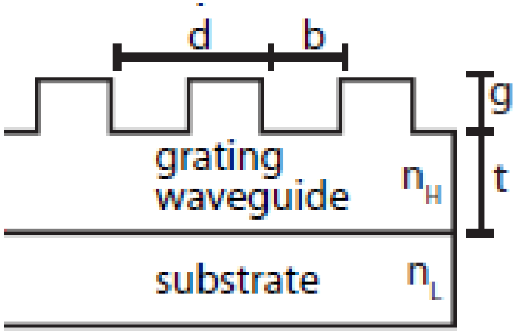


Grating Design

- Rigorous coupled wave analysis (RCWA)

  M.G. Moharam et al. J. Opt. Soc. Am. 71 (1981)

- For given wavelength, materials and polarization



d grating period
b ridge width
} *b/d* fill factor
g groove depth
t waveguide thickness

- Numerical implementation: e.g. UNIGIT

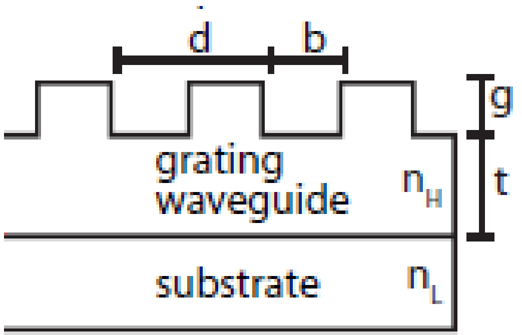
  www.unigit.com

Outline of this talk

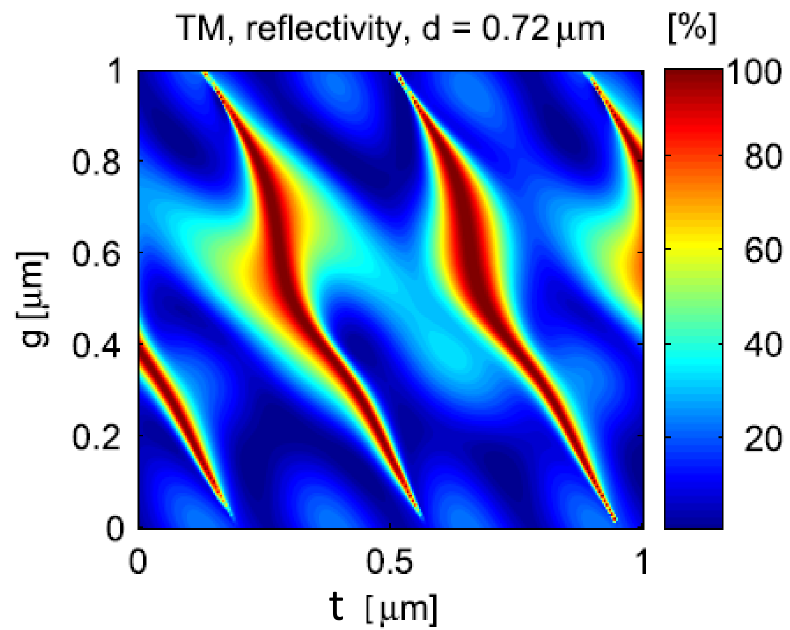
- AEI Hannover
- Introduction
- Resonant waveguide gratings (WGG)
- **WGG @ 1064nm**
- WGG @ 1550nm
- Summary

WGGs for GW Detectors

- Proposed as low thermal noise mirror
- Based on 1st generation materials

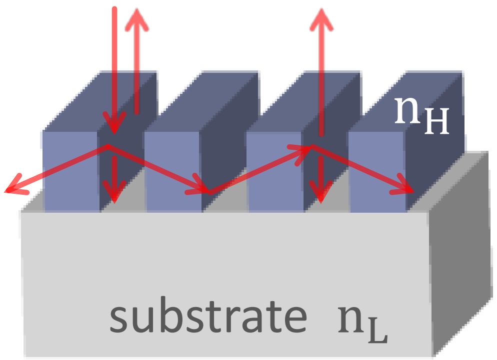


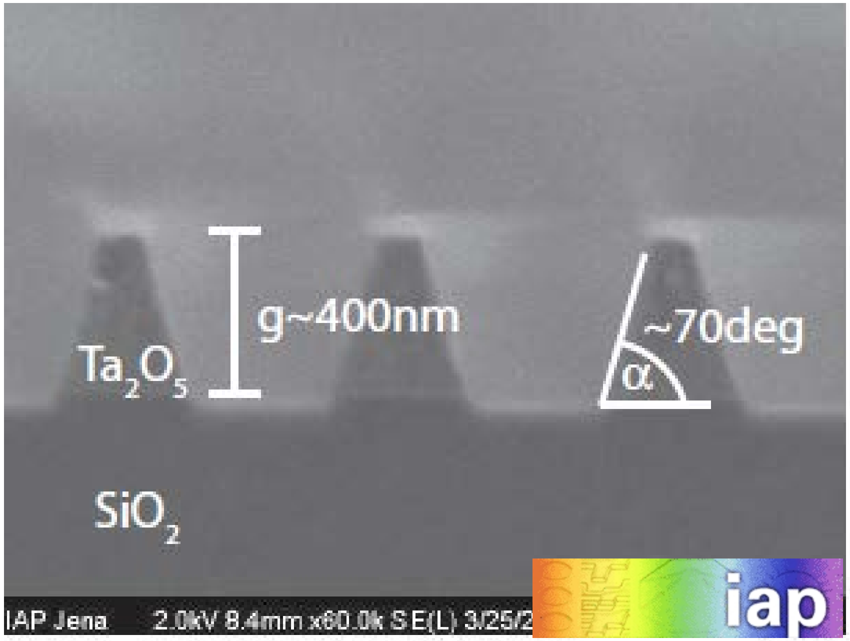
- ✓ 1064nm laser wavelength
- ✓ Ta_2O_5 grating (n_H=2.04)
- ✓ SiO_2 substrate (n_L=1.45)



High reflectivity grating waveguide coatings for 1064nm
A. Bunkowski, …, DF et al. CQG **23**, 7297 (2006)

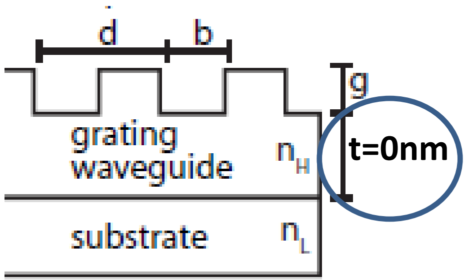
WGG @ 1064nm

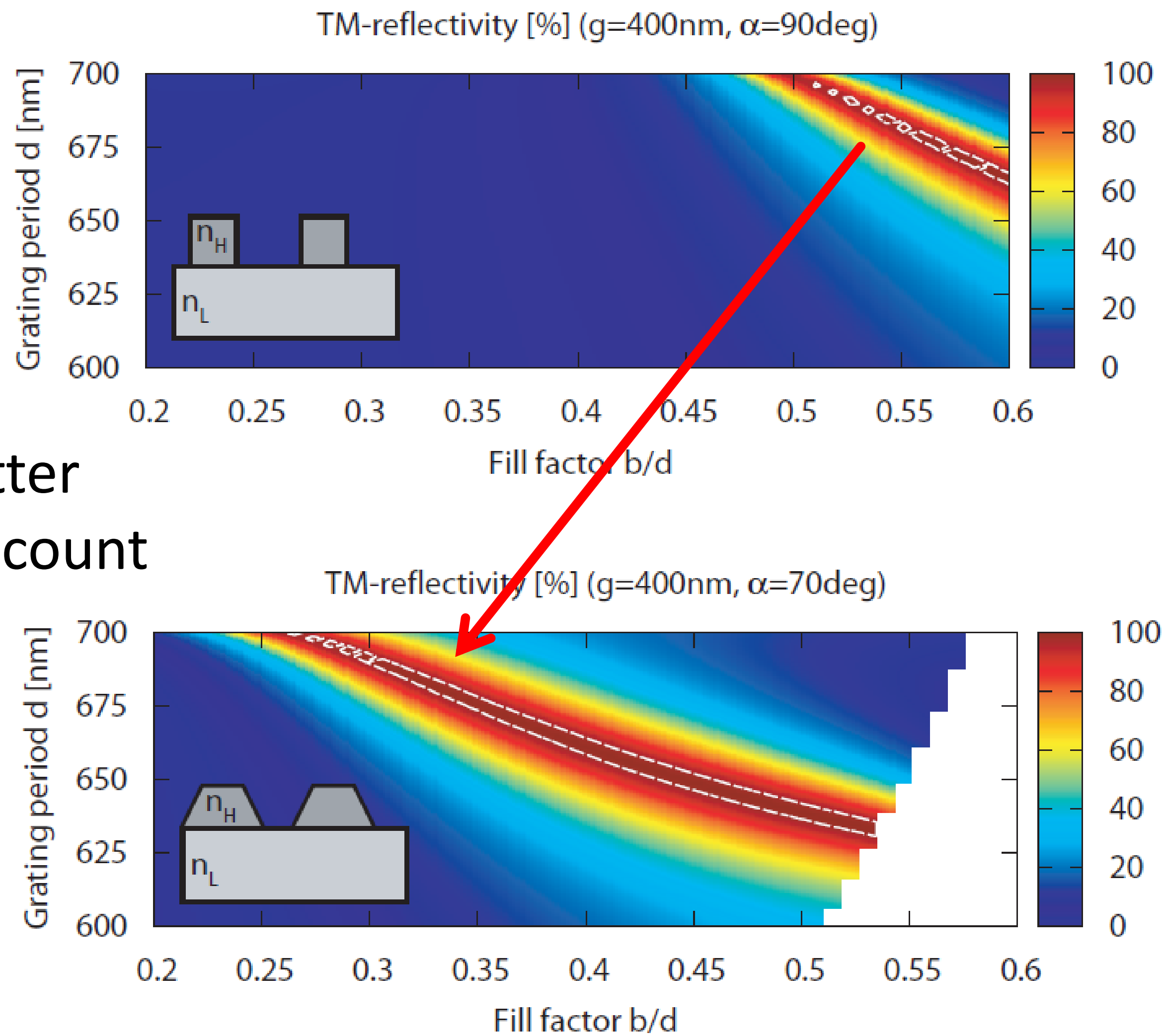




- Concept
- Realization

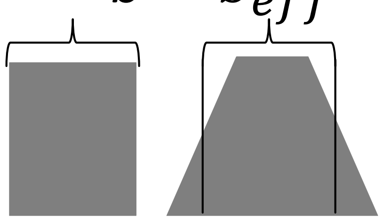
Trapezoidal Structures - Design





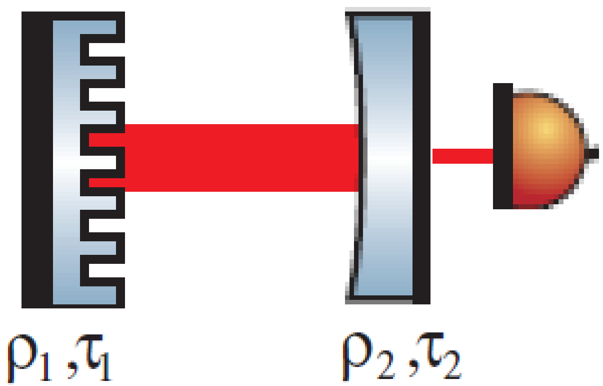
- Effective parameter matter
- Design takes this into account

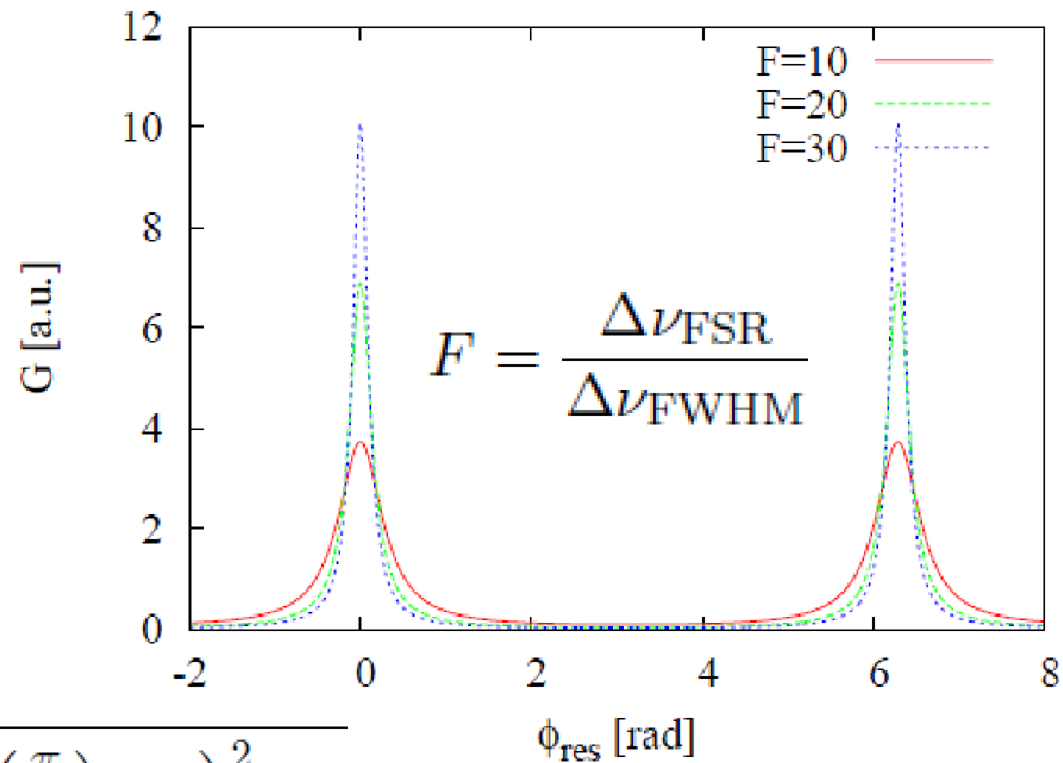
$$b \sim b_{eff}$$



WGG as Cavity Mirror

- Finesse *F* measurement
  - Determine reflectivity under well defined conditions
  - Normal incidence, cavity eigenmode, ...

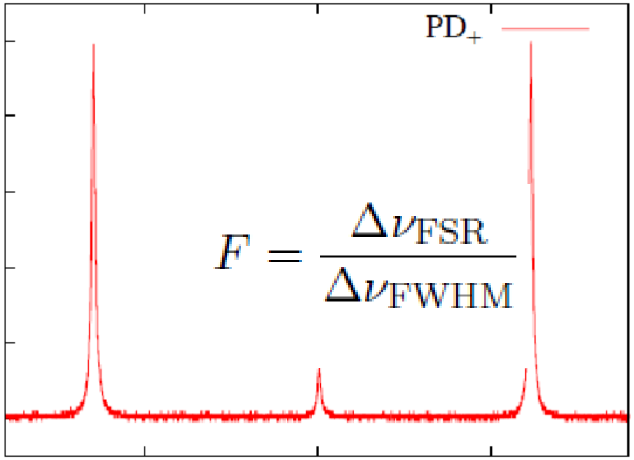


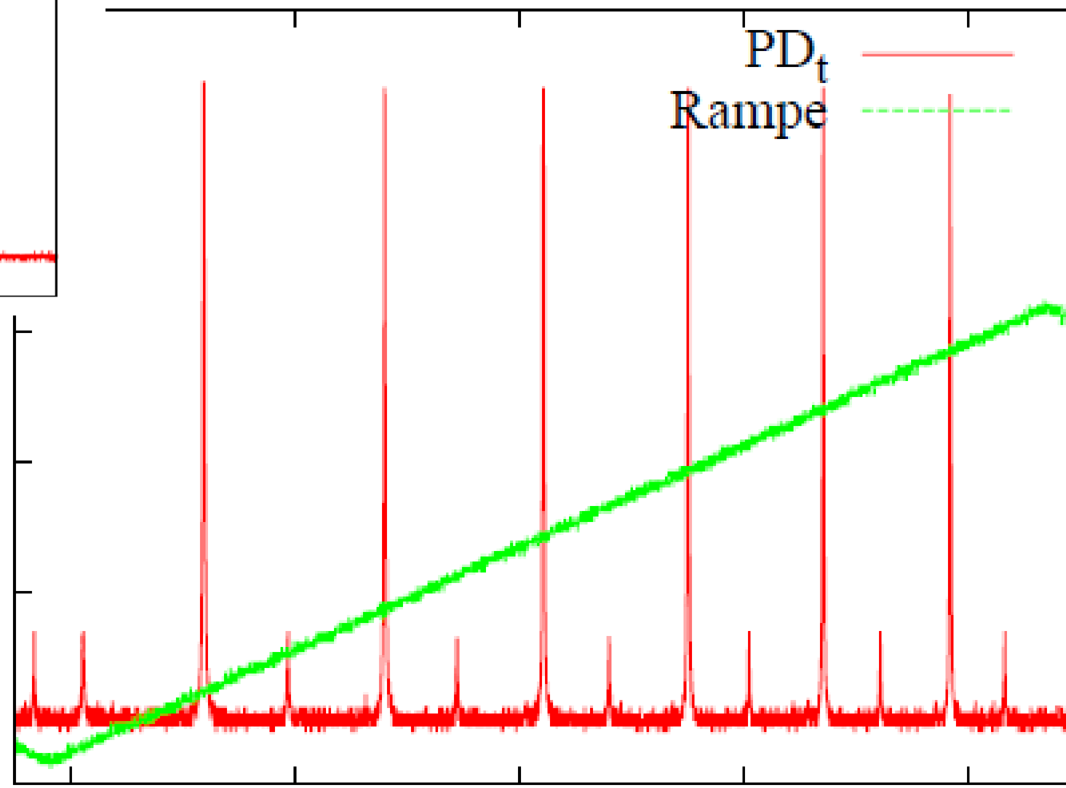


$$F = \frac{\pi}{\arccos\left(1 - \frac{(1-\rho_1\rho_2)^2}{2\rho_1\rho_2}\right)}$$

$$\rho_1\rho_2 = 2 - \cos\left(\frac{\pi}{F}\right) - \sqrt{\left(\cos\left(\frac{\pi}{F}\right) - 2\right)^2 - 1}$$

Experiment



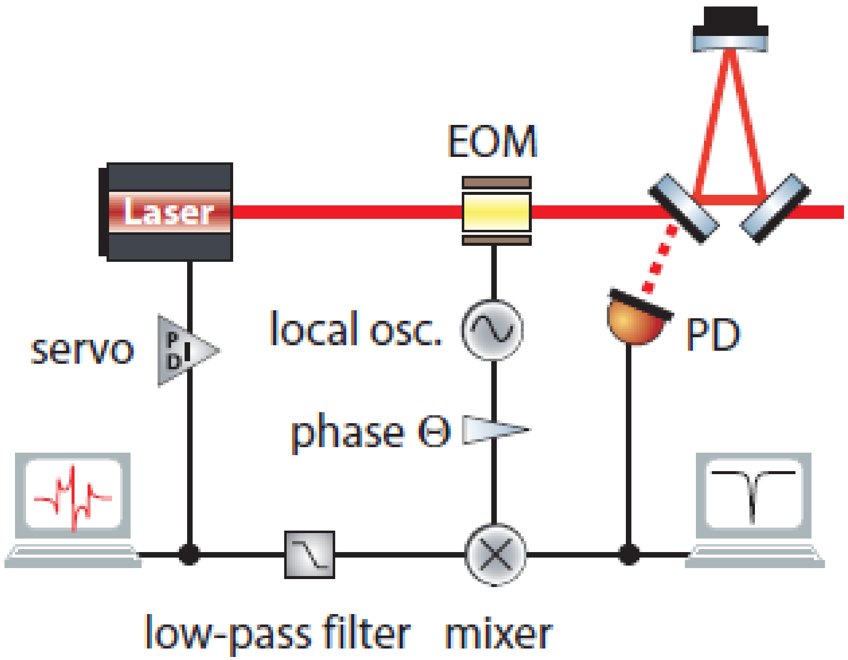


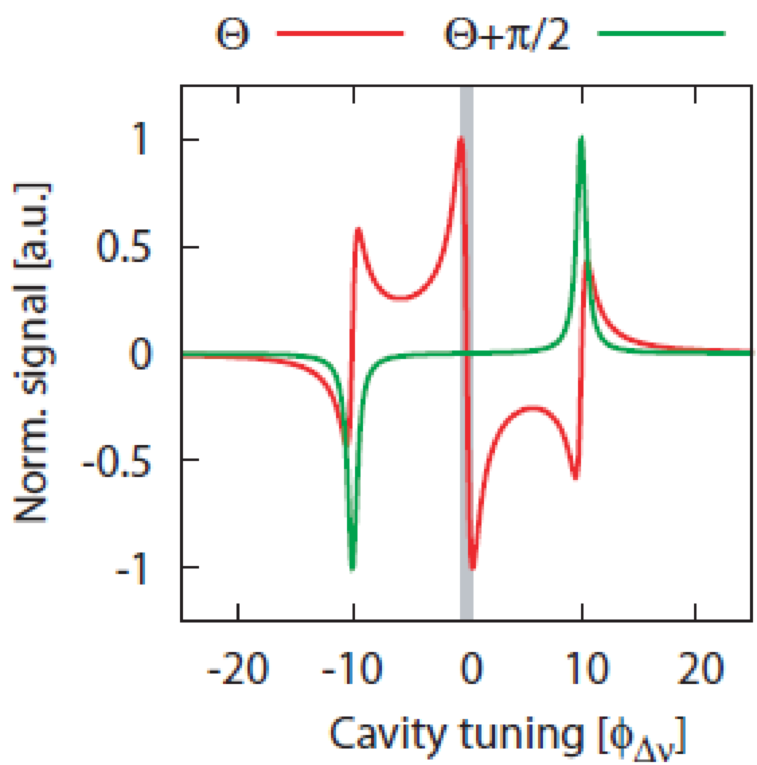
Potential problems

- Actuator range
- Non-linear actuation
- Resolution of data
- Air fluctuations
- ...

Pound-Drever-Hall Technique

- Calibrate tuning via frequency marker → bandwitdh
- Cavity length measurement $\Delta\nu_{\mathrm{FSR}} = \frac{c}{2l}$ → free spectral range

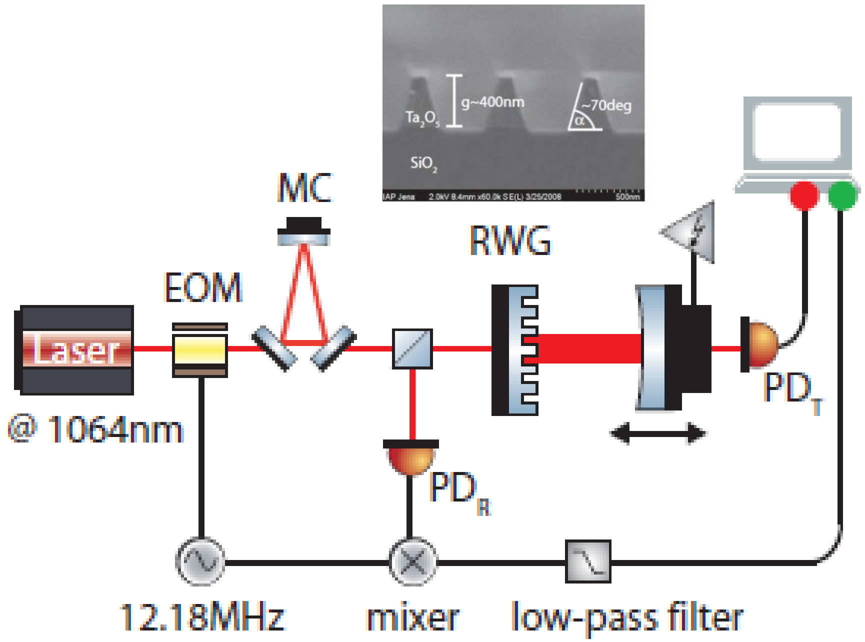


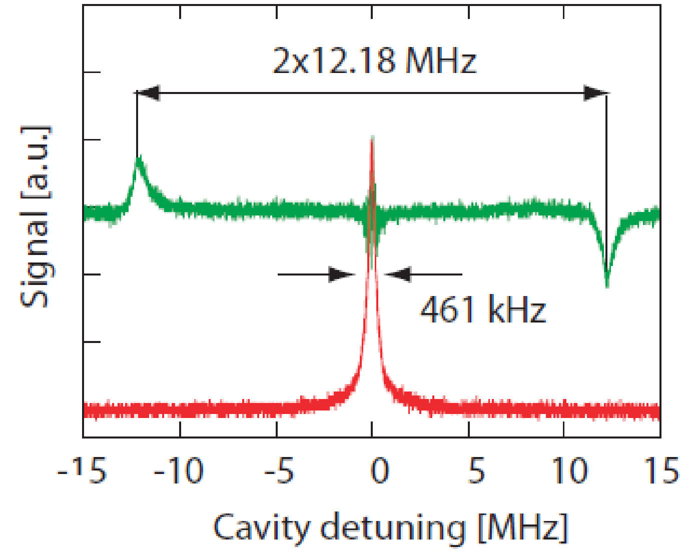


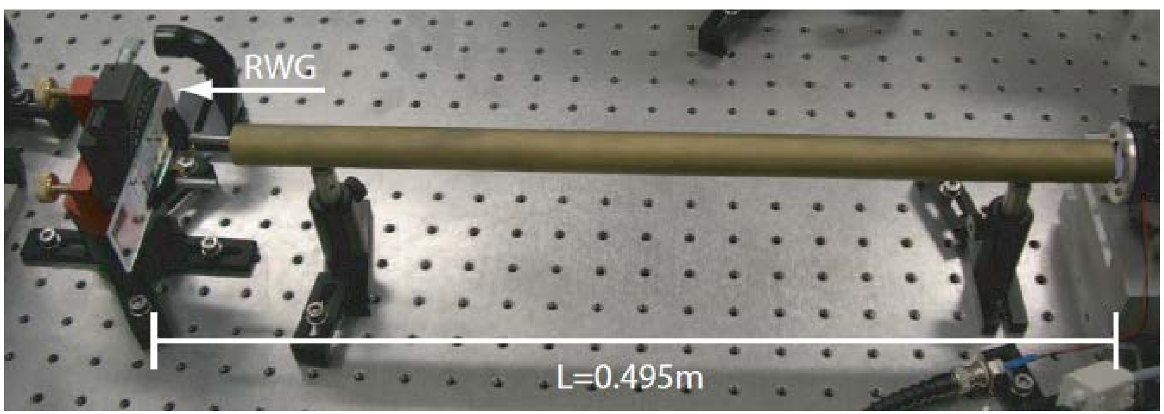
Error signal / Frequency marker

R.W.P. Drever et al. Appl. Phys. B **31**, 97 (1983) E. Black American Journal of Physics **69**, 79 (2001)

WGG as Cavity Mirror @1064nm







Finesse = 660 (±30)

R = 99.08 (±0.04)%

T = 0.94 (±0.09)%

optical loss ≤ 1300ppm

Demonstration of a cavity coupler based on a resonant waveguide grating

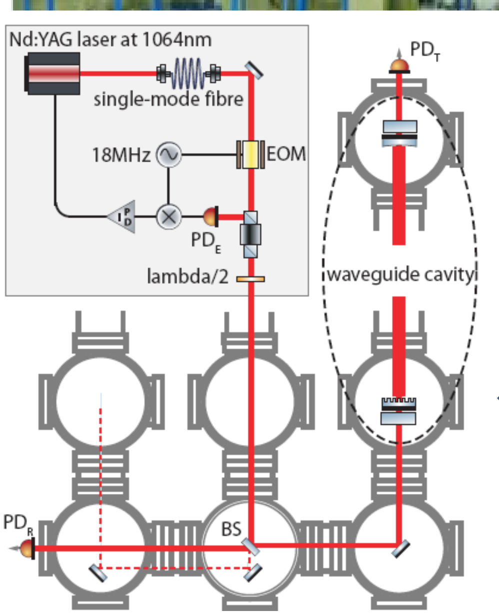
F. Brückner, DF et al. Opt. Express 17 (2009)

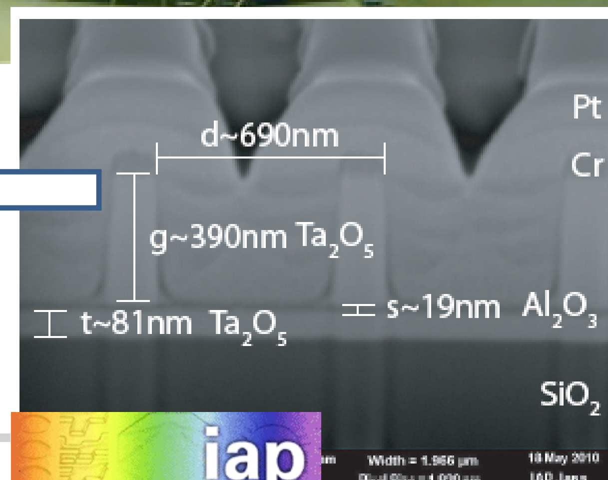
Glasgow Prototype Facility

UNIVERSITY of GLASGOW

- Test compatibility with large scale experiments

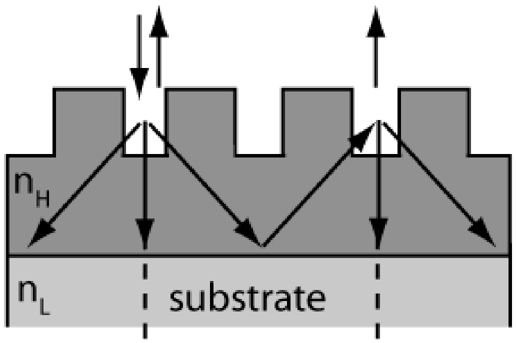
Tantala based WGG for 1064nm





Glasgow group:
B.W. Barr, S. Hild,
J. Nelson, J. Mcarthur,
M.V. Plissi, S. Huttner,
M.P. Edgar and K. Strain

WGG Including Etch Stop Layer

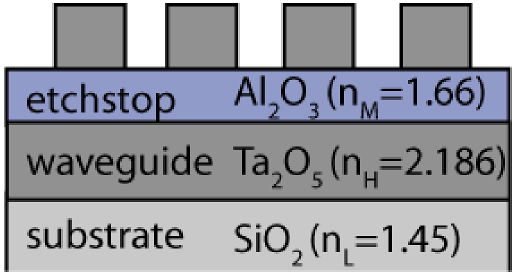


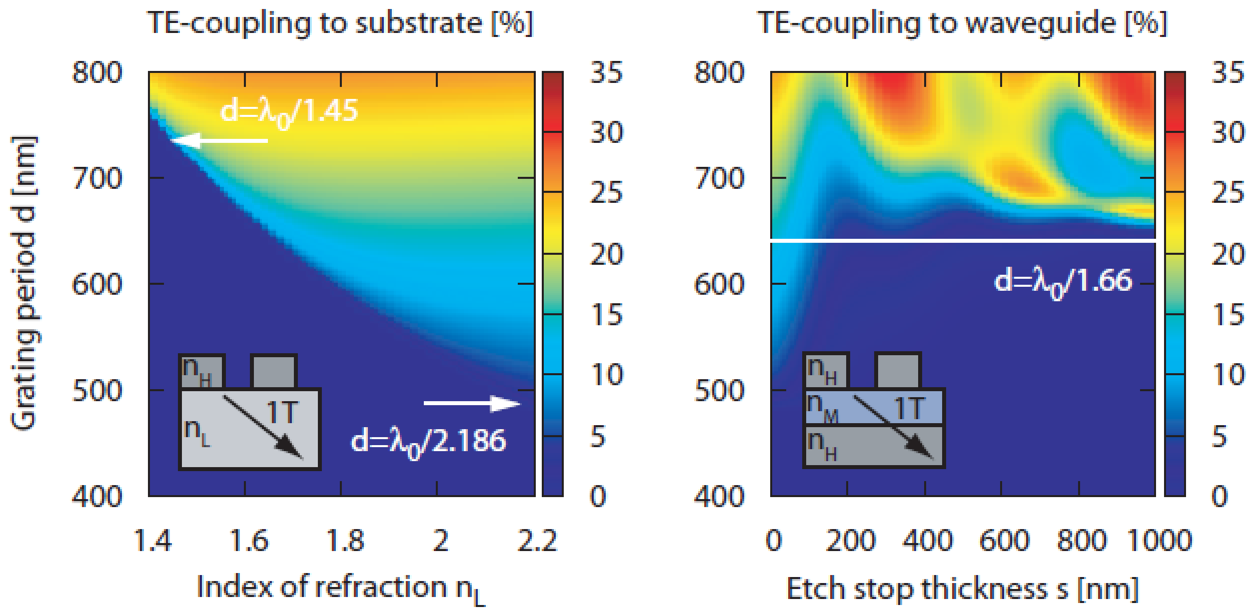
- Etch stop

→ defines grating depth / waveguide thickness

- Thin etch stop layer

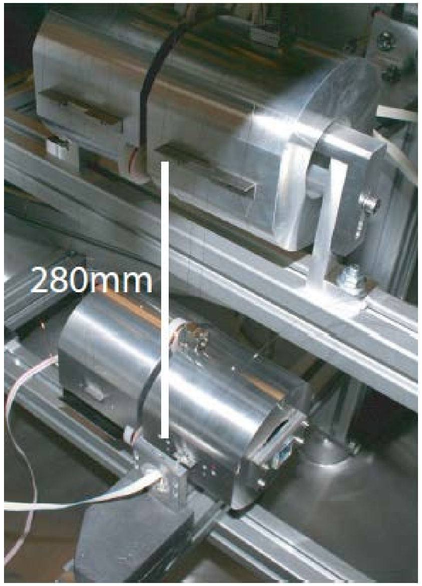
→ Optical properties can be preserved

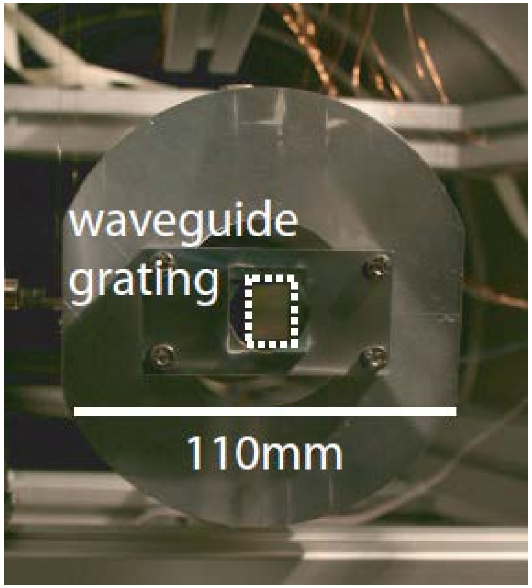




Low Noise Environment

UNIVERSITY
of
GLASGOW

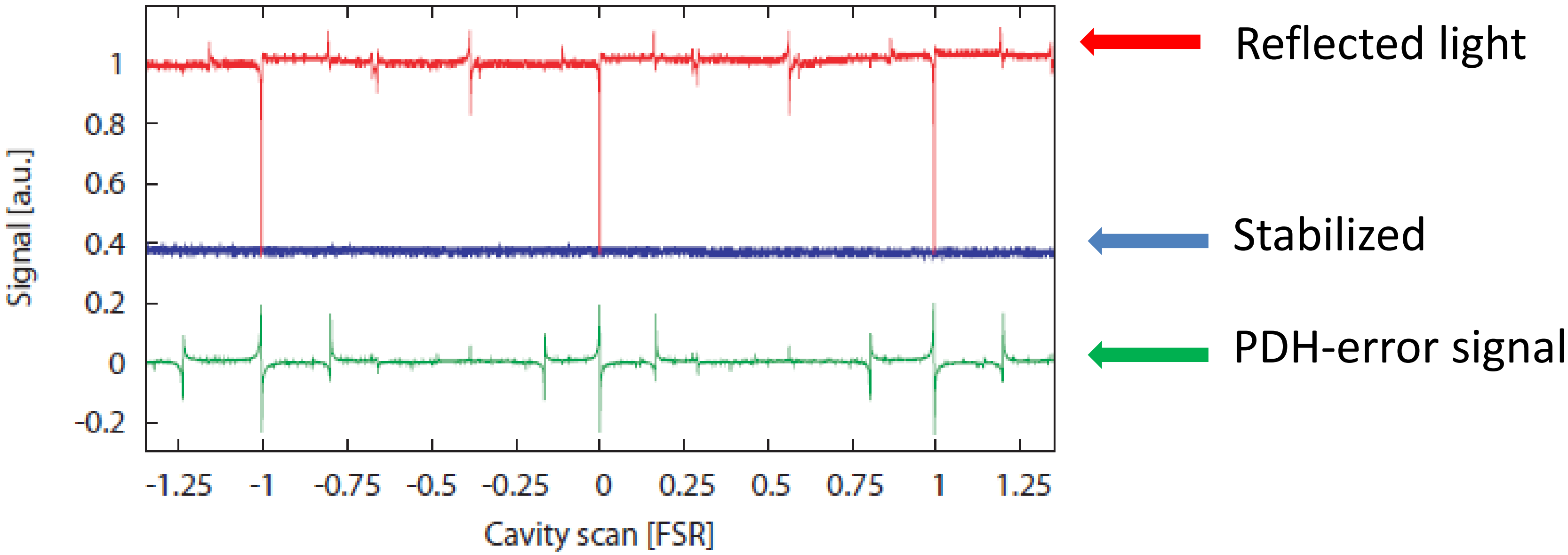




- ✓ Vacuum condition
- ✓ Suspended optics

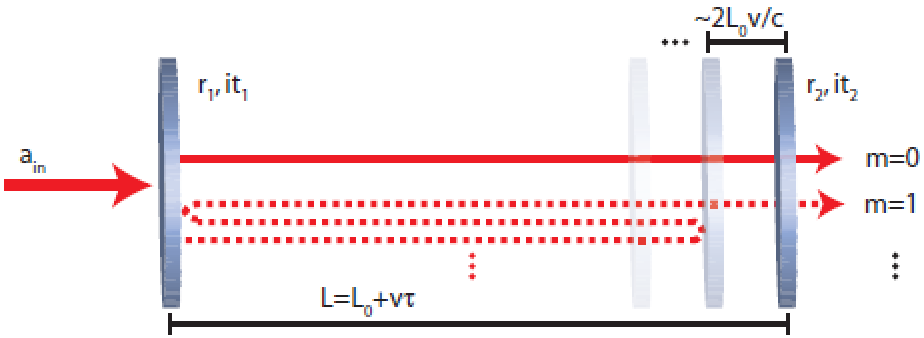
Experimental Results

UNIVERSITY of GLASGOW



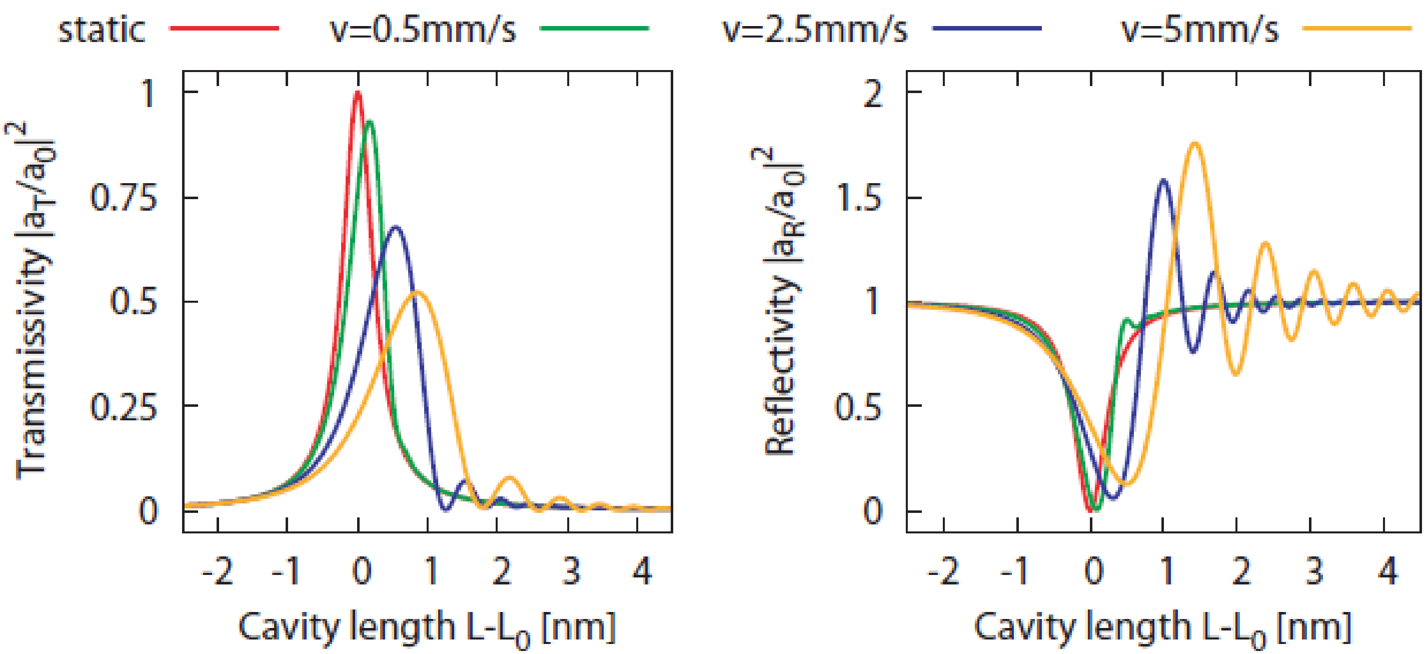
- Cavity stabilization with standard PDH-technique
- Technical feasability was shown

Dynamical Effects (Ringing)



$$\frac{a_T}{a_{in}} = -t_1 t_2 \sum_{m=0}^{\infty} (r_1 r_2)^m \exp(i\phi_m)$$

$$\phi_m \approx (2m+1)kL - m(m+1)kv\frac{2L_0}{c}$$



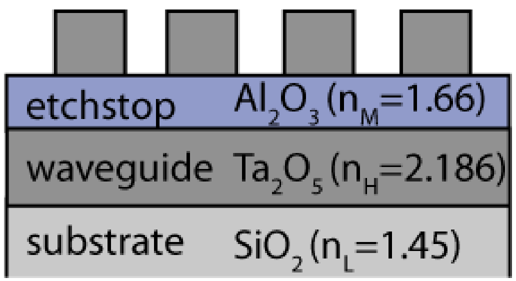
Cavity parameter: Finesse=1000, L_0=0.1m

A.E. Dangor et al. J. Phys. D: Appl. Phys. ***3****, 413 (1970)*

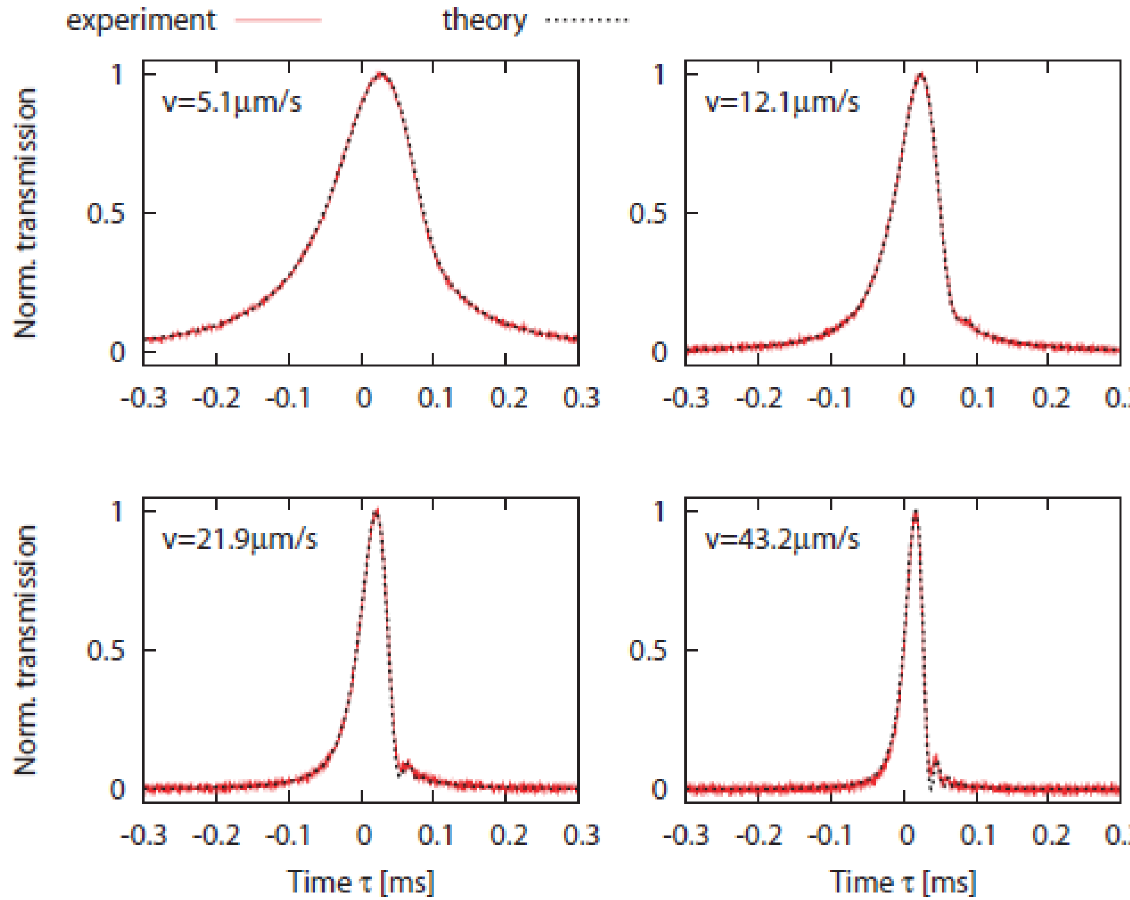
Fitting Dynamical Model

UNIVERSITY *of* GLASGOW

$R \geq 99.2\ (\pm 0.1)\%$



Finesse = 790 (±100)



Waveguide grating mirror in a fully suspended 10 meter Fabry-Perot cavity
DF et al. Opt. Express 19, 14955 (2011)

Outline of this talk

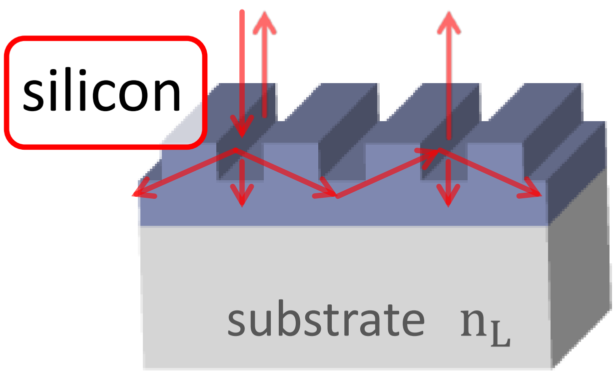
- AEI Hannover
- Introduction
- Resonant waveguide gratings (WGG)
- WGG @ 1064nm
- **WGG @ 1550nm**
- Summary

Silicon WGGs @ 1550nm

- Promising material for 3rd generation detectors

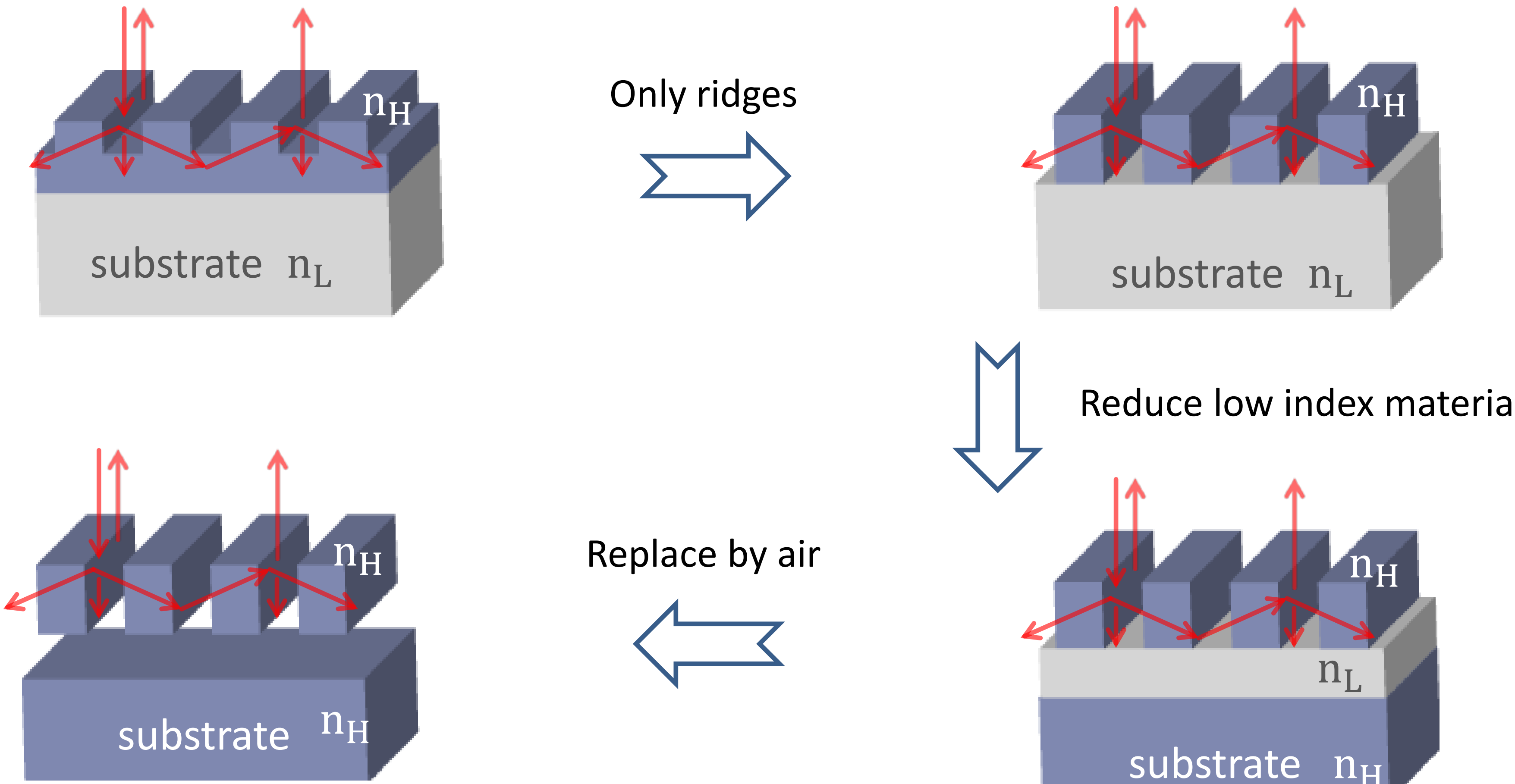
Design study: ET-0106C-10

- Very well suited for cryogenic temperatures
  - Thermoelastic noise
    ~0 @ T=18 and 125K
  - Low mechanical loss
    $\phi_{Si} \sim 10^{-9}$ @ T=10K



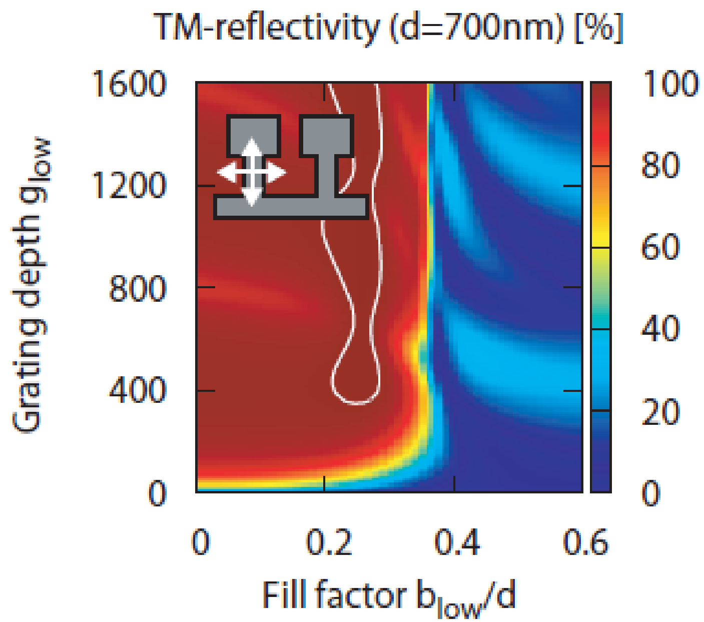
- Very well suited for WGG
  n_H=3.5 @ 1550nm
  → high coupling efficiencies
  → parameter tolerant WGG

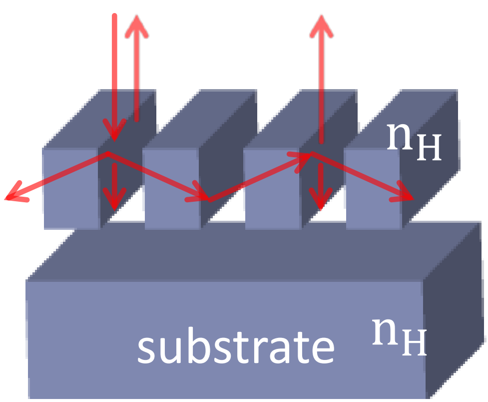
Reduction of Low Index Material



J.-S. Ye et al., J. Mod. Opt **53**, 1995 (2006)

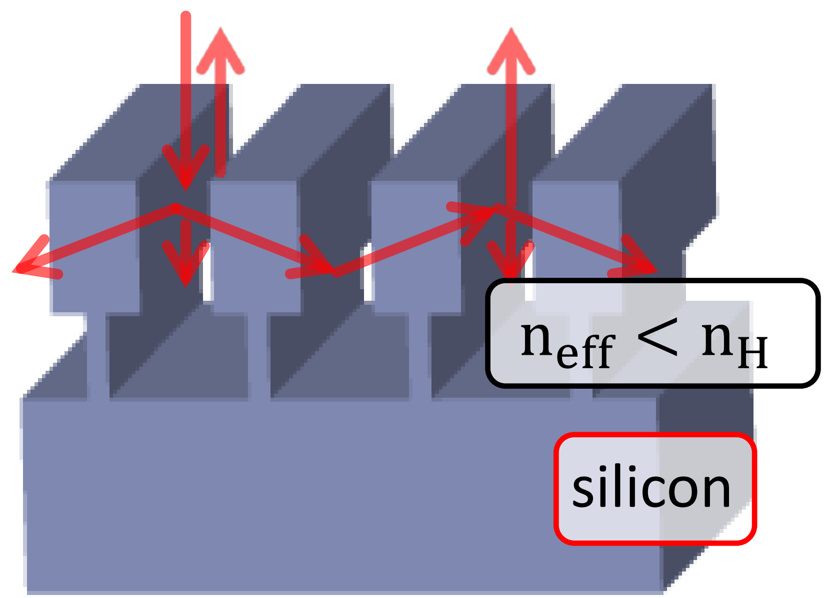
Monolithic Design





J.-S. Ye et al., J. Mod. Opt **53**, 1995 (2006)

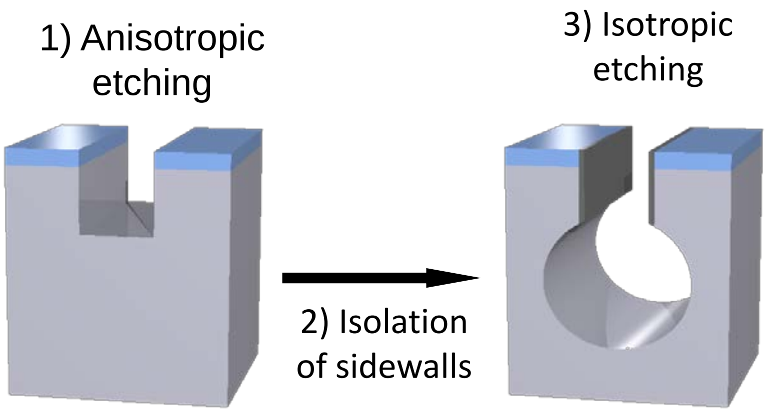
Thin grating structure



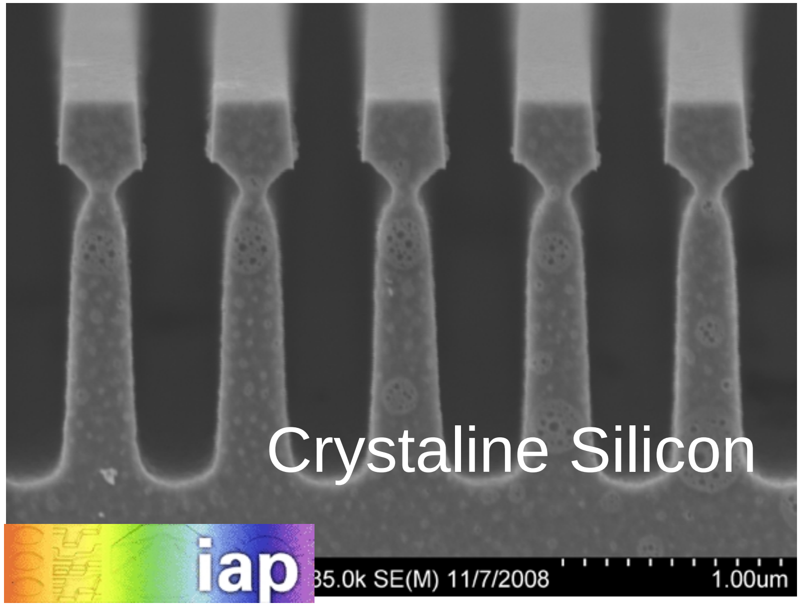
Monolithic dielectric surfaces as new low-loss light-matter interface

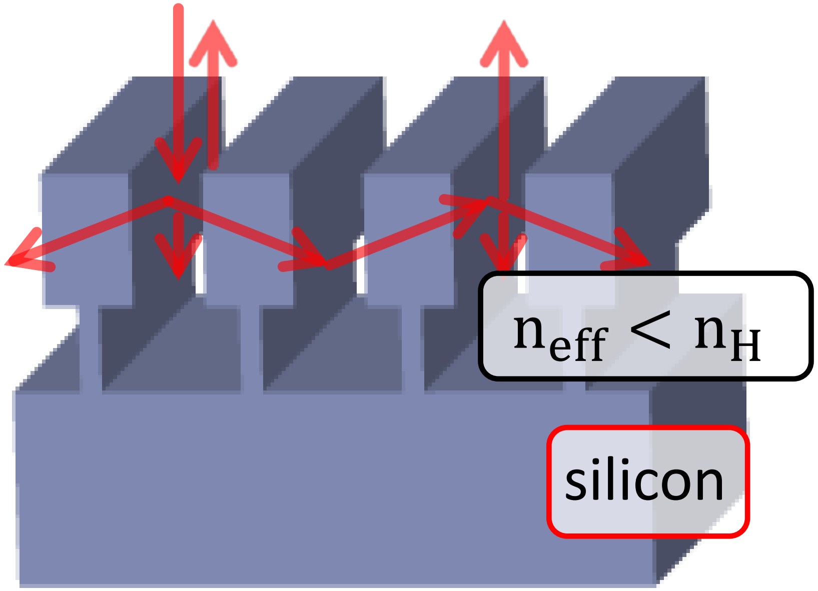
F. Brückner, …, DF et al. Opt. Lett. **33**, 264 (2008)

Monolithic Realization



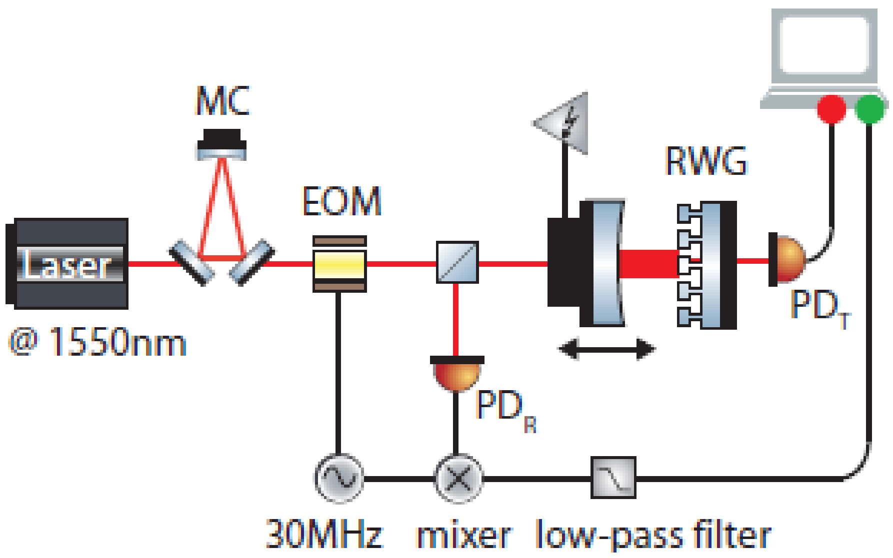
no material is added

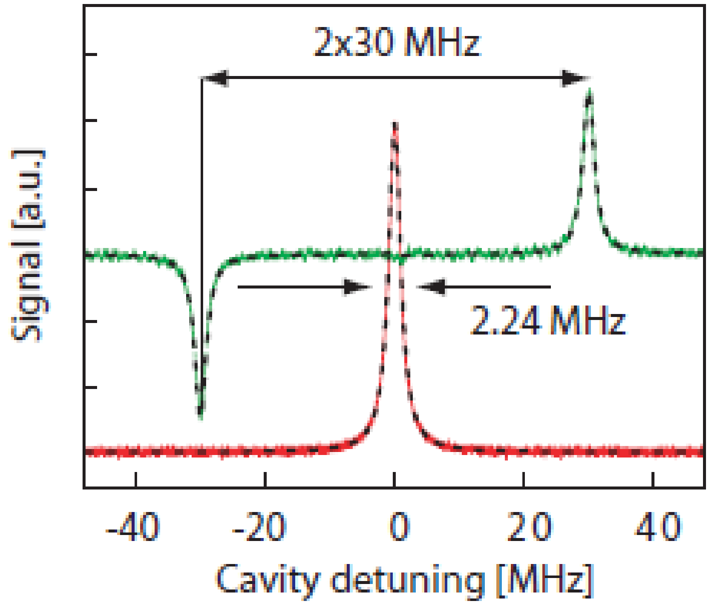


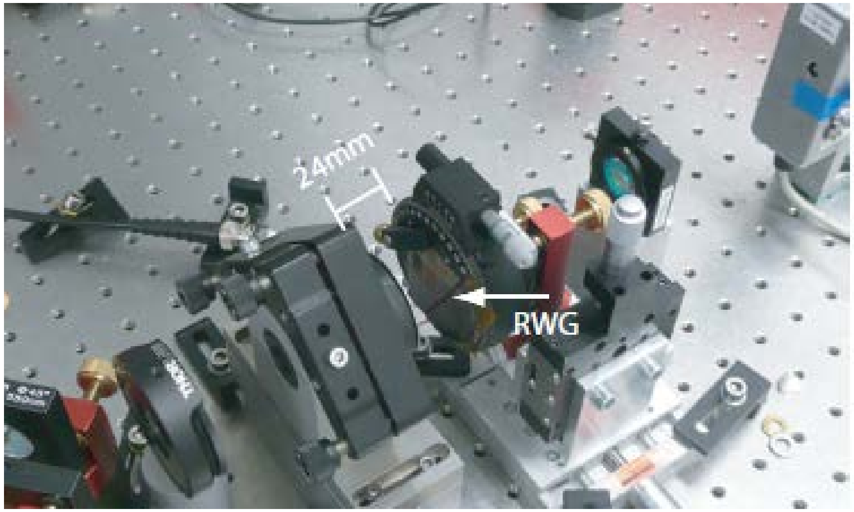


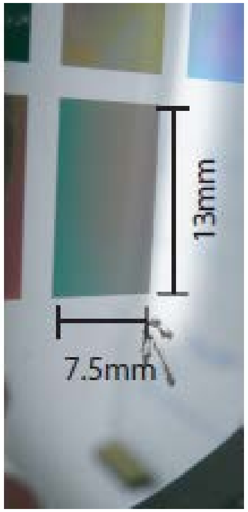
- Realization
- Concept

WGG as Cavity Mirror @ 1550nm

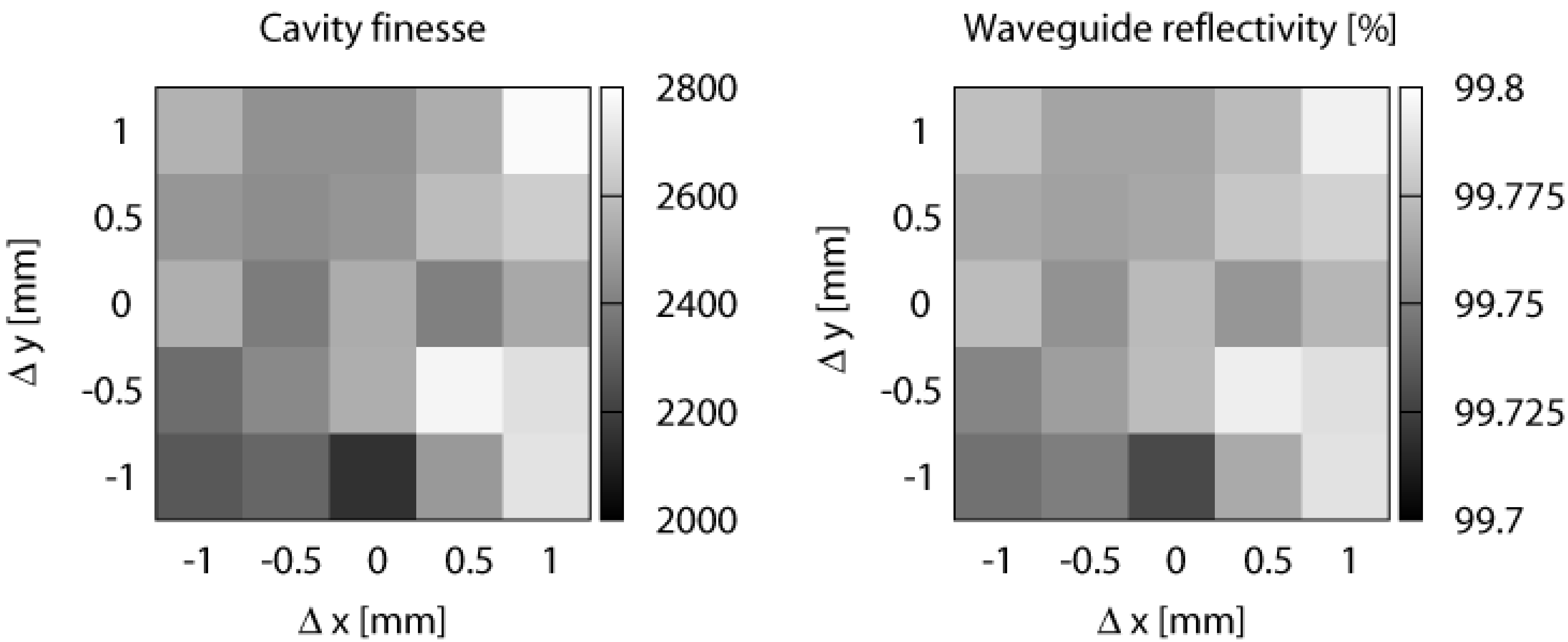








Experimental Results



Finesse 2780 (±100)

R = 99.795 (±0.009)%

T ≥* 0.023 (±0.002)%

optical loss ≤ 1800ppm

Realization of a monolithic high-reflectivity cavity mirror …
F. Brückner, DF et al. PRL **104**, 163903 (2010)

*unpolished back side

Outline of this talk

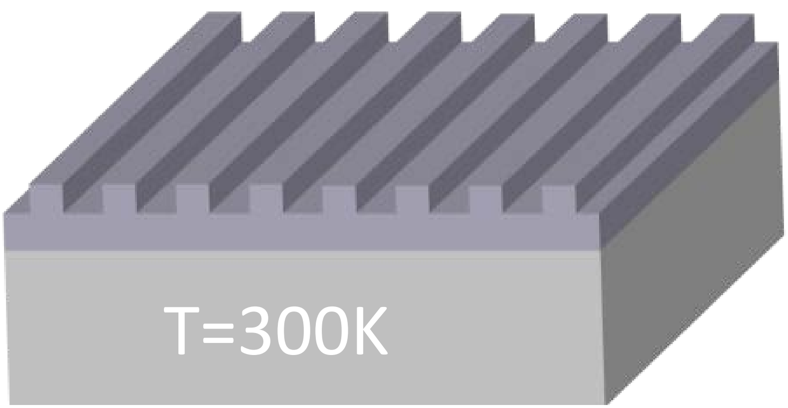
- AEI Hannover
- Introduction
- Resonant waveguide gratings (WGG)
- WGG @ 1064nm
- WGG @ 1550nm
- Summary

Waveguide Grating Mirrors

- ✓ Ta_2O_5 grating (n_H=2.04)
- ✓ SiO_2 substrate (n_L=1.45)

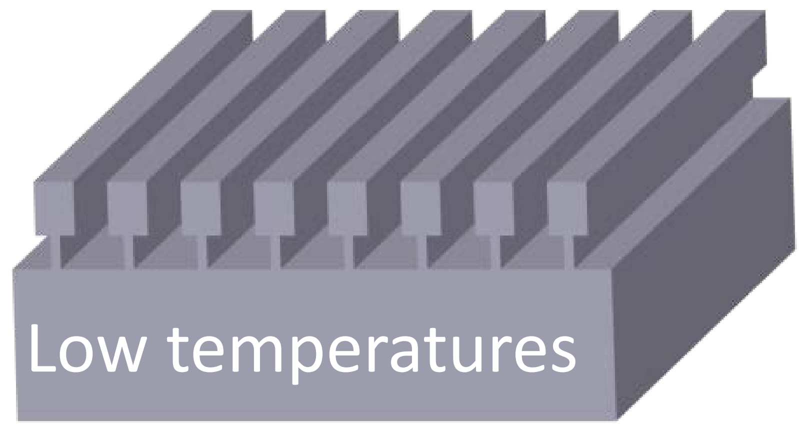
R = 99.08 (±0.04)%

R = 99.2 (±0.1)%

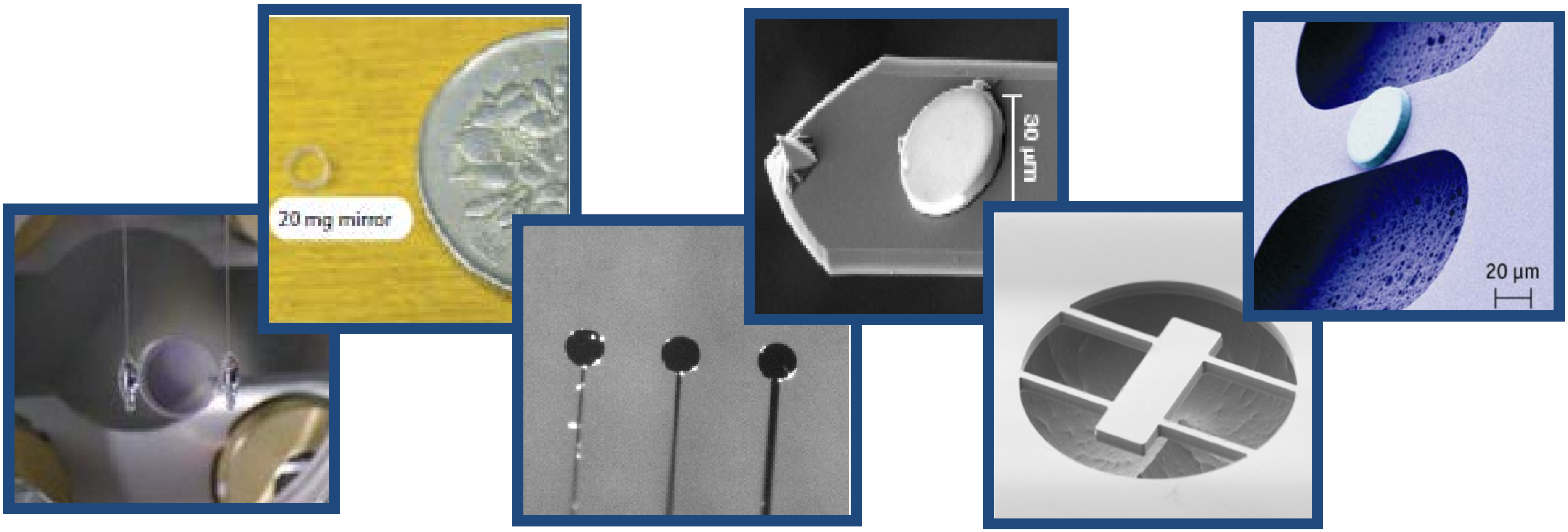


- ✓ Crystalline silicon (n_H=3.5)

R = 99.795 (±0.009)%



Opto-Mechanics



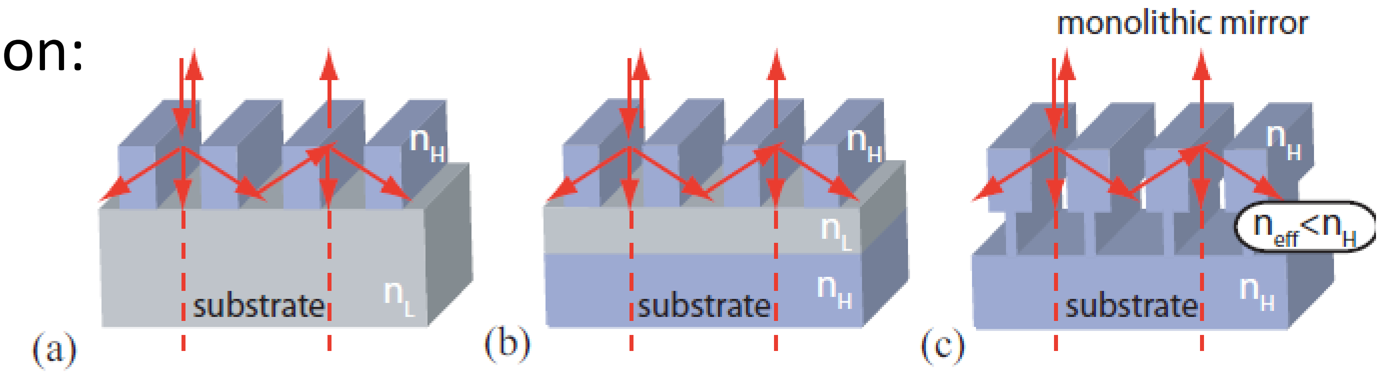
Hz — mechanical frequency — MHz

kg — mass — ng

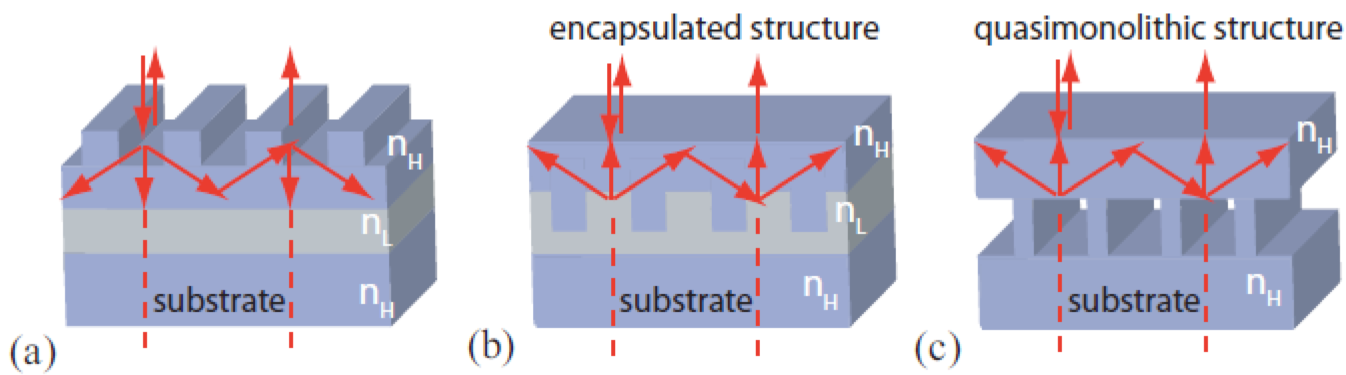
images: www.mit.edu// S.Sakata pers.comm.// T.Corbitt GWADW2010// Kleckner 06// www.aspelmeyer.quantum.at

A Variety of WGGs

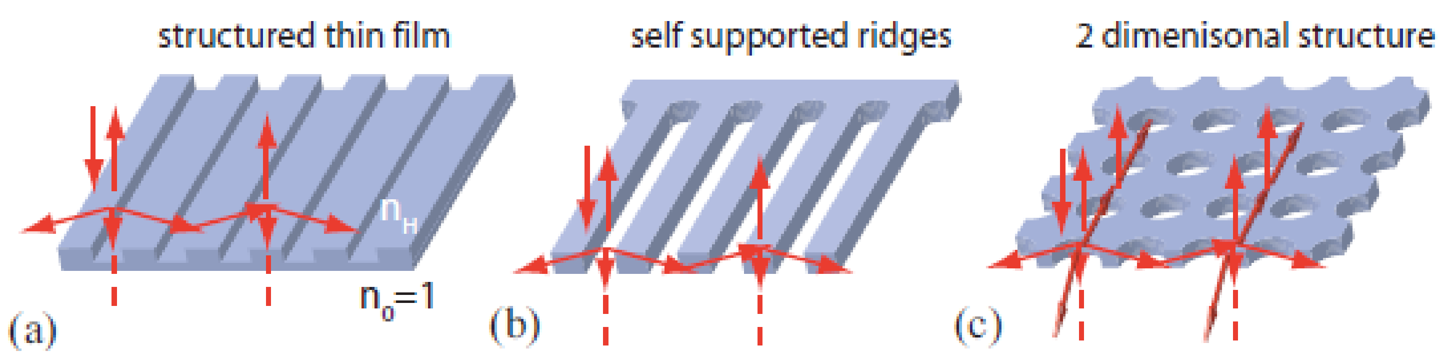
Today`s presentation:



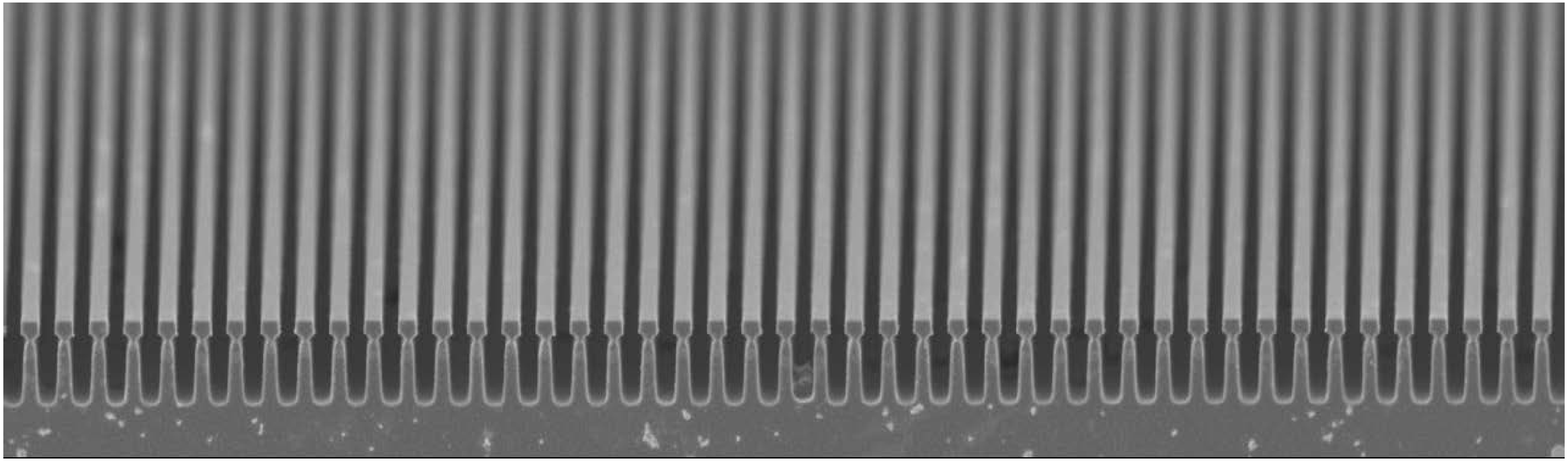
Flat surfaces:



Thin oscillators:



おわり



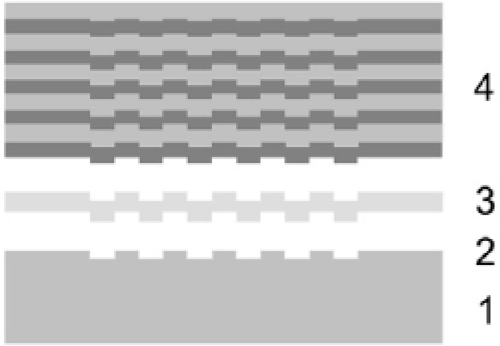
F. Brückner
S. Kroker
E.-B. Kley
A. Tünnermann

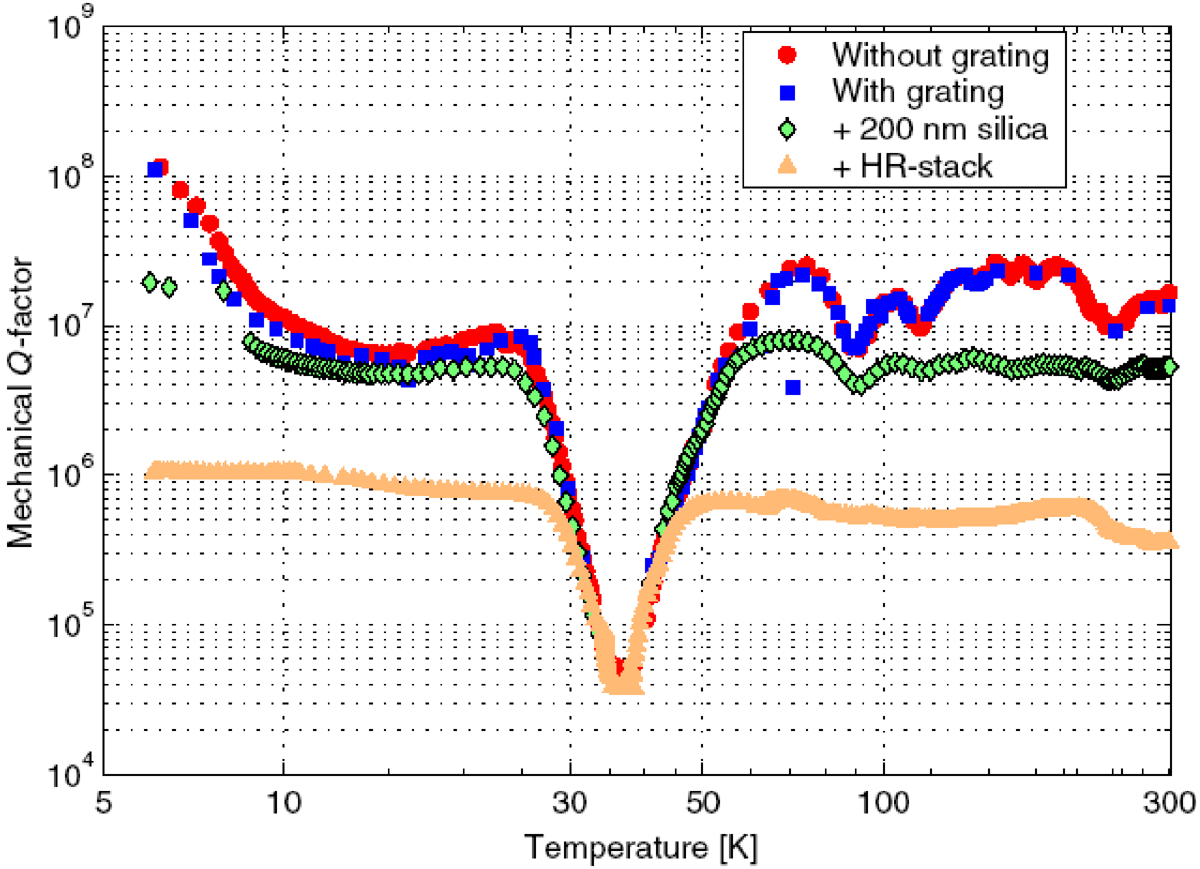
Albert-Einstein-Institut
Hannover

D. Friedrich
M. Britzger
R. Schnabel
K. Danzmann

UNIVERSITY of GLASGOW

B.W. Barr, S. Hild,
J. Nelson, J. Mcarthur,
M.V. Plissi, S. Huttner,
M.P. Edgar and K. Strain





- Grating structure does not „destroy“ high Q-factor of substrate!
- but surface loss is crucial, need to be measured seperately!

R. Nawrodt et al. New Journal of Physics 9, 225 (2007)