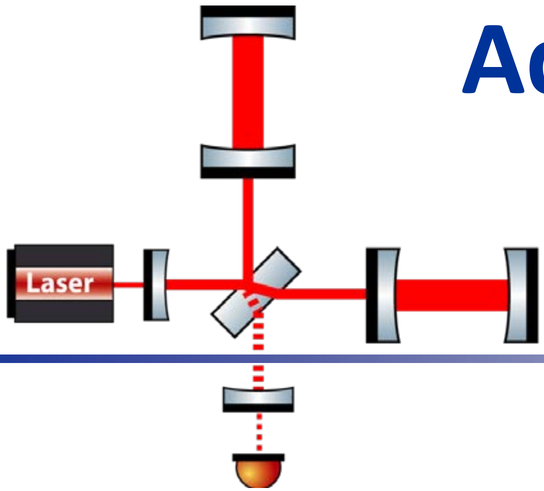
Diffractive Optics for *Beyond* Advanced Detectors



Daniel Friedrich (ICRR)

f2f meeting
4th of Feb. 2012

Hannover, Germany → 東京, 日本

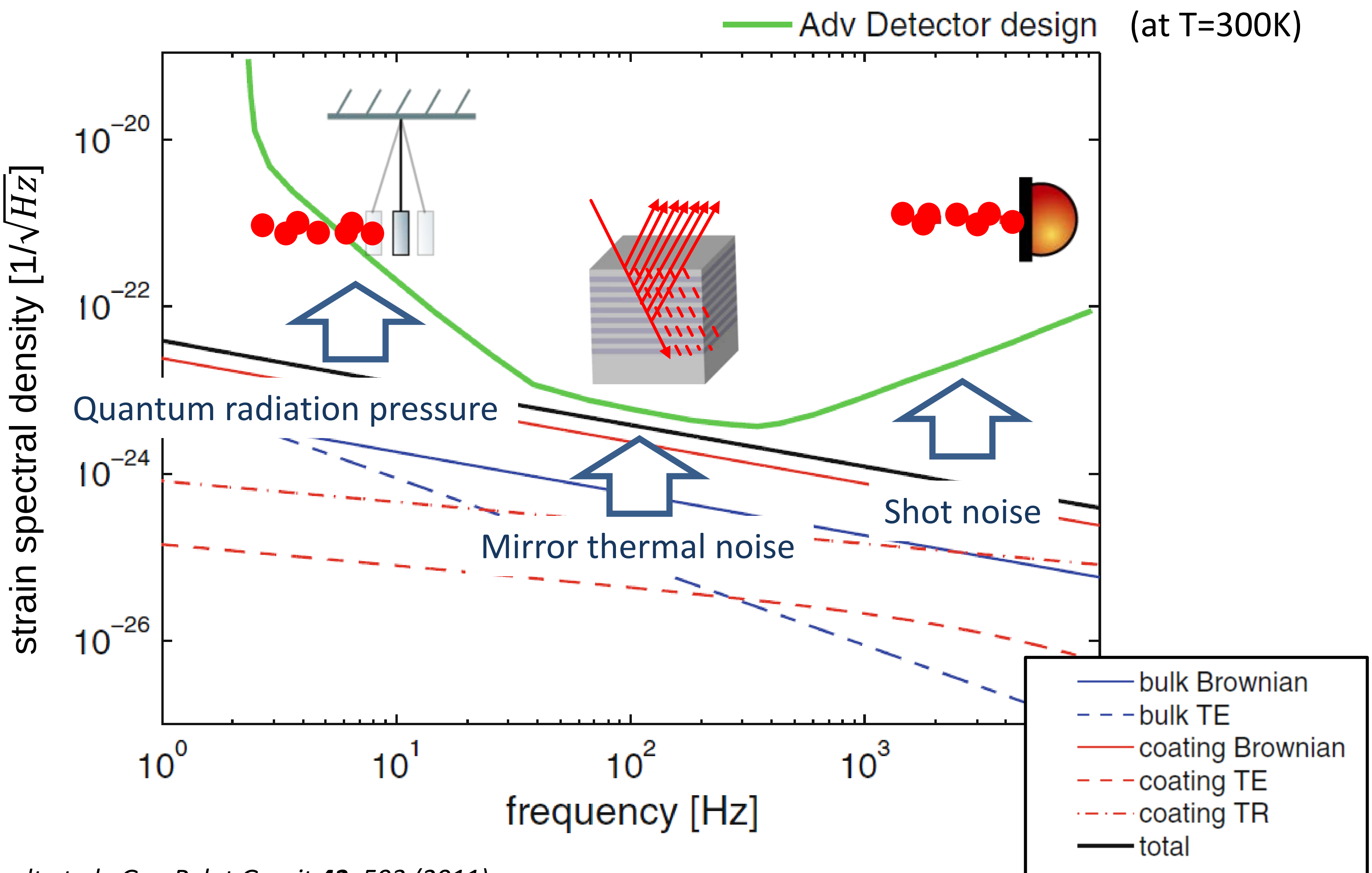
- Since Nov. 2011:
  JSPS research fellow
  with Prof. Kawamura

ICRR
Institute for Cosmic Ray Research
University of Tokyo

- Nov. 2011:
  PhD thesis
  "Laser interferometry with coating-free mirrors"

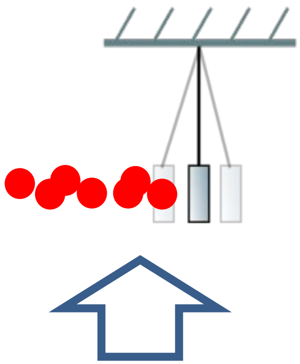
Albert-Einstein-Institut
Hannover

3 Main Noise Sources

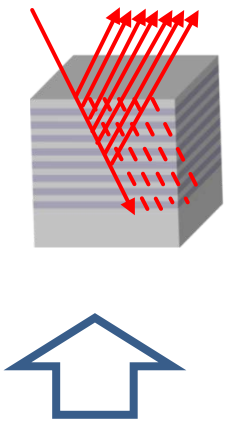


R. Nawrodt et al. Gen Relat Gravit ***43****, 593 (2011)*

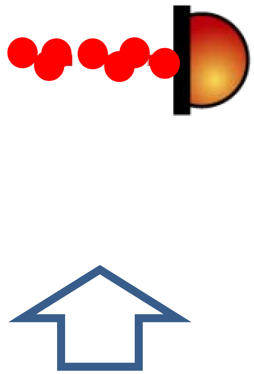
High Quality Optics



Quantum radiation pressure



Mirror thermal noise

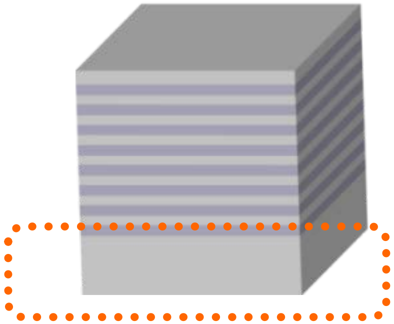


Shot noise

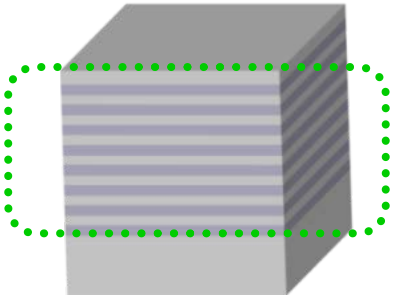
- Core optics must
  - ... be highly transparent
  - ... have low mechanical loss
  - ... be available in large sizes

Outline of this talk

- All-reflective interferometry
  - Avoid transmission through substrates
  - Reflection gratings



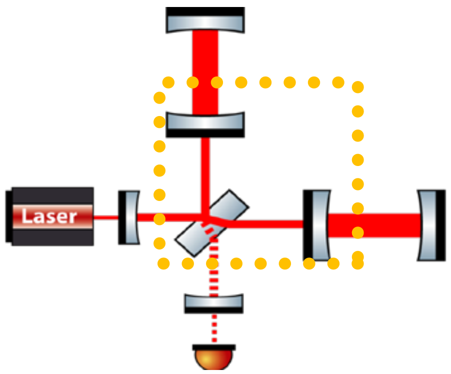
- Coating free mirrors
  - Avoid mechanical lossy multilayer coatings
  - Waveguide gratings



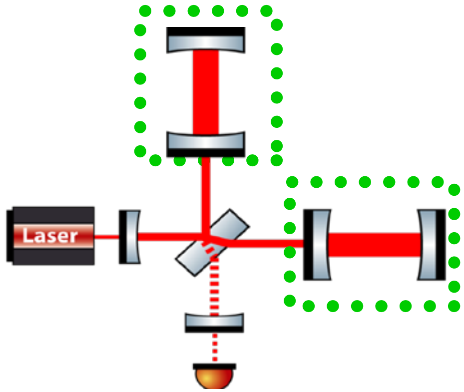
- Outlook/Summary

Outline of this talk

- All-reflective interferometry
  - ➢ Avoid transmission through substrates
  - ➢ Reflection gratings as BS or ITMs



- Coating free mirrors
  - ➢ Avoid mechanical lossy multilayer coatings
  - ➢ Waveguide gratings as ITMs and ETMs

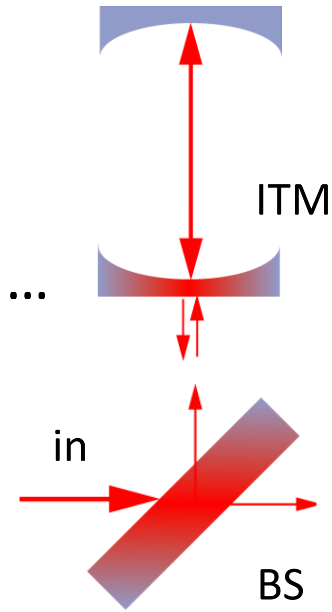


- Outlook/Summary

All-reflective interferometry

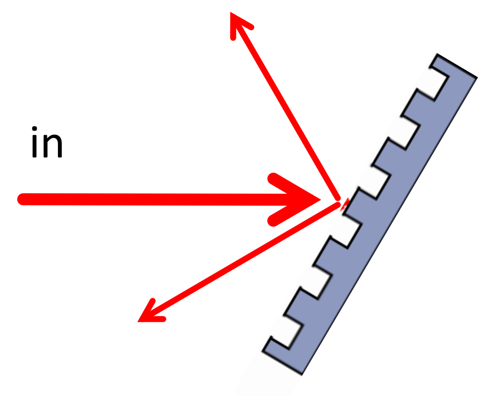
- Transmission through substrates

➢ Optical absorption / heating / thermorefractive noise, …
➢ Substrates must be highly transparent
➢ Substrates must have low mechanical loss

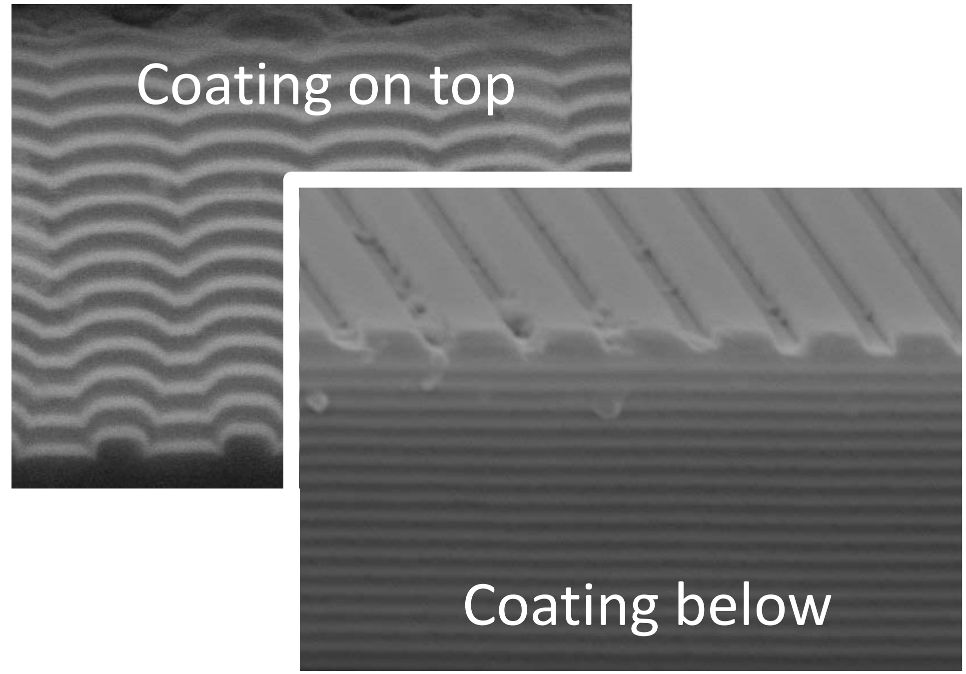


- Reflection gratings

➢ Allow for opaque substrate materials
(e.g. Si @ 1064nm)



Dielectric Reflection Gratings

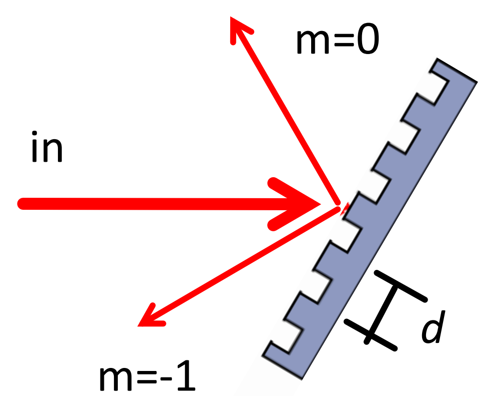


- Multilayer coating
  - ➢ High reflectivity

- Grating structure
  - ➢ Diffraction → beam splitting

➢ Existence and direction of diffraction orders *m*

$$n_{\mathrm{b}} \sin(\beta_{\mathrm{m}}) = n_{\mathrm{a}} \sin(\alpha) + \frac{m\lambda}{d}$$

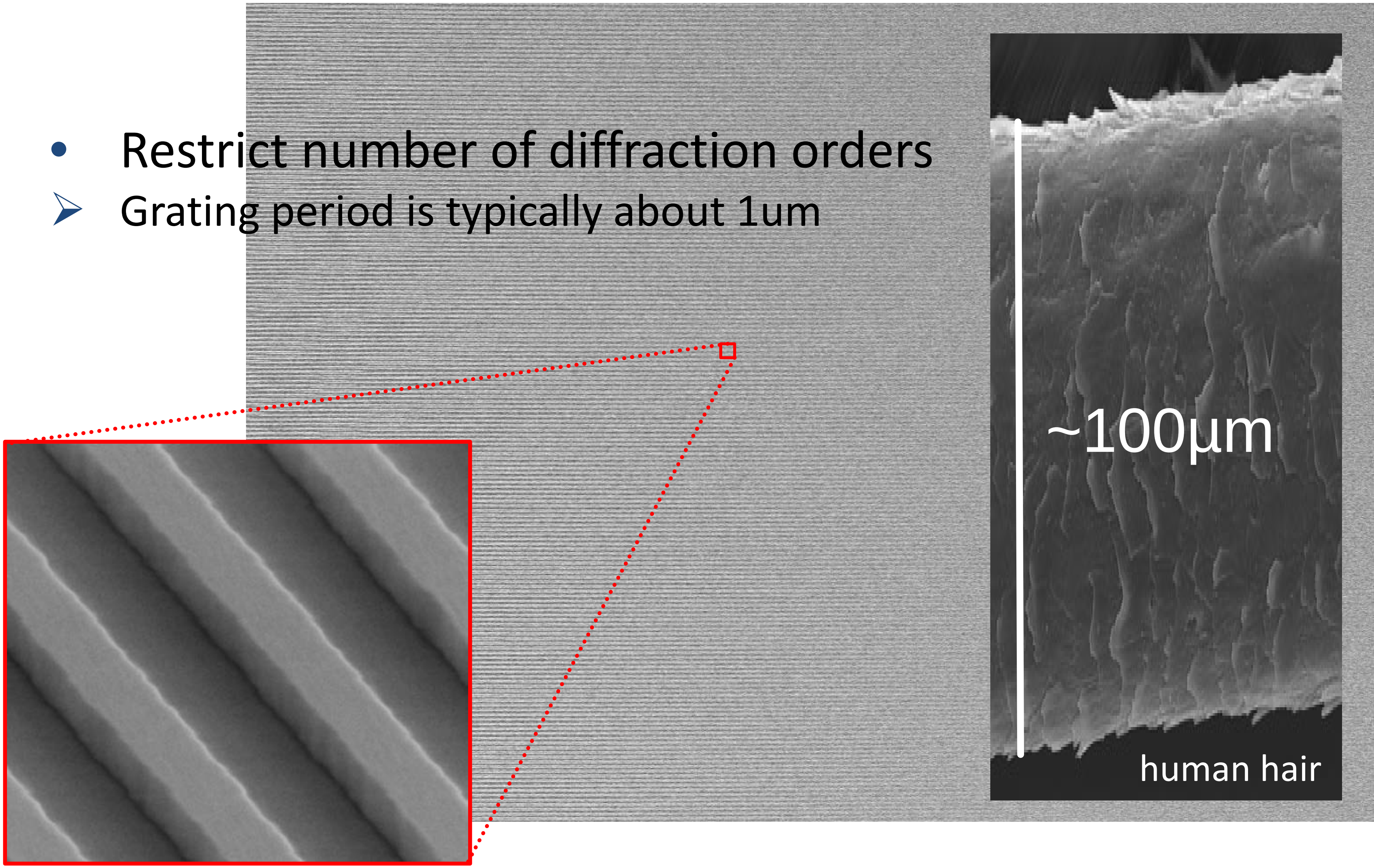


- Design via rigorous methods (RCWA)

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

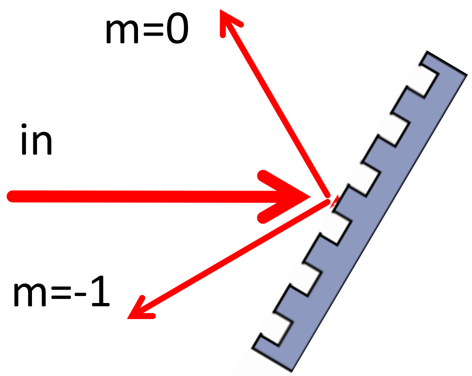
Grating Dimension

- Restrict number of diffraction orders
  - ➢ Grating period is typically about 1um



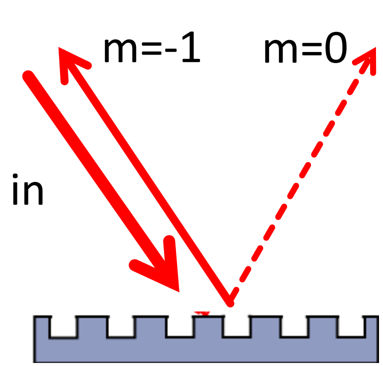
Various concepts

- 50/50 beam splitter

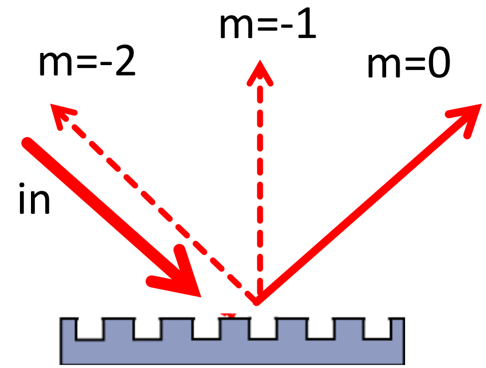


S.Fahr *et al.,Appl.Opt.* ***46*** *,6092 (2007)*

- 1st/2nd order Littrow gratings



L.Li et al.,Opt.Lett. ***20****, 1349 (1995)*



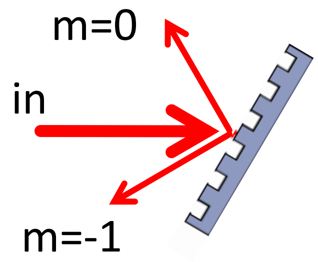
A.Bunkowski *et al,*
Opt.Lett. ***30****, 1183 (2005)*

➢ Michelson ifo.

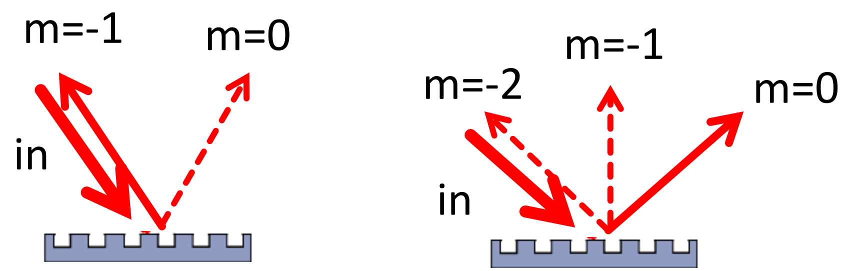
➢ Cavity coupler

Various applications

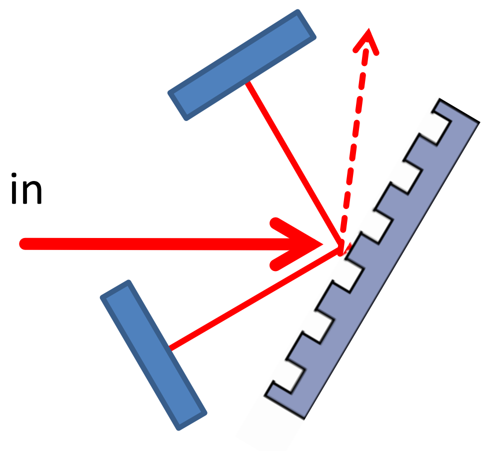
- 50/50 beam splitter



- 1st/2nd order Littrow gratings

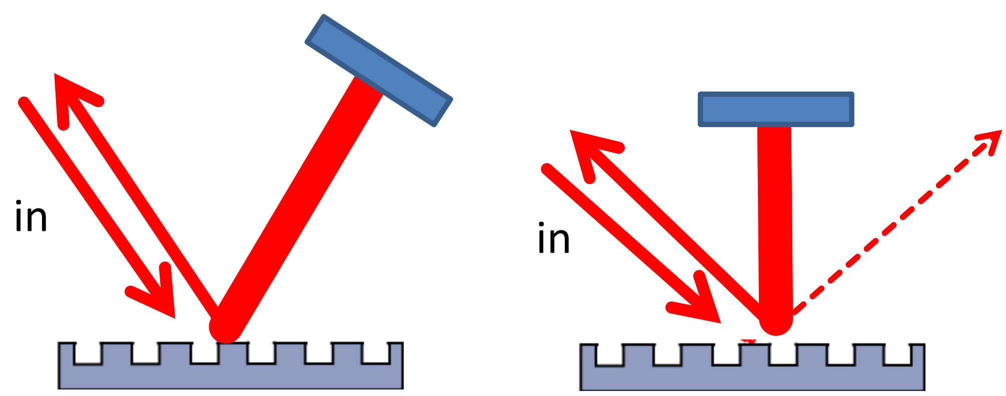


➤ Michelson ifo.



K.Sun. *et al.,Opt.Lett.* ***23***, *567(1998)*
DF. *et al., Opt.Lett.* ***33***, *101 (2008)*

➤ Cavity coupler

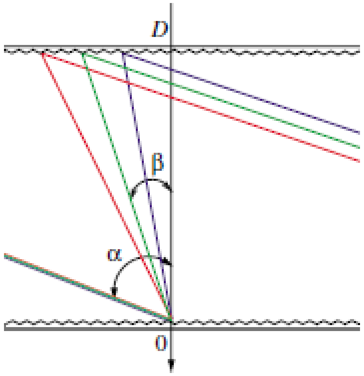


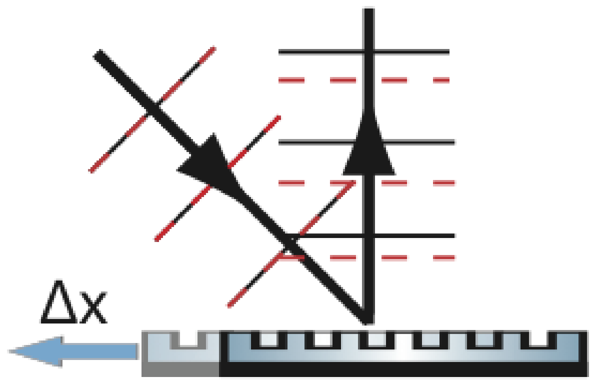
K.Sun. *et al.,Opt.Lett.* ***23***, *567 (1998)*
A.Bunkowski *et al., Appl.Opt.* ***45***, *5795 (2006)*
A.Bunkowski *et al., Opt.Lett.* ***31***, *2384 (2006)*
M.Edgar *et al., Opt.Lett.* ***34***, *3184 (2009)*
M.Britzger *et al., Appl.Opt.* ***50***, *4340 (2011)*

The "uninvited guest"

- Lateral displacement induces phase shift

  *S.Wise et al., PRL **95**, 013901 (2005)*





$$\phi_m = -m \frac{\Delta x}{d} 2\pi$$

diffraction order↑ ↑grating period

- Lateral displacement noise

  *A.Freise et al., New Journal of Physics **9**, 433 (2007)*

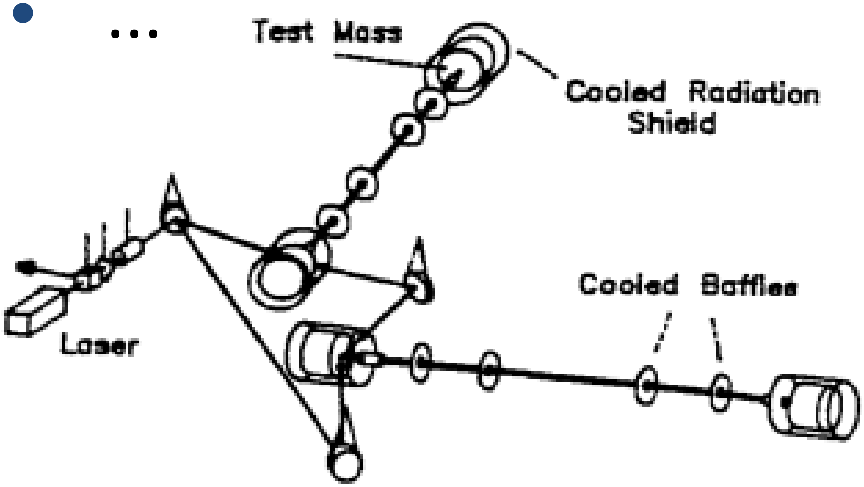
  *J. Hallam et al., J. Opt. A: Pure Appl. Opt. **11**, 085502 (2009)*

  *B.Barr et al., Opt.Lett. **36**, 2746 (2011)*

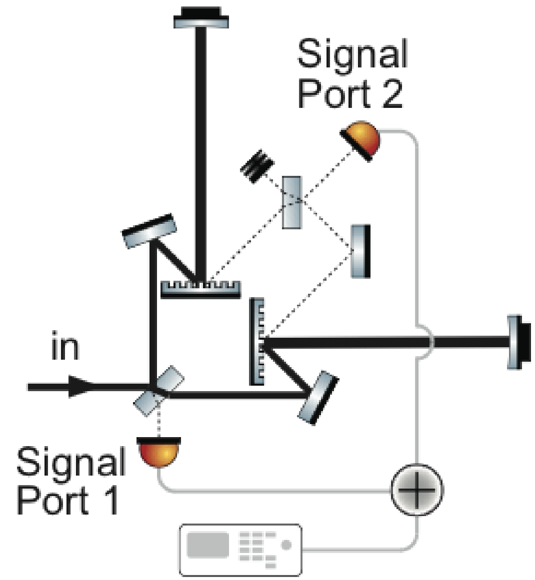
- Unsolved problem so far, but...

New topologies

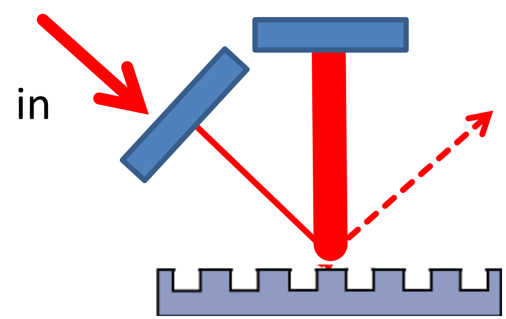
- ..., many possibilities left e.g.
- Having two signal ports→
- Add recycling mirrors↘
- Connect the arms↓
- ...



R.W.P.Drever, Proc. of the 7th Marcel Grossman Meeting on Gen.Rel. , 1401 (1995)



M.Britzger, pers.comm.

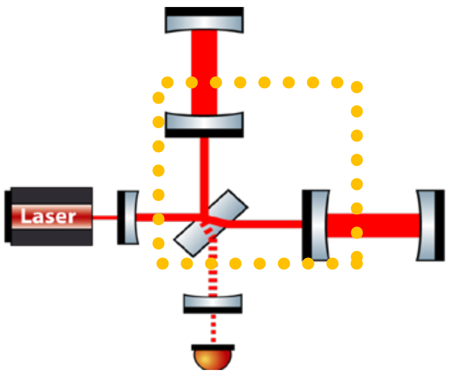


O.Burmeister et al., Opt.Express. ***18****, 9119 (2010)*

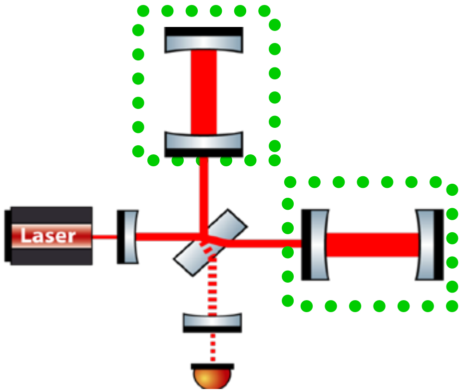
M.Britzger *et al., Opt.Express* ***19****, 14960 (2011)*

Outline of this talk

- All-reflective interferometry
  - Avoid transmission through substrates
  - Reflection gratings as BS or ITMs



- Coating free mirrors
  - Avoid mechanical lossy multilayer coatings
  - Waveguide gratings as ITMs and ETMs



- Summary

Waveguide Gratings (WGGs)

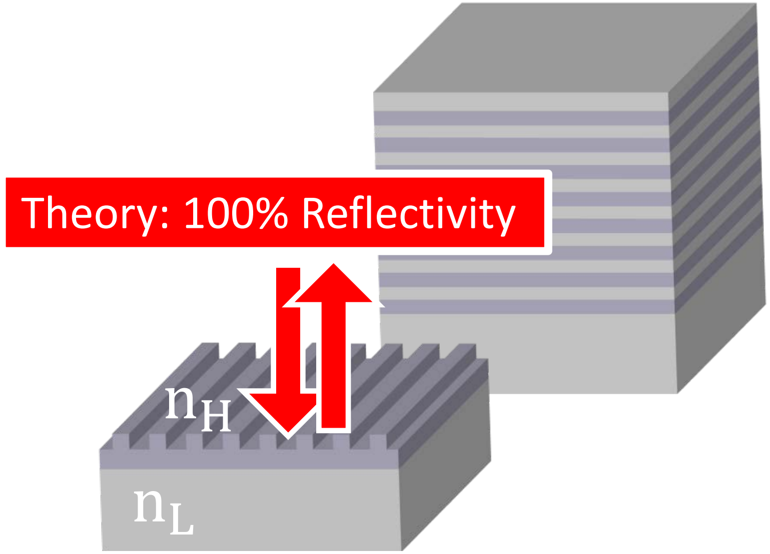
- Motivation: Coating thermal noise
- Approach: Significant reduction of coating material

- Resonant excitation of light

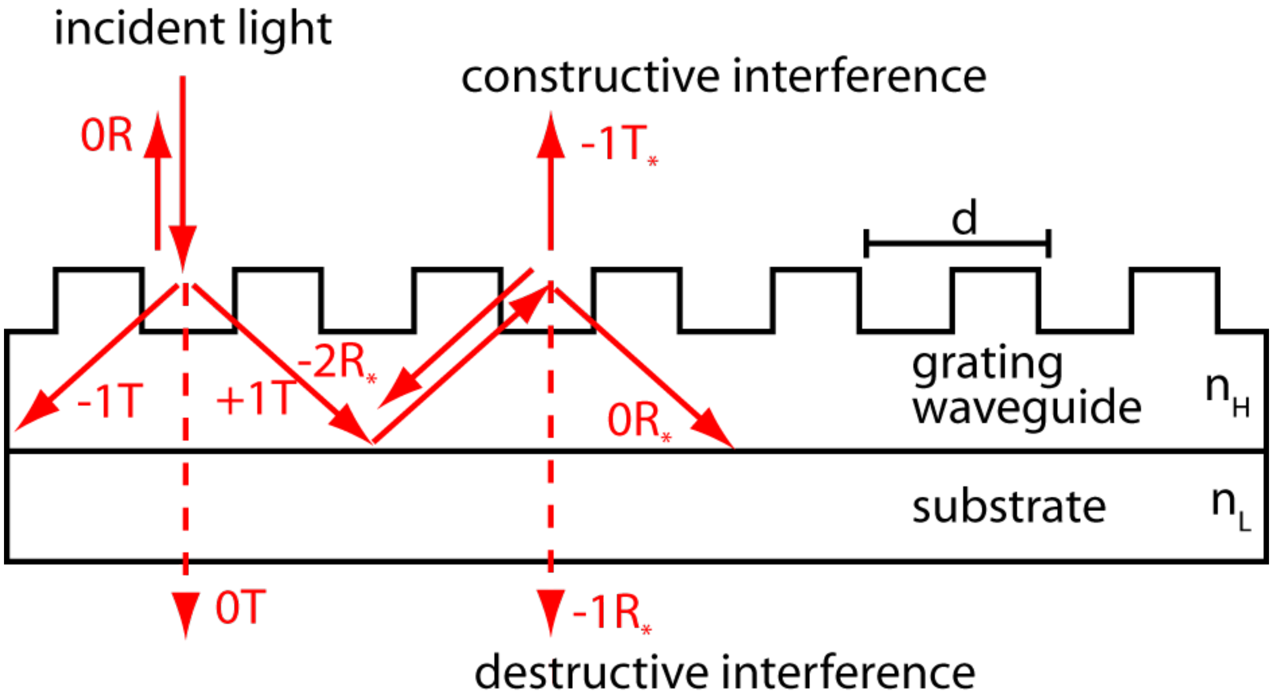
  A. Hessel et al. Appl. Opt. ***4****, 1275 (1965)*

- Structured surfaces

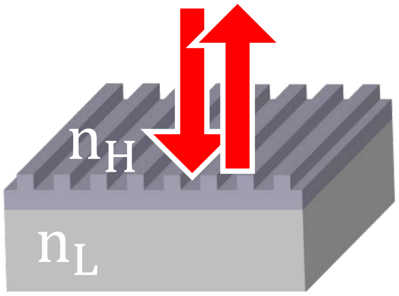
- Indices of refraction ($n_H > n_L$)



Ray Picture



Normal incidence



- Existence and direction of diffraction orders *m*

$$n_{\mathrm{b}} \sin(\beta_{\mathrm{m}}) = n_{\mathrm{a}} \sin(\alpha) + \frac{m\lambda}{d}$$

- Restrict diffraction orders

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

±1st orders in waveguide $\lambda/n_{\mathrm{H}} \leq d \leq 2\lambda/n_{\mathrm{H}}$

Only 0th order in substrate $d \leq \lambda/n_{\mathrm{L}}$

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

WGGs @ 1064nm

- Proposed as low thermal noise mirror
- Design based uses on 1st generation materials

A. Bunkowski et al., CQG **23**, 7297 (2006)

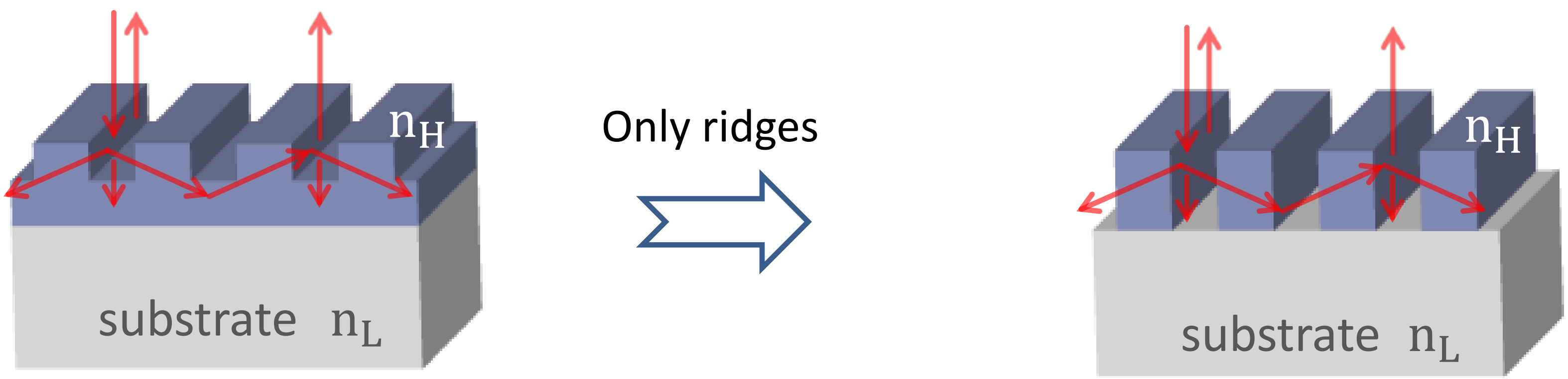
1064nm laser wavelength

Ta_2O_5 grating (n_H=2.04)

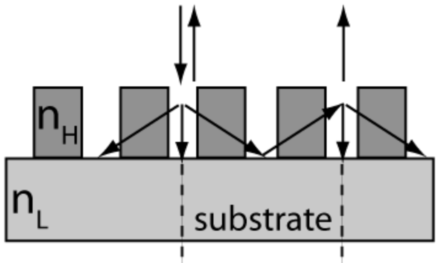
SiO_2 substrate (n_L=1.45)

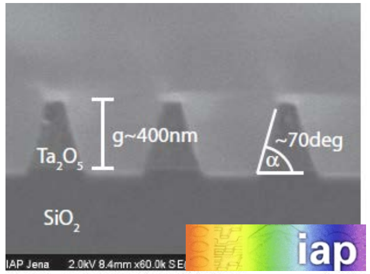
- Design via rigorous methods (RCWA)

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



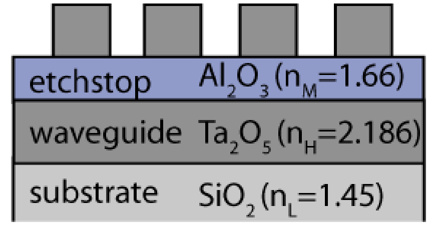
WGGs @ 1064nm

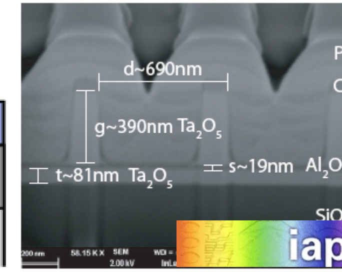




- Single ridges
- Table-top experiment
  Finesse = 660 (±30)
  → R = 99.08 (±0.04)%

F. Brückner et al., Opt.Express **17,** 163 (2009)





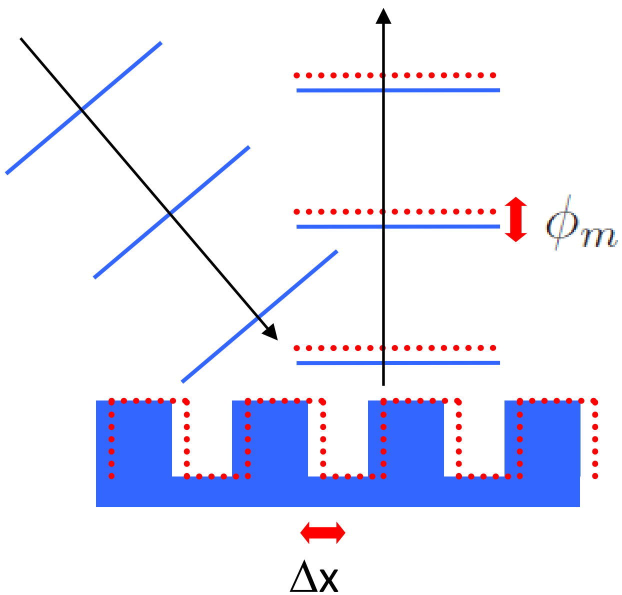
- Etch stop design
- Fully suspended 10 meter cavity
  Finesse = 790 (±100)
  → R ≥ 99.2 (±0.1)%

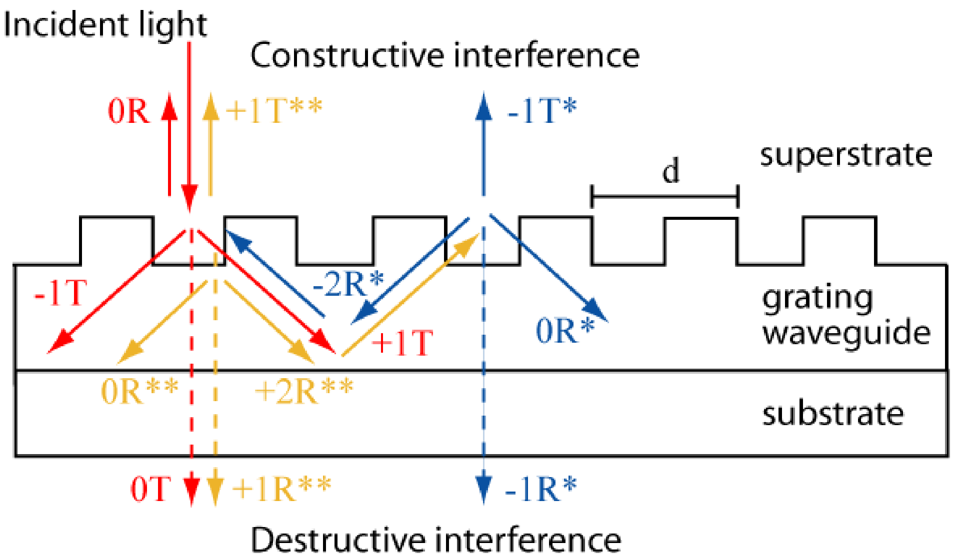
DF et al. Opt. Express ***19****, 14955 (2011)*

UNIVERSITY of GLASGOW

Lateral displacement

$$\phi_m = -m\frac{\Delta x}{d}2\pi$$





- ✓ All phase shifts cancel (geometry)
- Also tested with rigorous methods

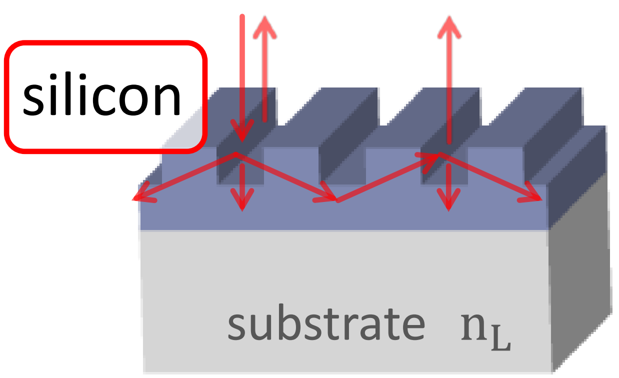
DF, PhD thesis

Silicon WGGs @ 1550nm

- Promising material for 3rd generation detectors

Design study: ET-0106C-10

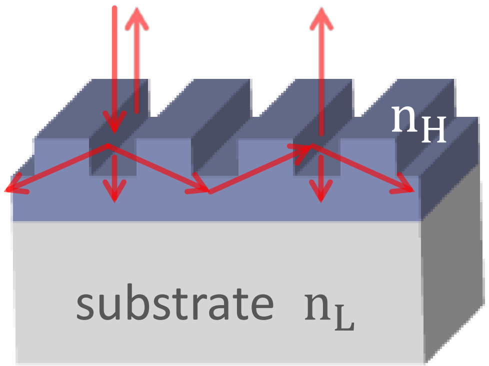
- Very well suited for cryogenic temperatures
  - Thermoelastic noise ~ 0 @ T=18 and 120K
  - Low mechanical loss $\phi_{Si} \sim 10^{-9}$ @ T=10K



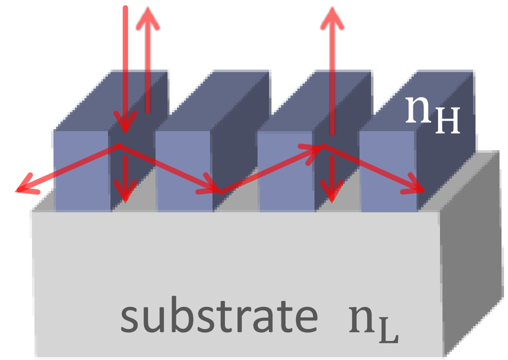
- Very well suited for WGG

n_H=3.5 @ 1550nm
→ high coupling efficiencies
→ parameter tolerant WGG

Reduction of Low Index Material

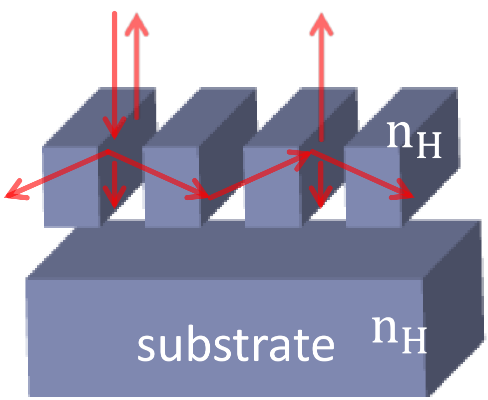


Only ridges

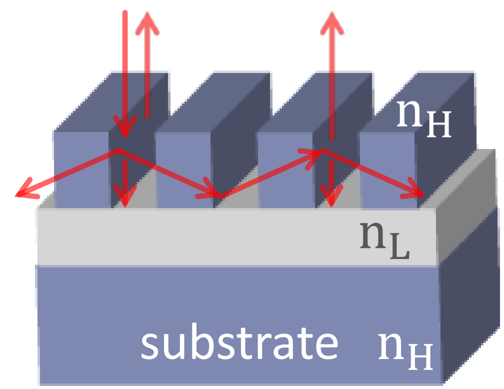


F. Brückner et al. Opt. Express ***17*** *(2009)*

Reduce low index material



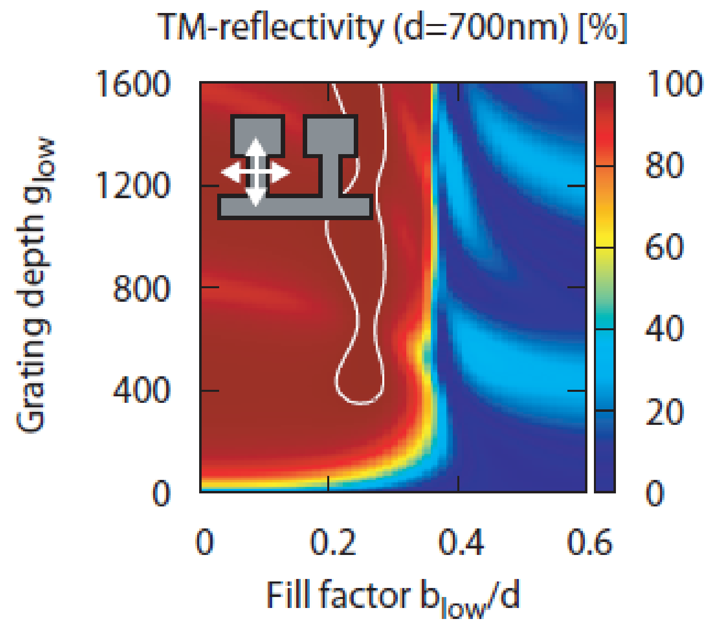
Replace by air

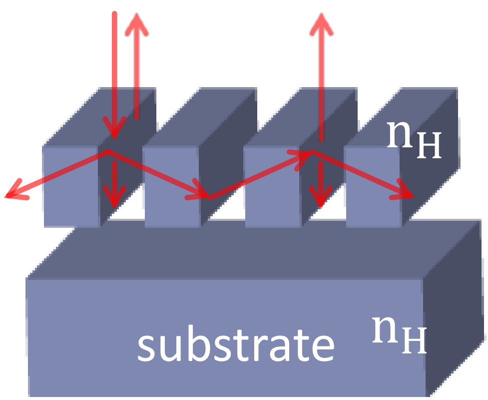


J.-S. Ye et al., J. Mod. Opt **53**, 1995 (2006)

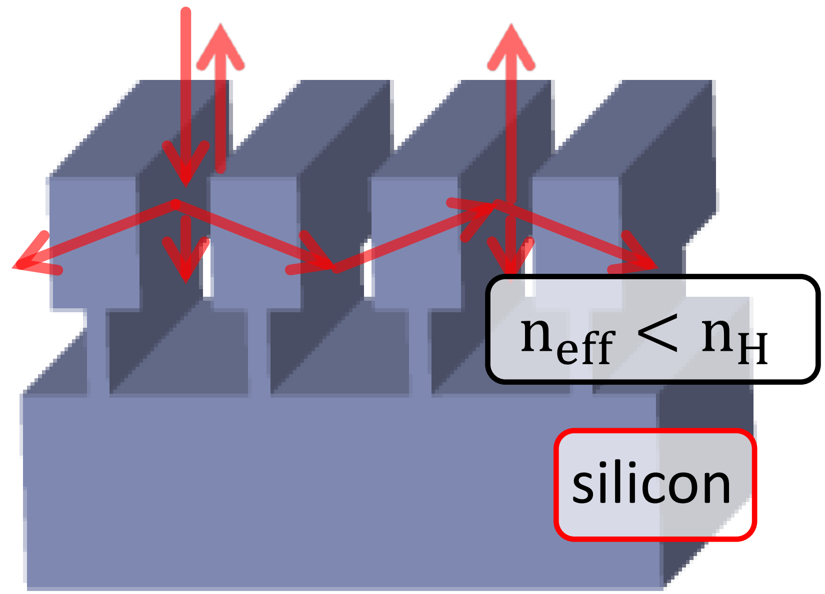
C.F.R. Mateus et al. IEEE Phot. Tech. Lett. ***16****, 1676 (2004)*

Monolithic Design





Thin grating structure

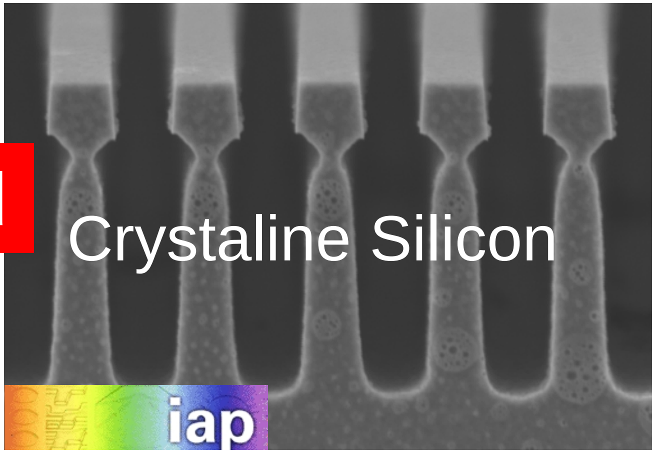


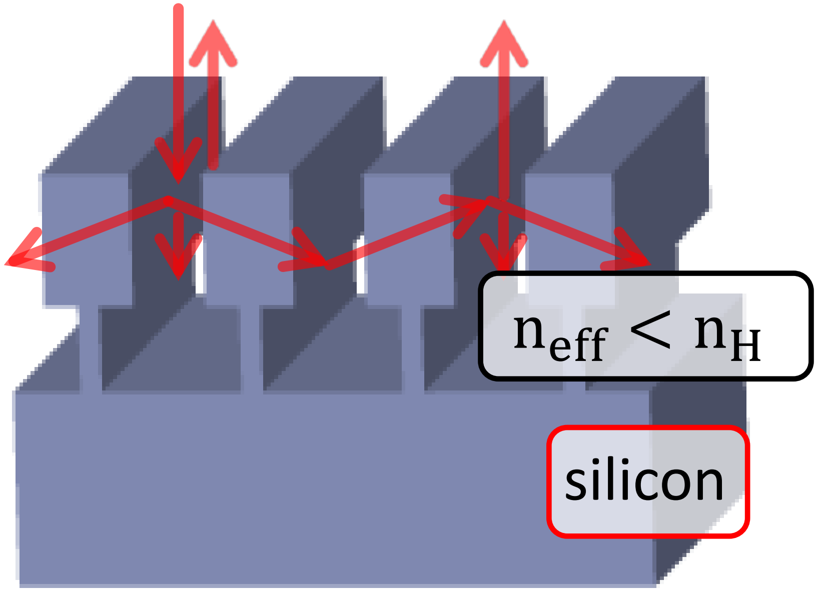
J.-S. Ye et al., J. Mod. Opt **53**, 1995 (2006)

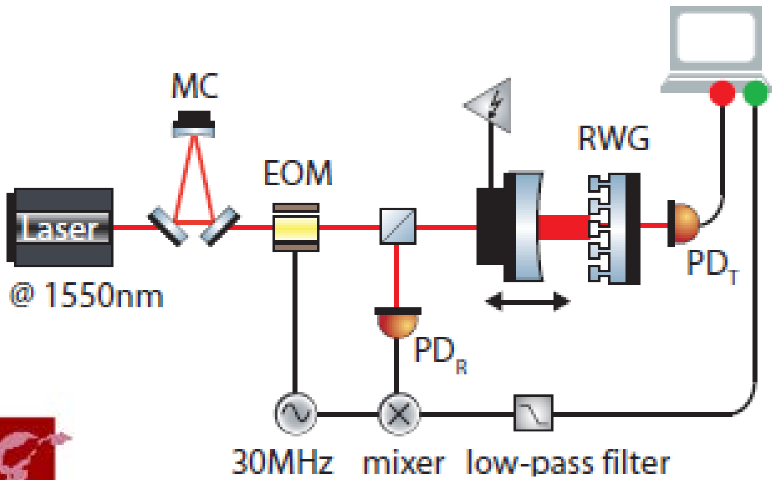
F. Brückner et al. Opt. Lett. ***33****, 264 (2008)*

Monolithic Realization

no material is added





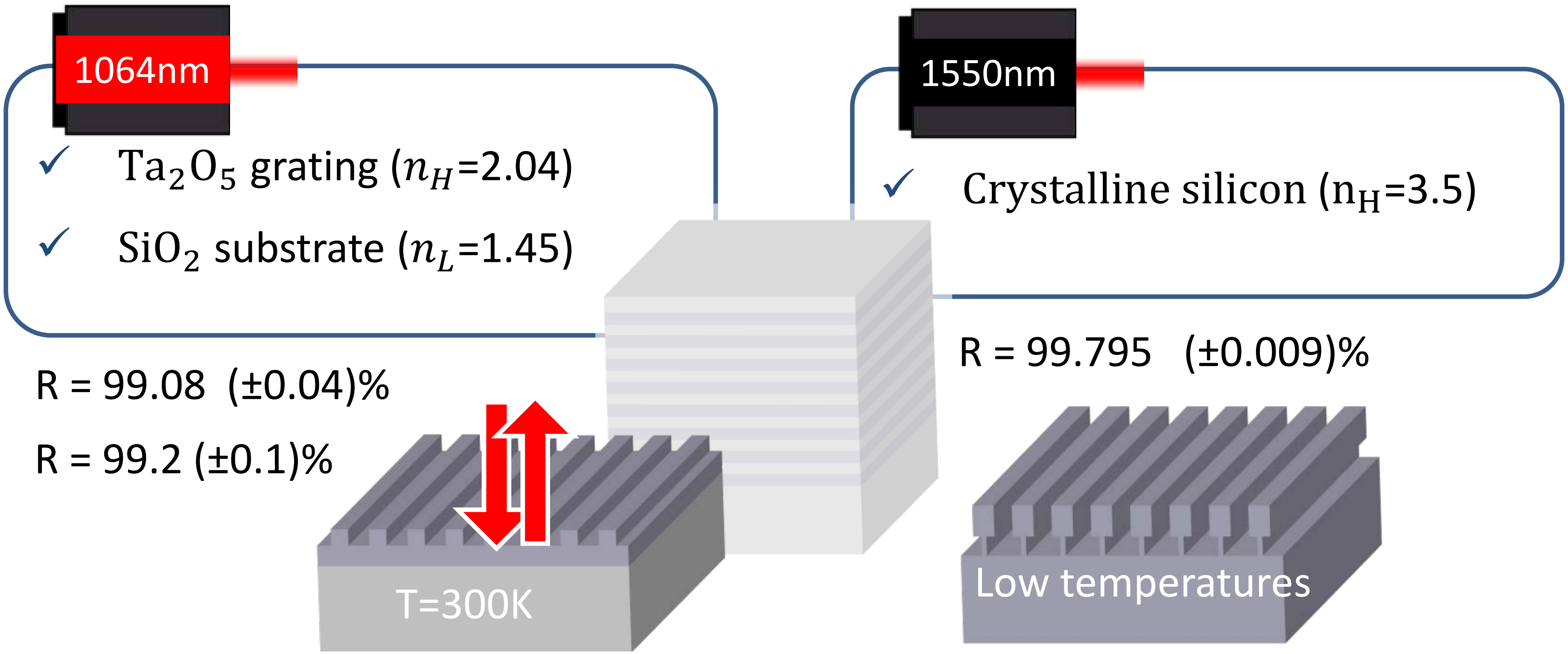


Finesse 2780 (±100)

→ R = 99.795 (±0.009)%

F. Brückner et al. PRL ***104****, 163903 (2010)*

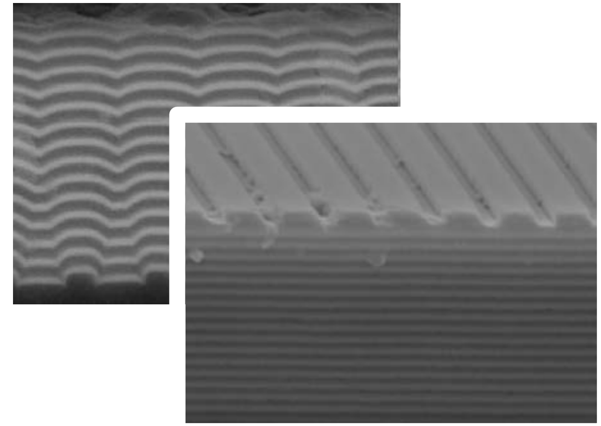
Summary: Waveguide Gratings



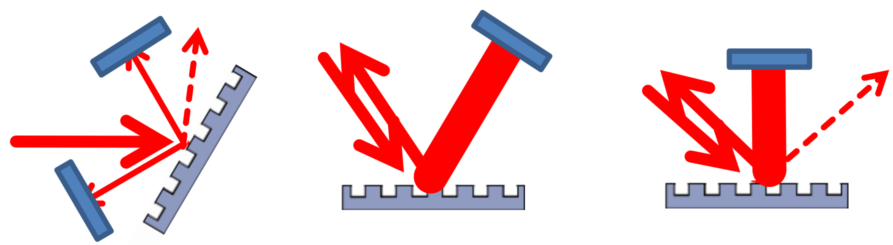
- Thermal noise needs further investigation
- Mirror quality and size need further improvements
- No fundamental differences to multilayer coatings found yet

Summary: Reflection Gratings

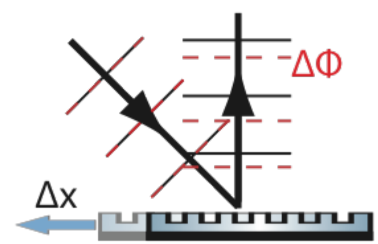
- All-reflective interferometry
- Avoid transmission related issues (absorption, heating, ...)



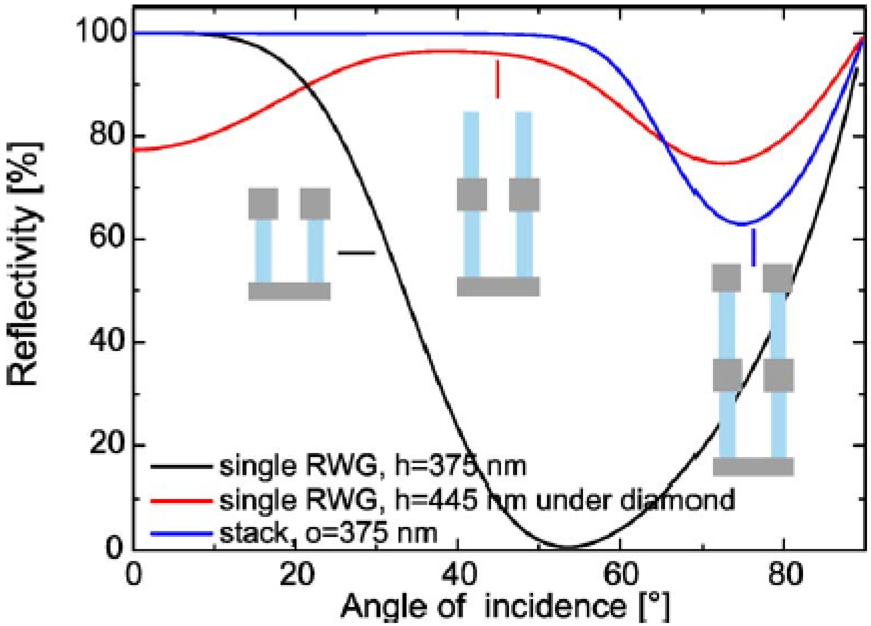
- Potential of using opaque materials
- Various concepts

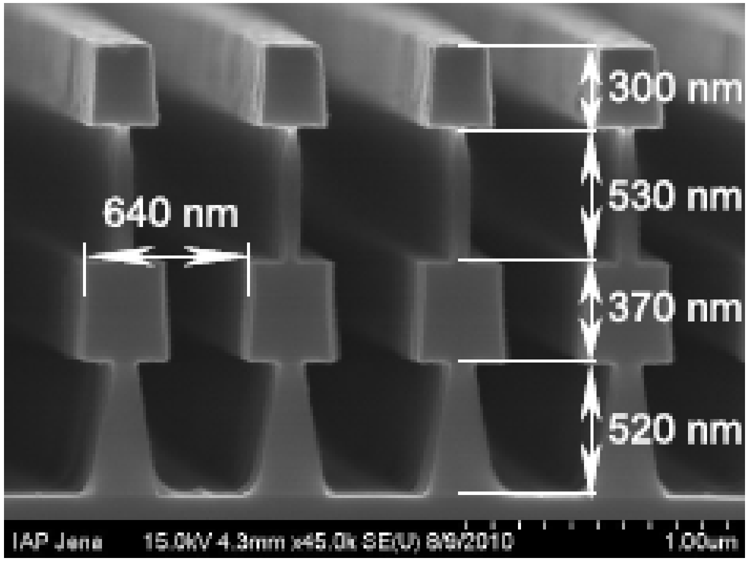


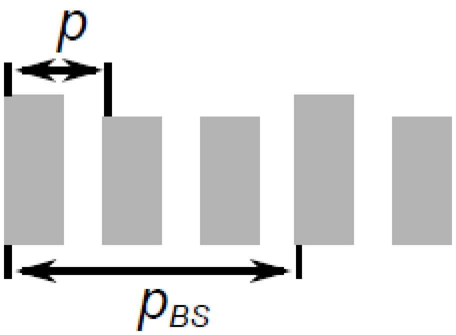
- Need to find solution for phase noise

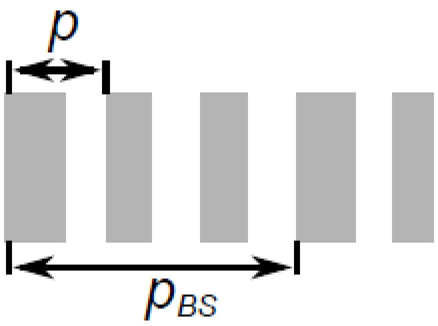


Merging the two concepts





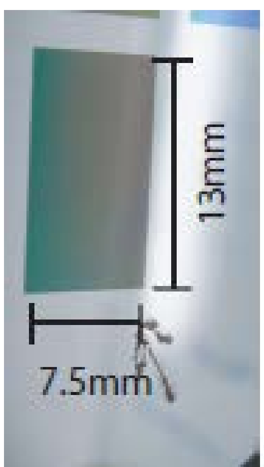


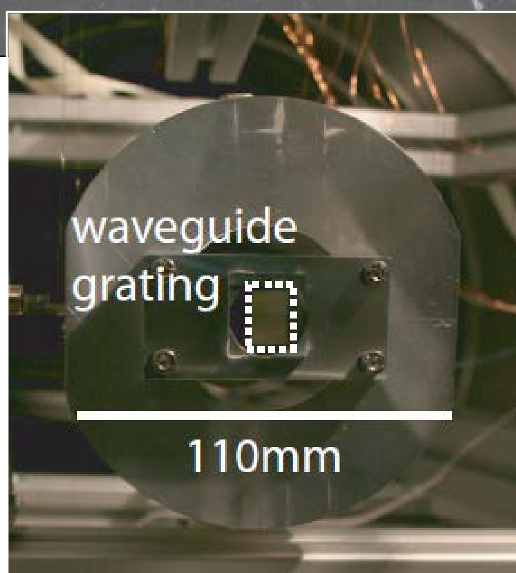


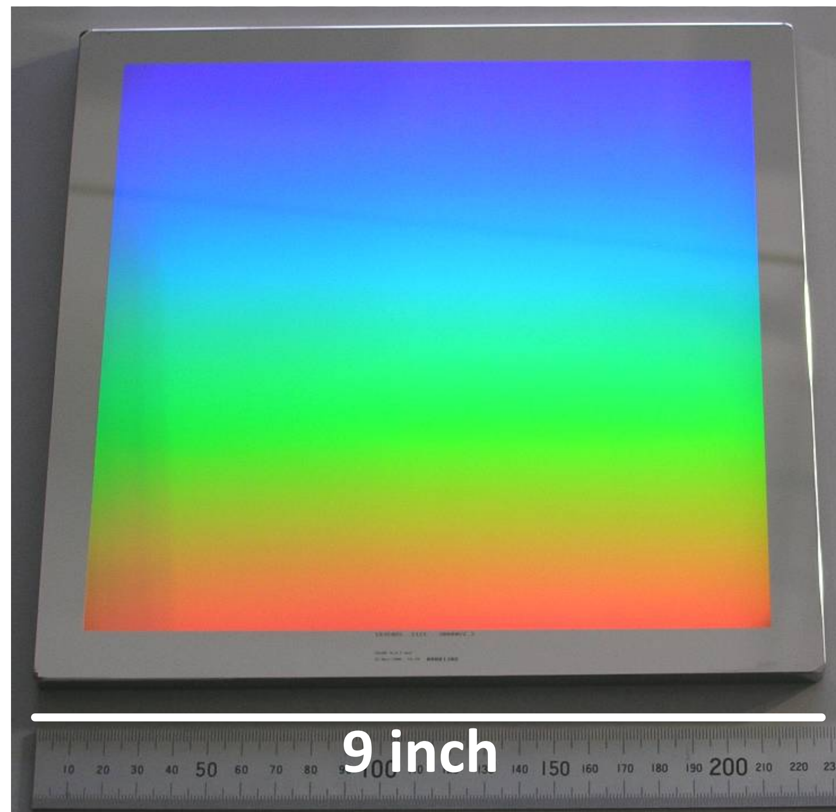
S. Kroker et al., Opt. Lett. **36**, 537 (2011)

S. Kroker et al., Opt.Express. **19**, 16469 (2011)

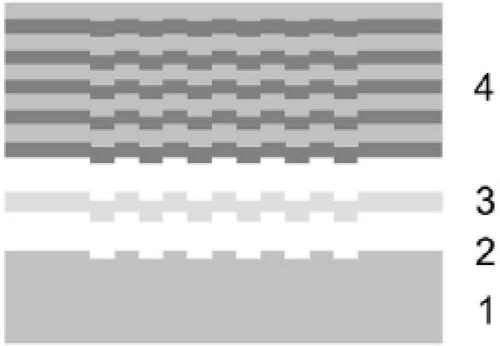
Thank You

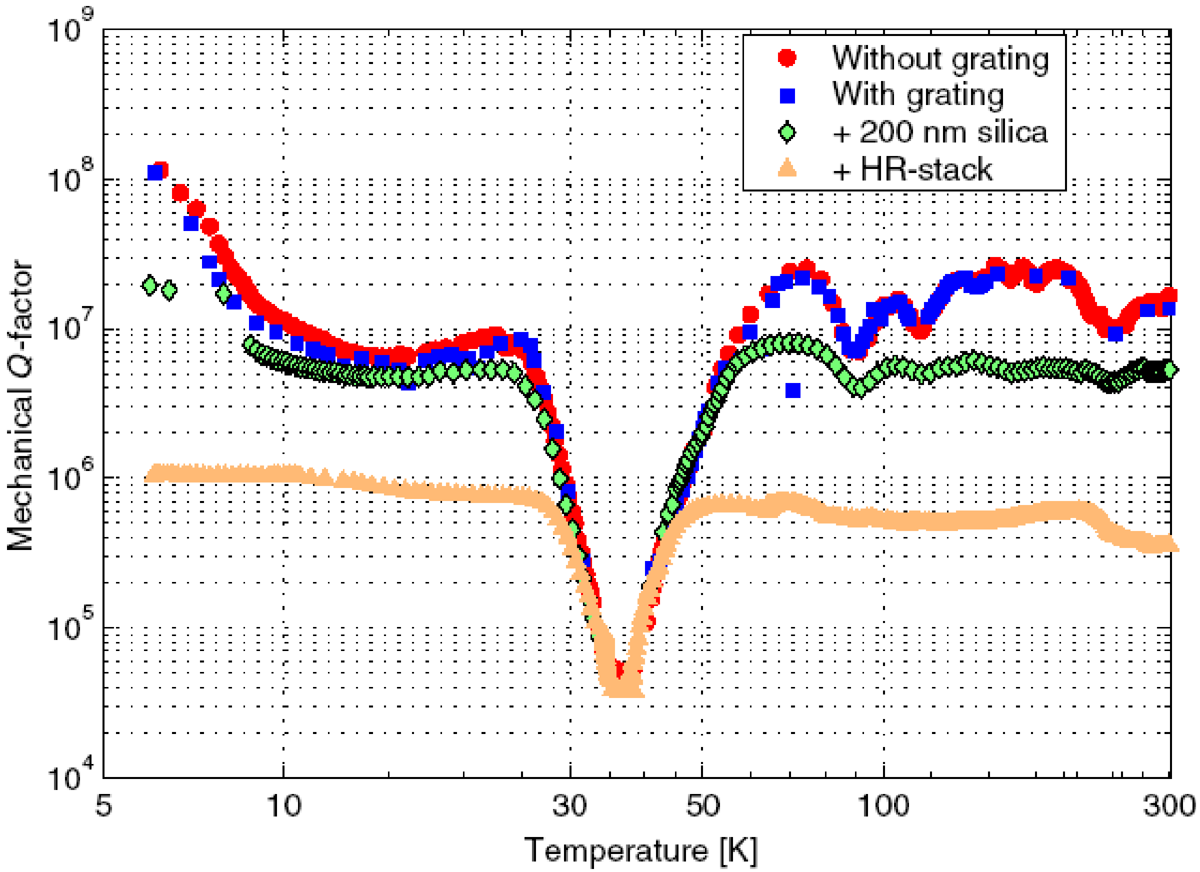






Mechanical loss of nanostructures





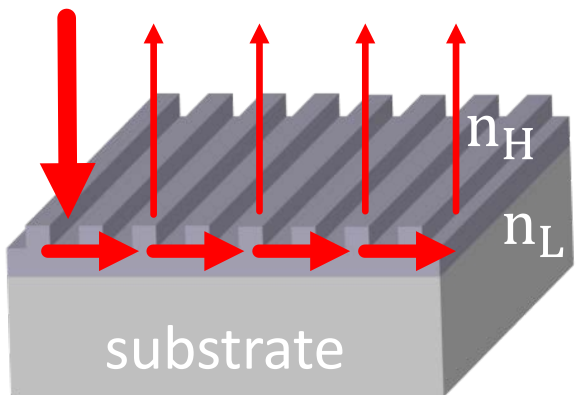
- Grating structure does not „destroy“ high Q-factor of substrate!
- but surface loss is crucial, need to be measured seperately!

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

Resonant Excitation

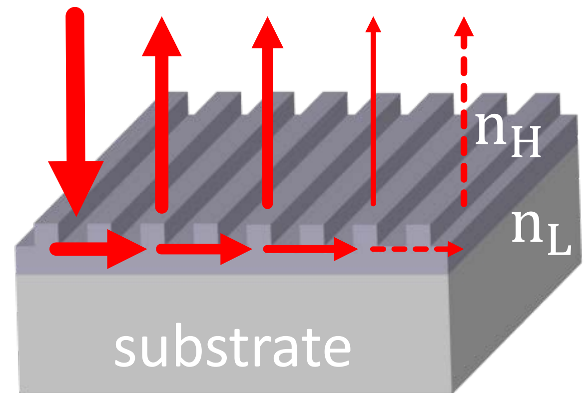
- Small coupling

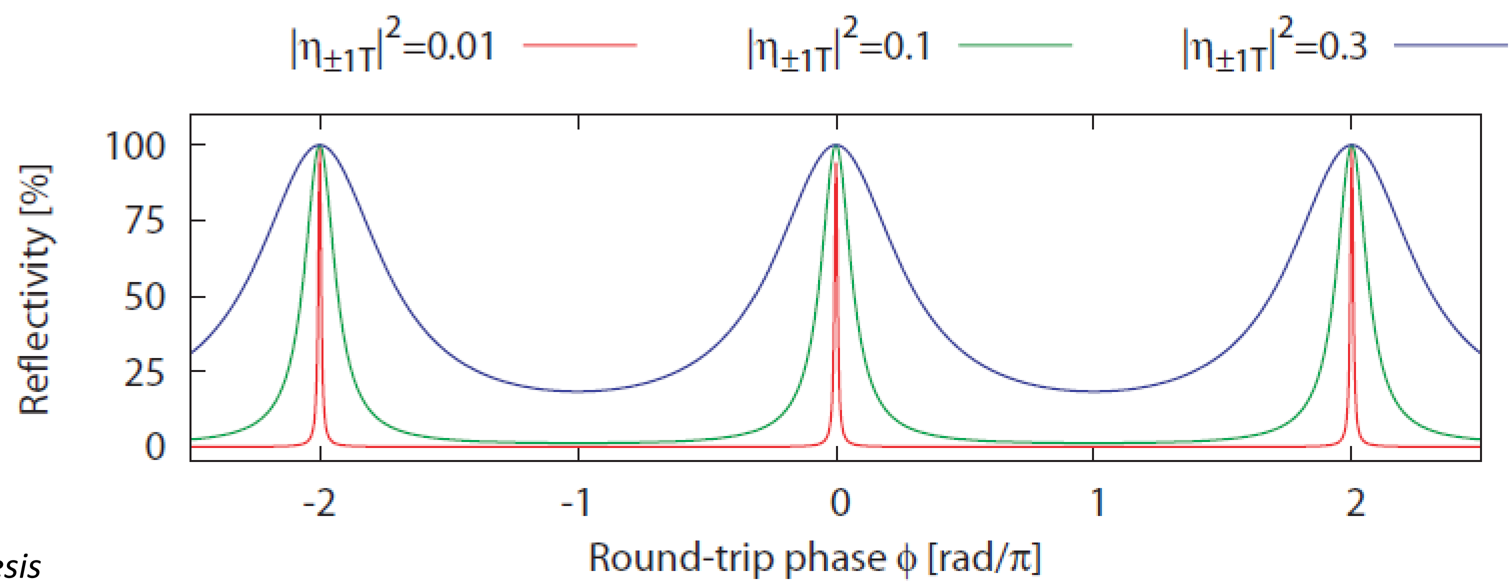
→ Long storage time



- Strong coupling

→ Short storage time





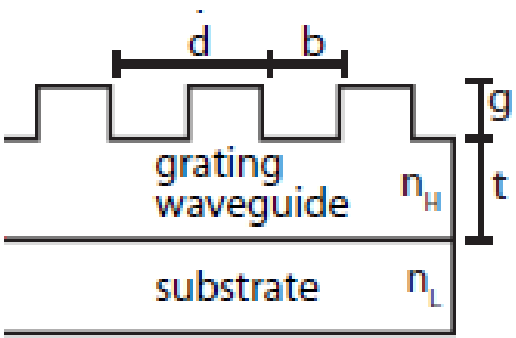
DF, PhD thesis

Diffraction efficiencies

- Rigorous coupled wave analysis (RCWA)

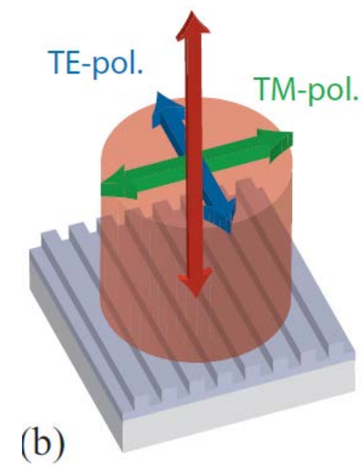
  M.G. Moharam et al. J. Opt. Soc. Am. 71 (1981)

- For given wavelength, materials and polarization



d grating period
b ridge width
g groove depth
t waveguide thickness

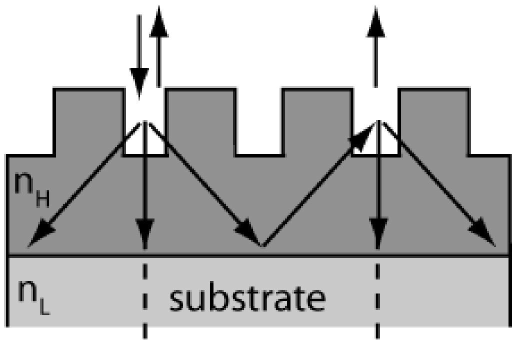
(*d*, *b*) } *b/d* fill factor



- Numerical implementation: e.g. UNIGIT

  www.unigit.com

WGG Including Etch Stop Layer

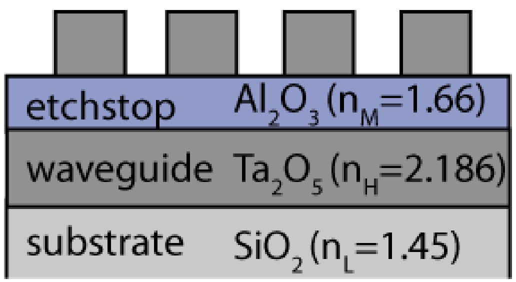


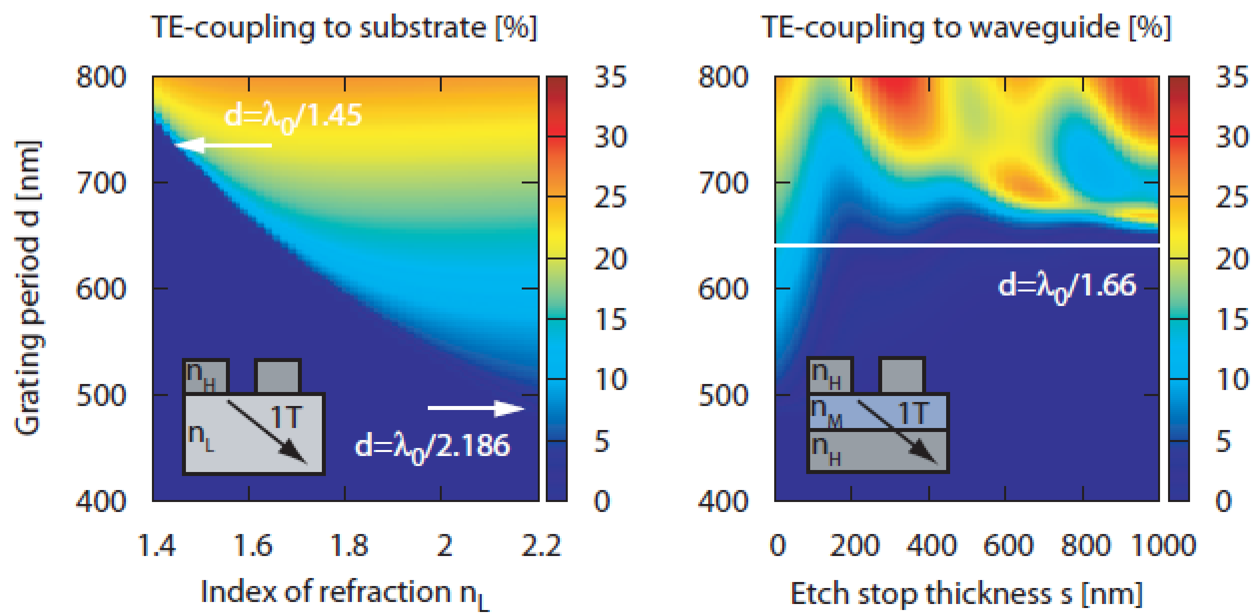
- Etch stop

→ defines grating depth / waveguide thickness

- Thin etch stop layer

→ Optical properties can be preserved

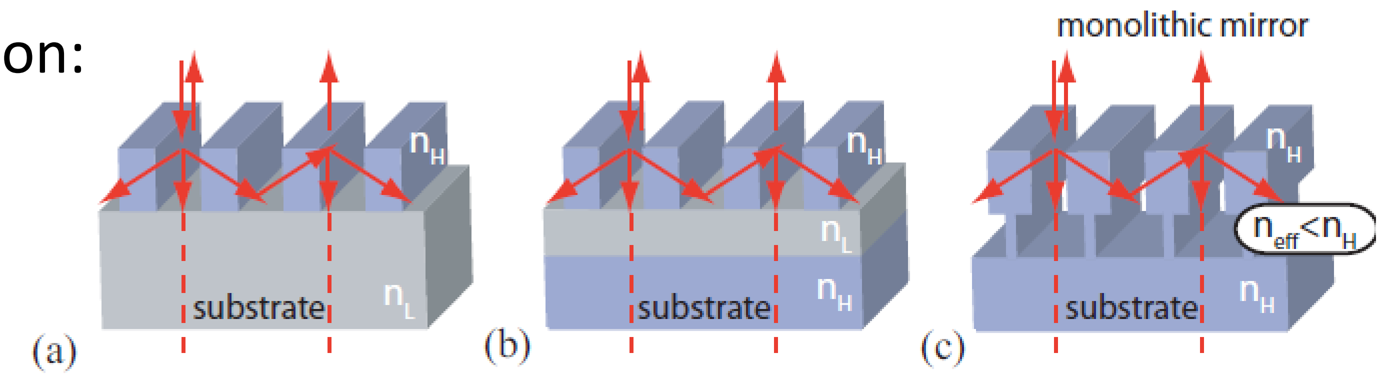




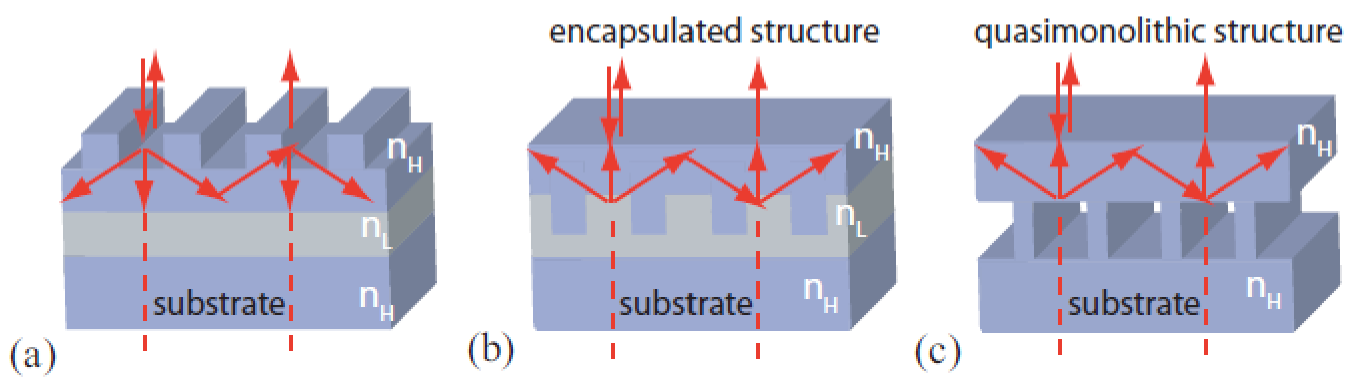
DF et al. Opt. Express ***19****, 14955 (2011)*

A Variety of WGGs

Today`s presentation:

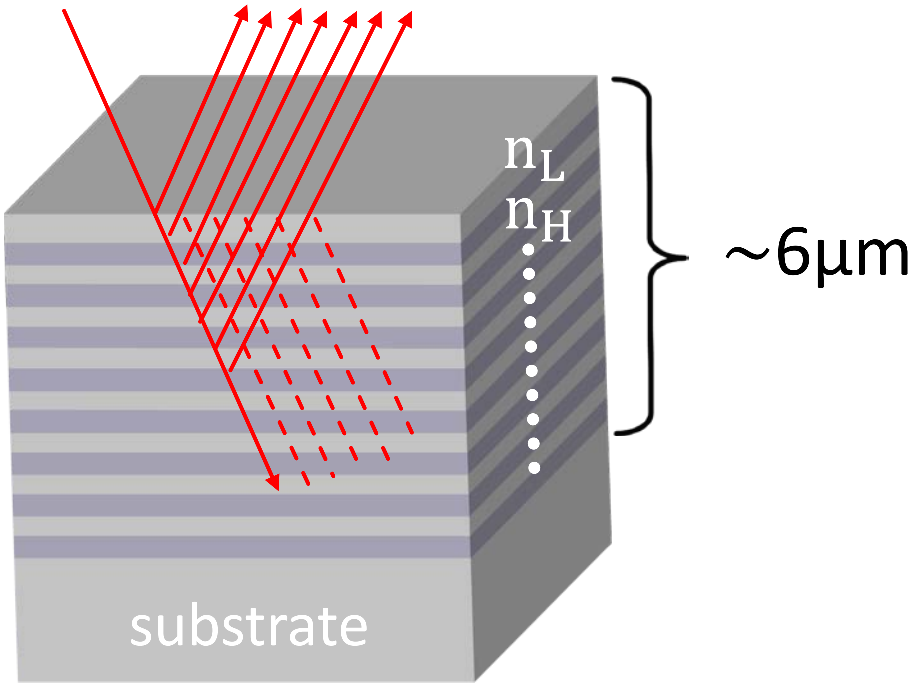


Flat surfaces:



*F. Brückner et al. Opt.Express **17**, 24334 (2009)*

Mirror Brownian Thermal noise



- Temperature T
- Mechanical dissipation ϕ
- Beam radius r_0
- Coating thickness h

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

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