NANOSTRUCTURED OPTICS

With transparencies from

- Bryan Barr
- Michael Britzger
- Frank Brückner
- Alexander Bunkowski
- Oliver Burmeister
- Daniel Friedrich
- Bernard Kley
- Roman Schnabel

Harald Lück, AEI

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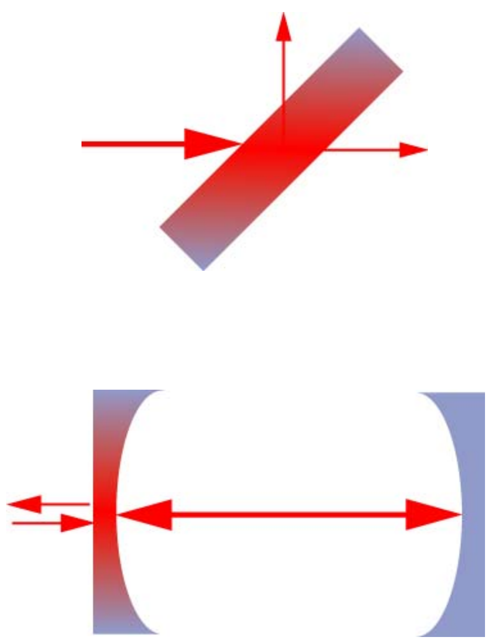
Gratings in Interferometers

- Gratings as cavitiy mirrors
  - 1st order Litrow
  - 2nd order Litrow
- Gratings as Beam Splitter
- Waveguide Coatings

Gratings: Why?

transmissive Optics



Thermal Effects from Absorption

- Thermal Lensing
- Thermal deformation
- Thermal effects limit power

$\Rightarrow$ Avoid Transmission using reflective optics

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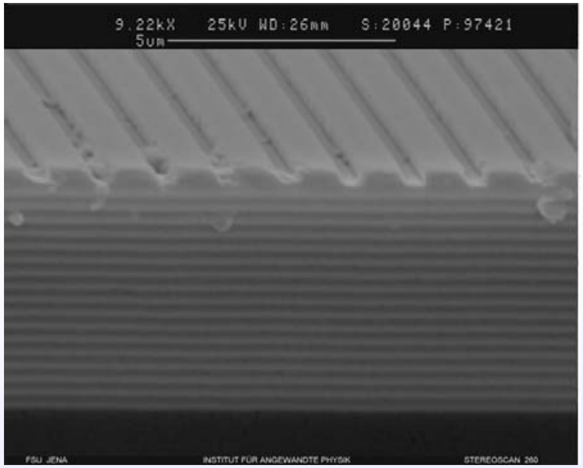
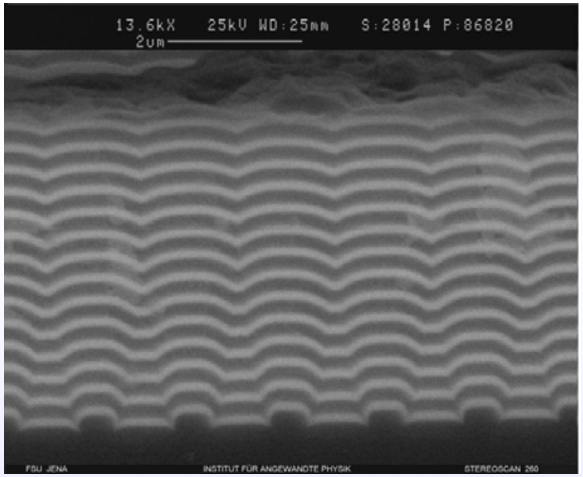
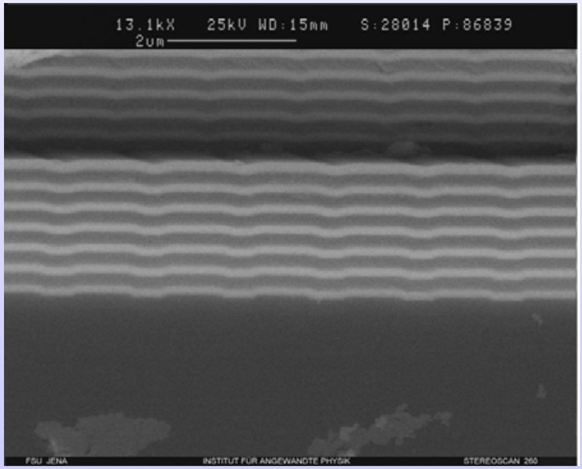
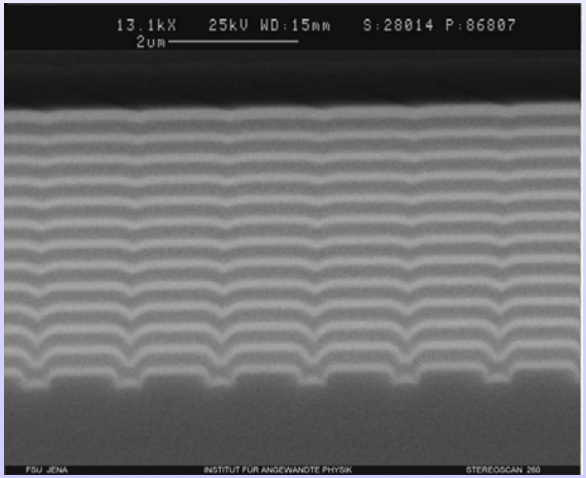
Examples









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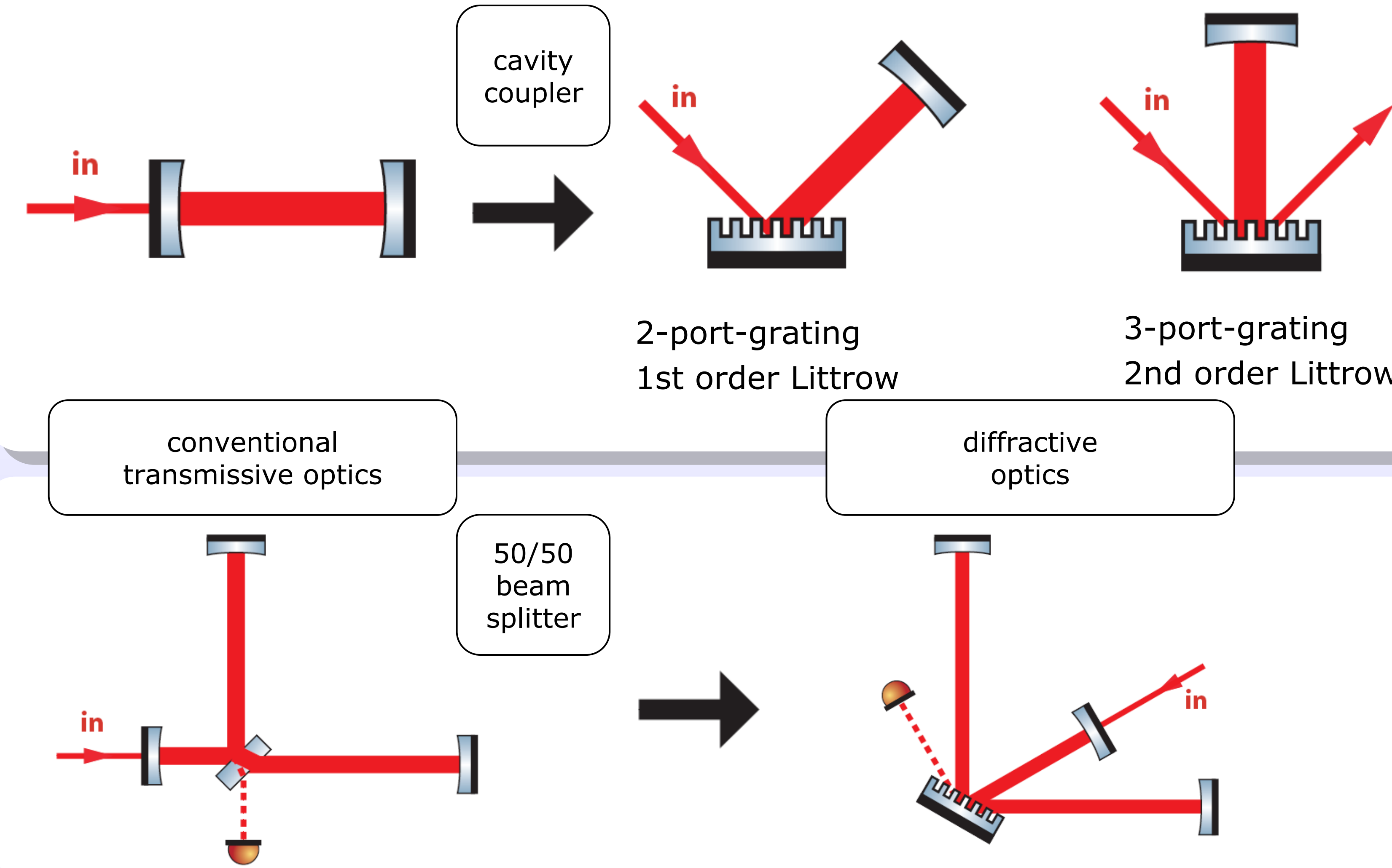
Basic Ideas



Appl. Opt. 45, 5795 (2006); Appl. Opt. 46, 24 (2007); Opt. Lett. 33, 101 (2008)

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Cavity couplers

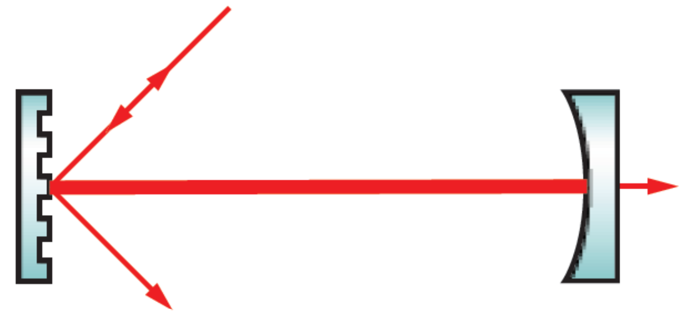
Option 1:

1st order Littrow mount

- Input light enters via the 1st diffracted order path
- Grating = 2 port device
- Requires high efficiency, low loss grating

Option 2:

2nd order Littrow mount



- Input light enters via the 2nd diffracted order path
- 1st order is normal to the grating surface
- Grating = 3 port device
- Requires low 1st order efficiency, low loss grating

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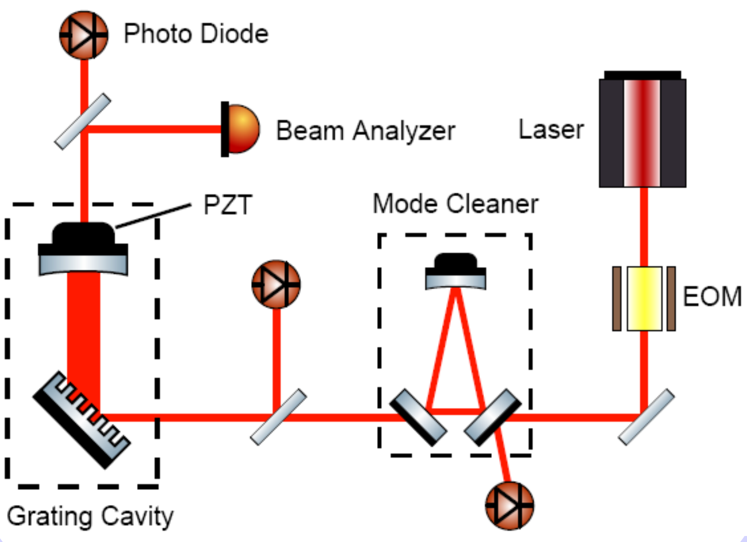
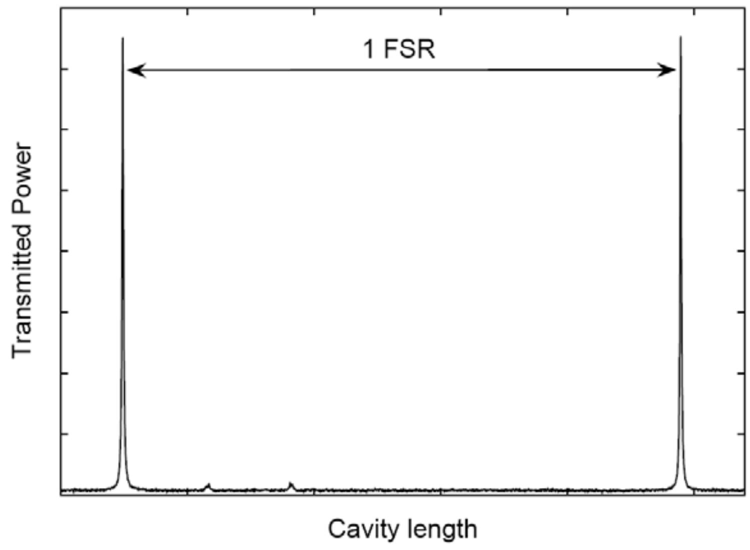
1st order Littrow cavity





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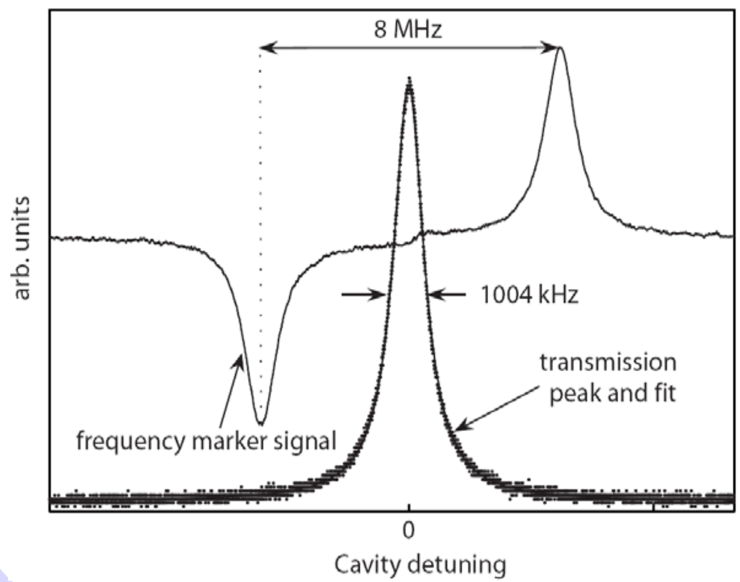
1st order Littrow cavity



Results:

Finesse: 1580 $\pm$ 60

Diffr. eff.: 99.63% $\pm$ 0.02%

Loss: 0.19 %

Bunkowski et al.

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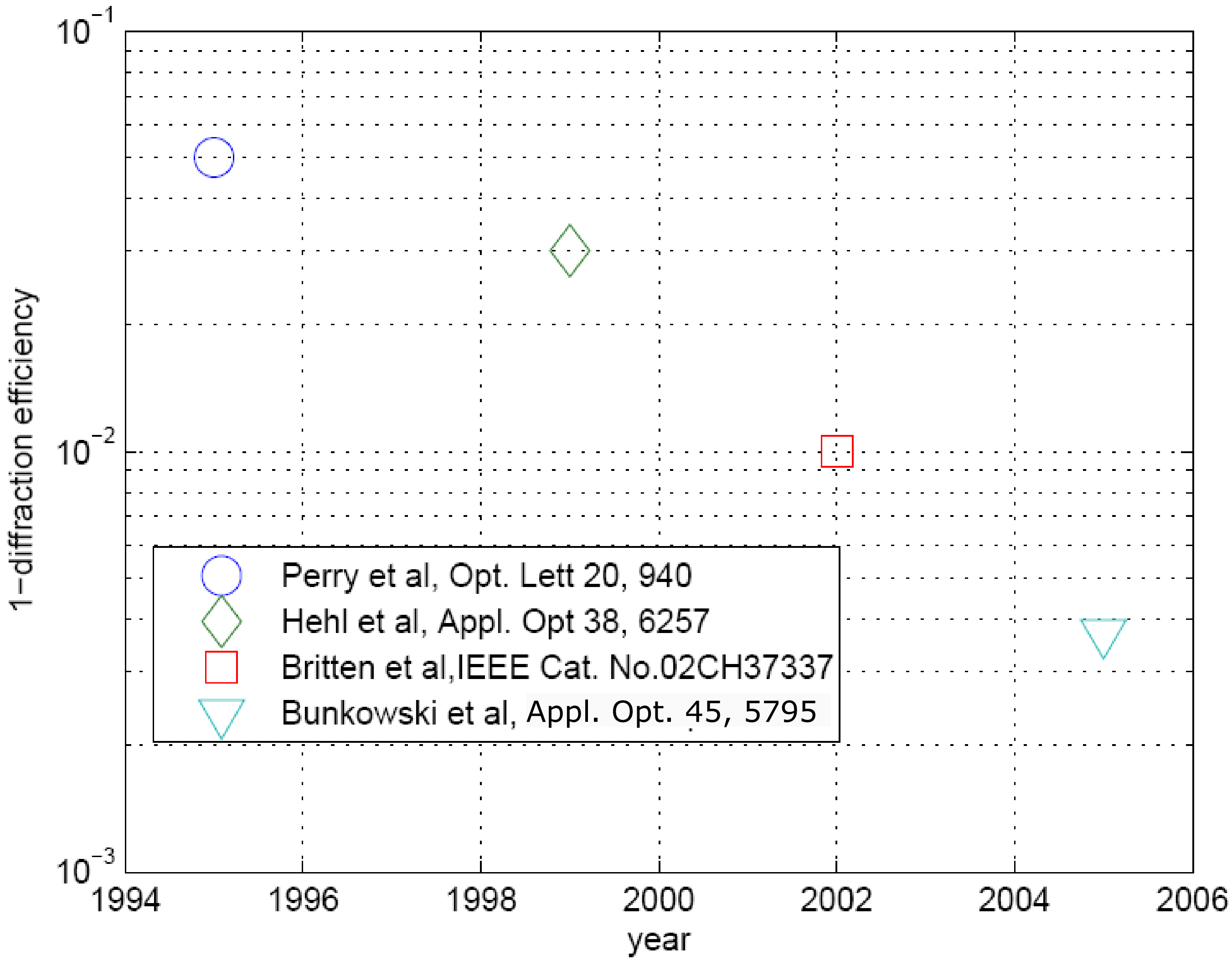
Diffraction efficiency evolution



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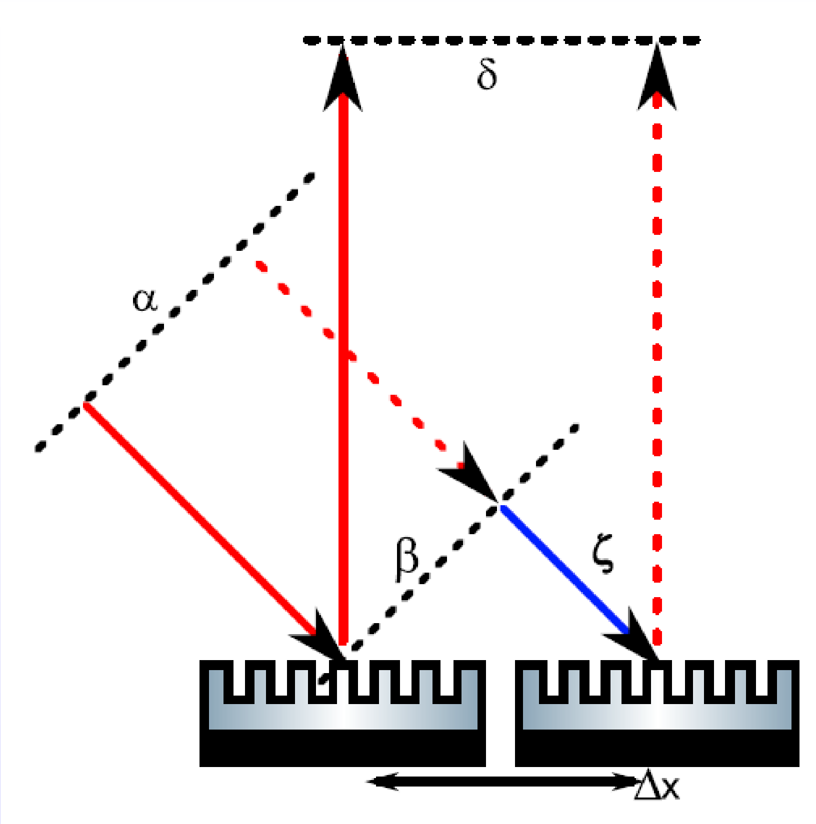
A Problem: Lateral motion



Well known effect, e.g. in acousto-optic Modulators

Phase of diffracted beam changes with lateral motion between the beam and the grating

Discussed in: J. Hallam J. Hallam

Hallam et al., arXiv:0903.3324v2 [gr-qc] 5 May 2009

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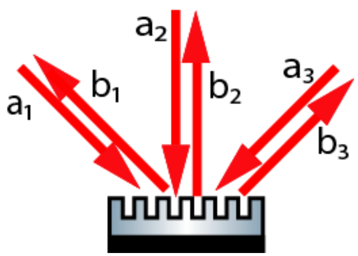
Three-port-grating

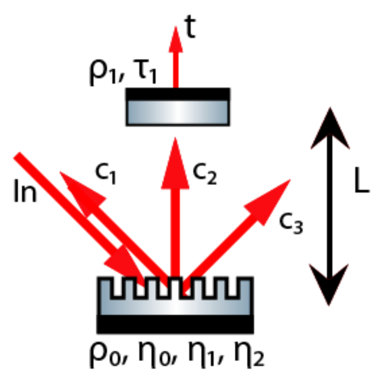


- Scattering-matrix-formalism
- Phases depend on diffraction efficiencies
- Non vanishing matrix elements

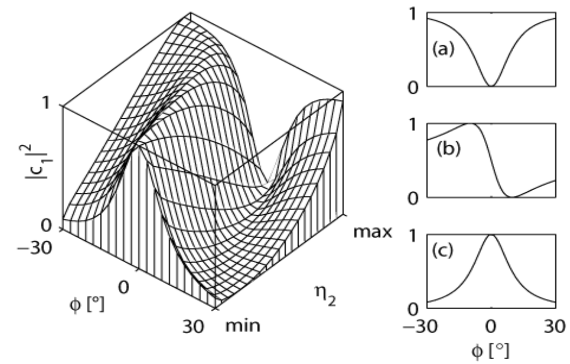
$$\mathbf{b} = \mathbf{S} \times \mathbf{a}$$

$$\mathbf{S}_{3\mathrm{p}} = \begin{pmatrix} \eta_2 e^{\mathrm{i}\phi_2} & \eta_1 e^{\mathrm{i}\phi_1} & \eta_0 e^{\mathrm{i}\phi_2} \\ \eta_1 e^{\mathrm{i}\phi_1} & \rho_0 e^{\mathrm{i}\phi_0} & \eta_1 e^{\mathrm{i}\phi_1} \\ \eta_0 e^{\mathrm{i}\phi_0} & \eta_1 e^{\mathrm{i}\phi_1} & \eta_2 e^{\mathrm{i}\phi_0} \end{pmatrix}$$

$$\eta_n \neq 0$$

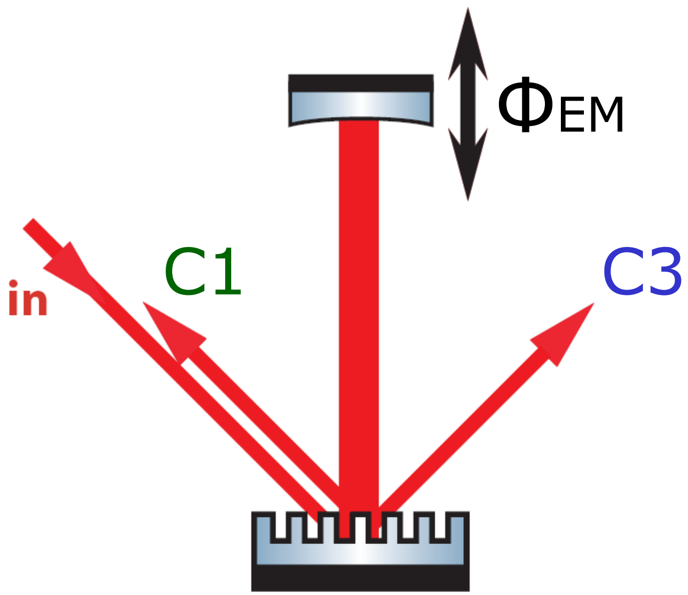


- Coupling to an optical resonator via 1st diffraction order
- Low diffraction efficiency η_1 / high reflectivity ρ_0
- Two reflection ports c_1 / c_3
- Grating design defines ratio of the radiation at the output ports



Opt. Lett. 29, 2342 (2004), Opt. Lett. 30, 1183 (2005), Opt. Lett. 31, 658 (2006), Opt. Lett. 31, 2384 (2006)

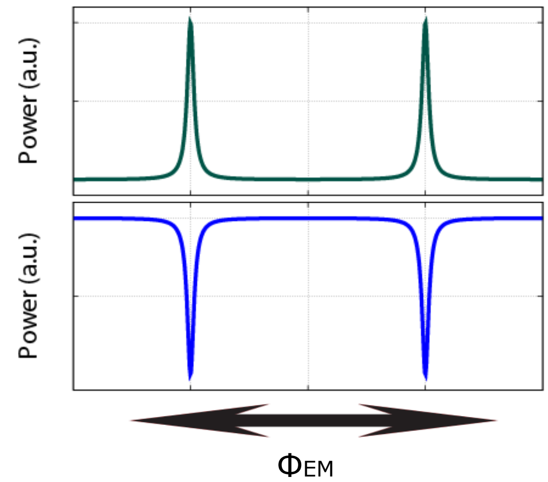
Three-port-grating resonator



η_{2min}-configuration

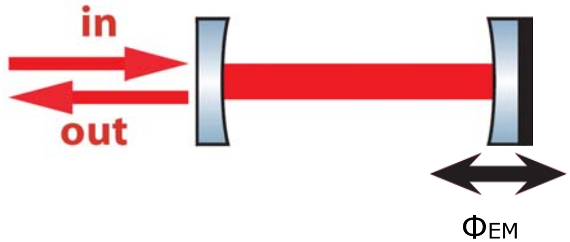
Port C1

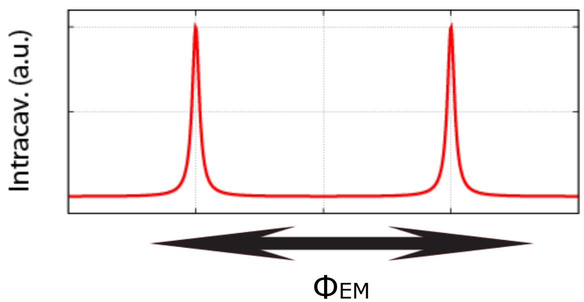
Port C3



- Resonant light reflected towards laser
- Modeselective mirror
- One degree of freedom (Φ_{EM})

linear resonator





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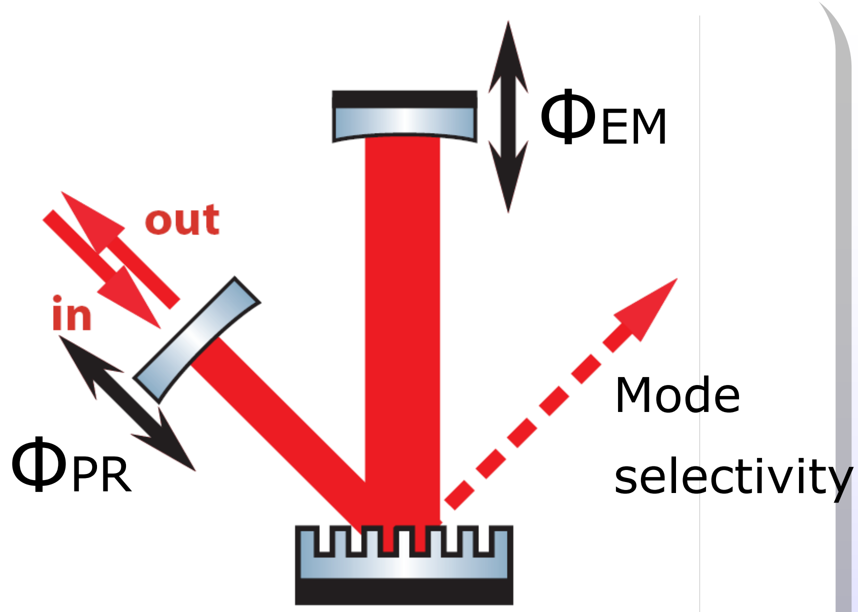
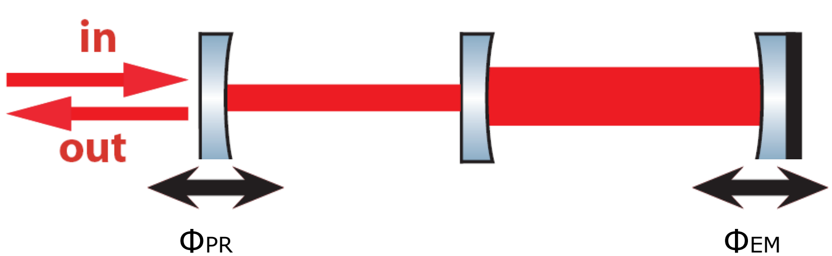
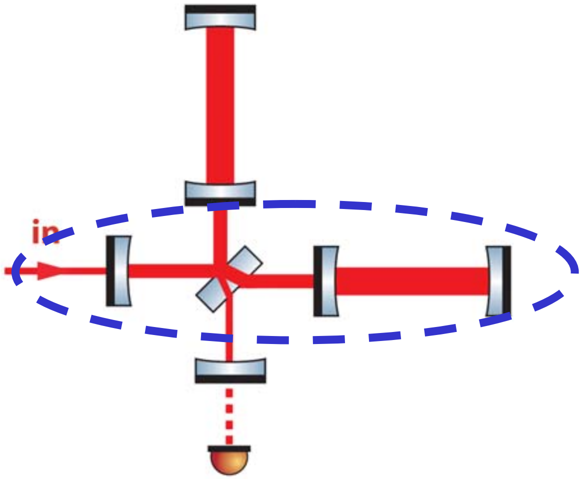




Power-recycling

- Power-recycling mirror (M_{PR}) in reflection port C1
- Additional power build-up in the grating cavity
- Grating-coupled double-resonator
- Two degrees of freedom (Φ_{EM}, Φ_{PR})



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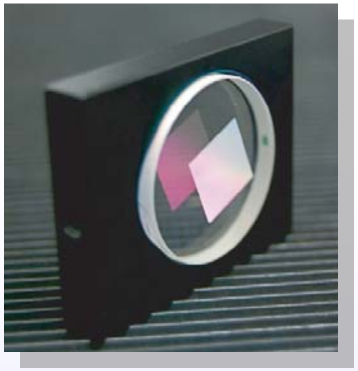
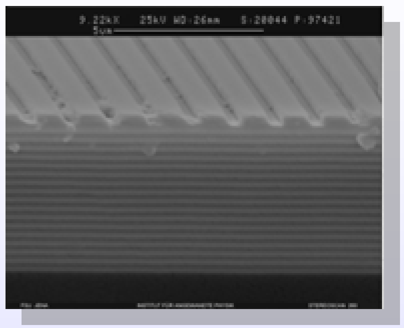
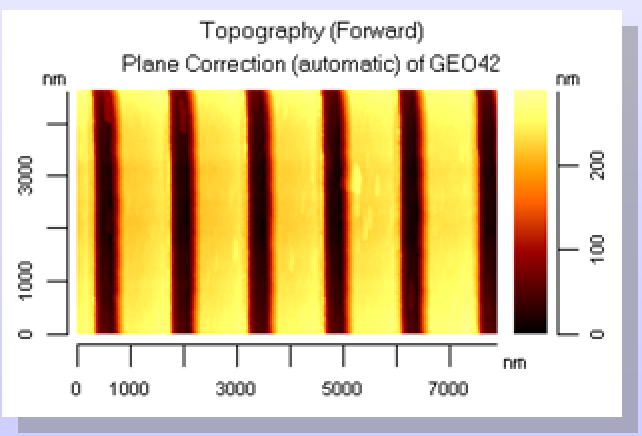
Facts I



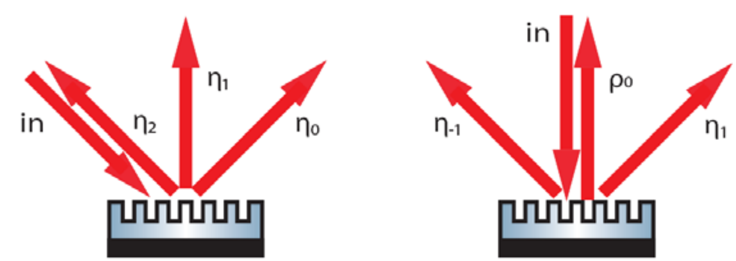




Grating GEO42

- Fused silica substrate
- HR-coating beneath grating structure
- d=1450nm / fill factor 0.47
- Efficiencies:

$$\begin{aligned} \eta_0^2 &= 92.368\,\% \\ \eta_1^2 &= 5.914\,\% \\ \eta_2^2 &= 0.096\,\% \\ \rho_0^2 &= 87.904\,\% \\ \tau_0^2 &= 0.013\,\% \\ \text{Loss} &= 0.268\,\% \end{aligned}$$



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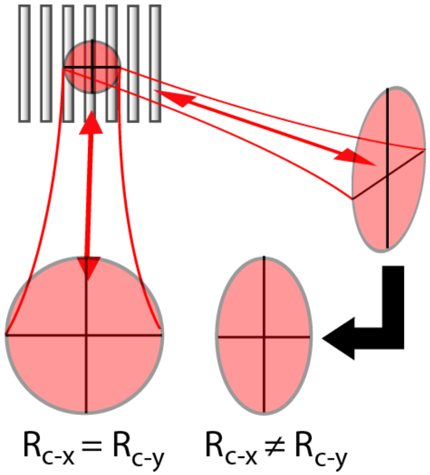
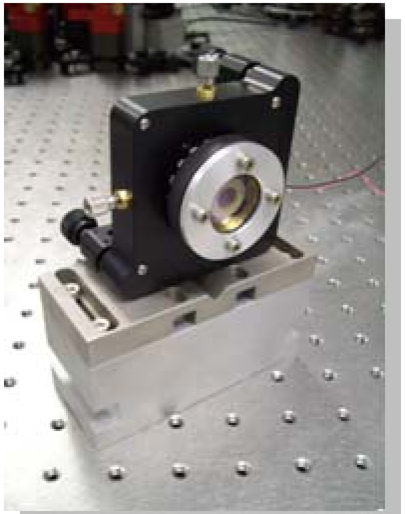
Facts II





- Elliptical beam profile due to different diffraction angles
- Modematching in two dimensions (cylindrical lenses)
- PR-mirror with two different radii of curvature (toroidal mirror)

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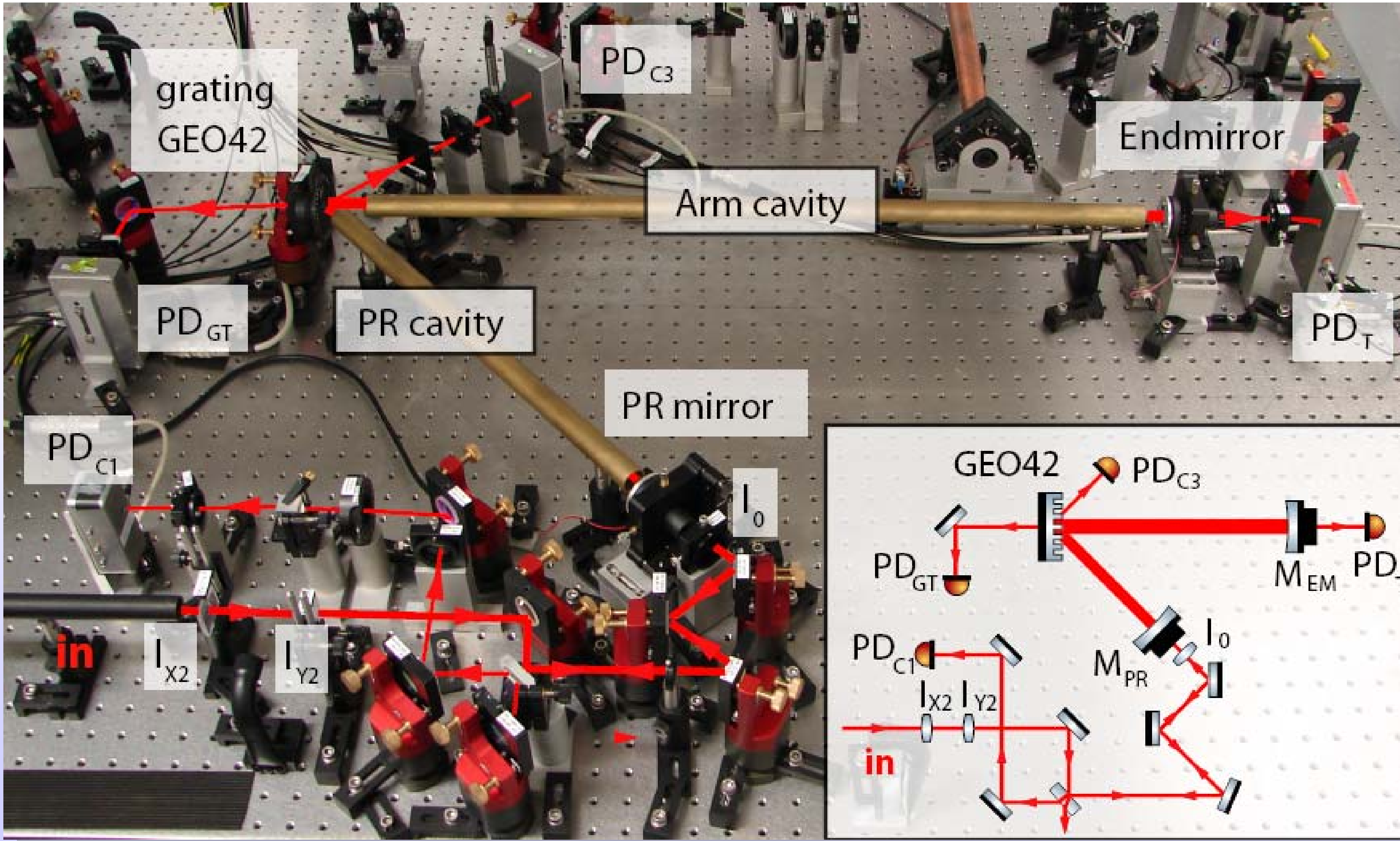
Grating Cavity + Power Recycling



Power build-up in arm w.r.t. input : ca. 300 (Britzger)

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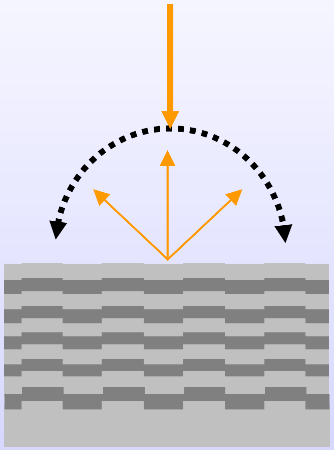
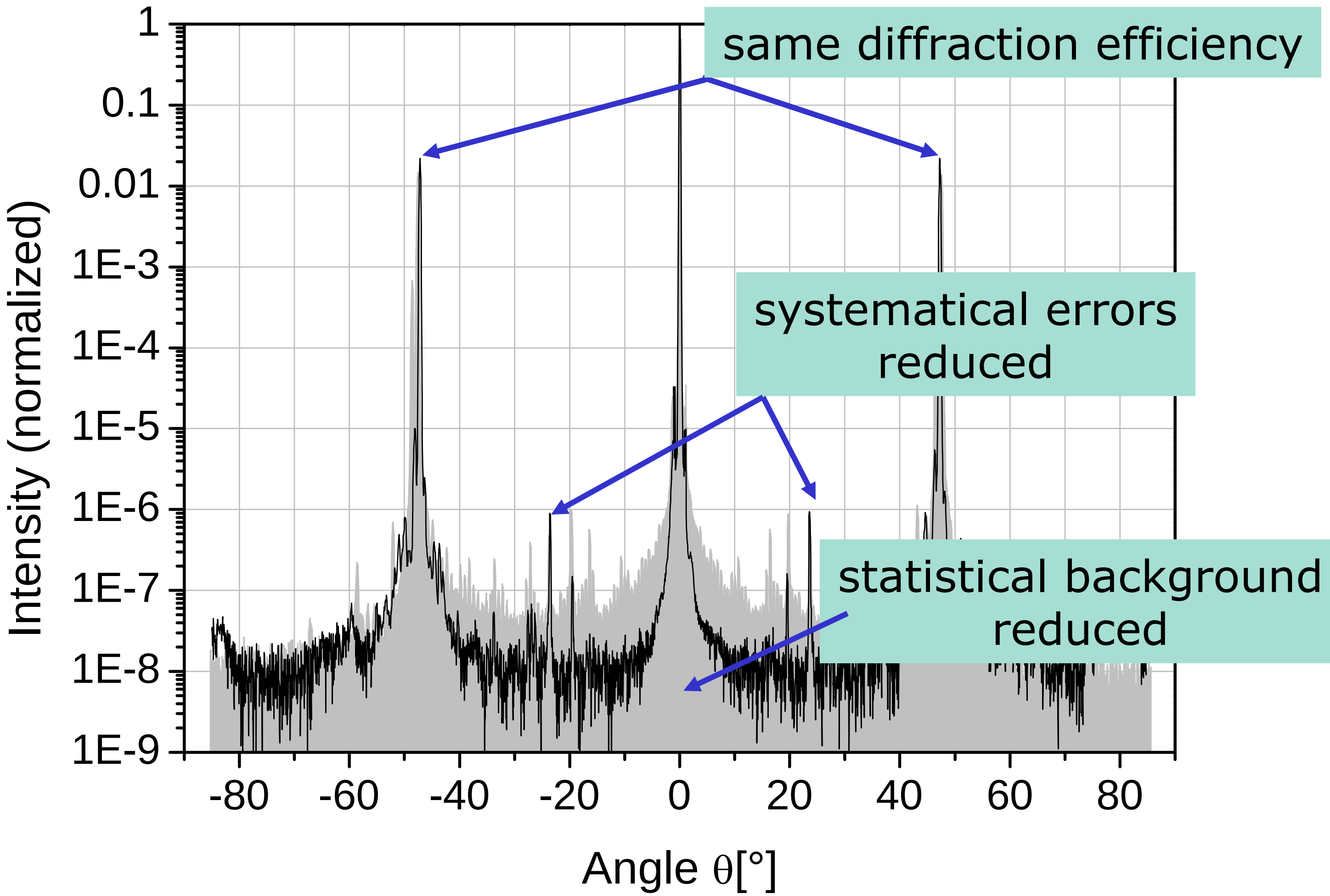
Reduced scattering by over-coating

Small fill factor

groove depth 40nm
fill factor 50%





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Reducing scattering by over-coating

- Grating changes dielectric stack performance. Hard to predict
- Stack changes grating performance hard to predict
- Grating manufacturing process improvements -> less scattering -> over coating will probably not be used in the future

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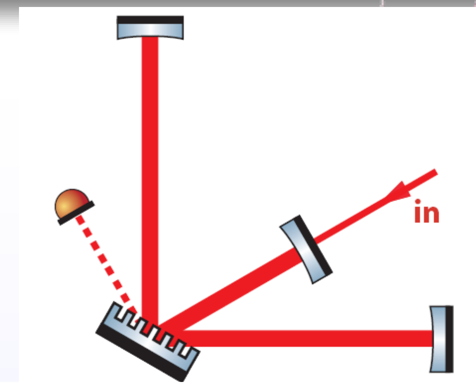
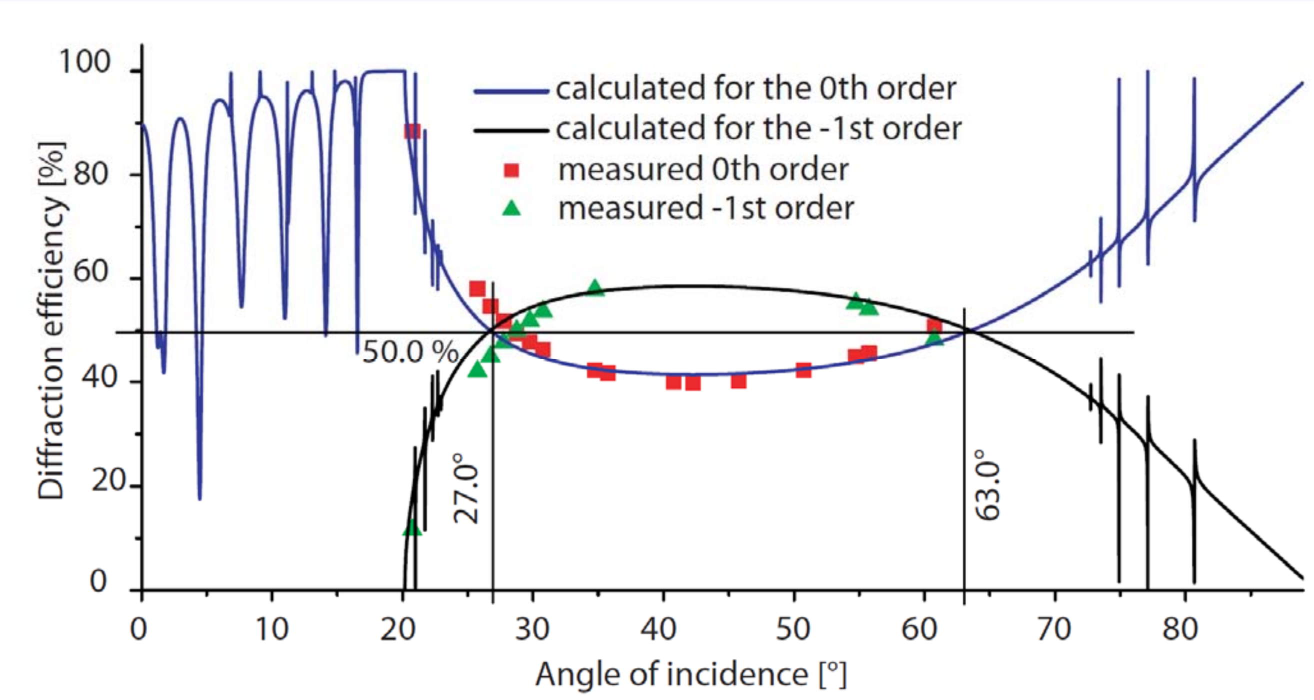
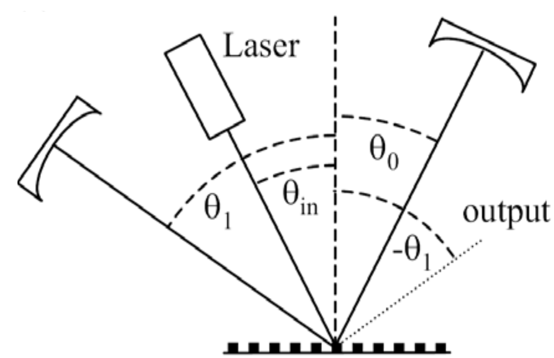
50/50 beamsplitter

- Interesting for GEO-like ifos,
- since full power at BS







Friedrich et al., Journal of Physics: Conference Series **122 (2008) 012018**

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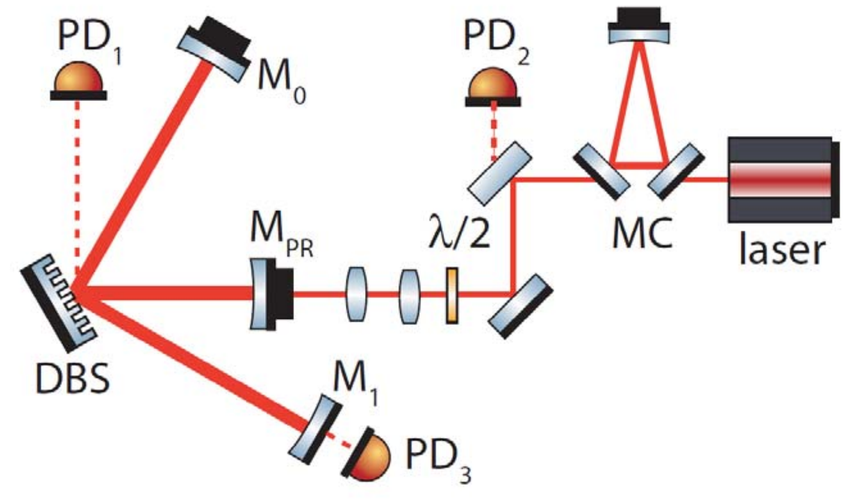
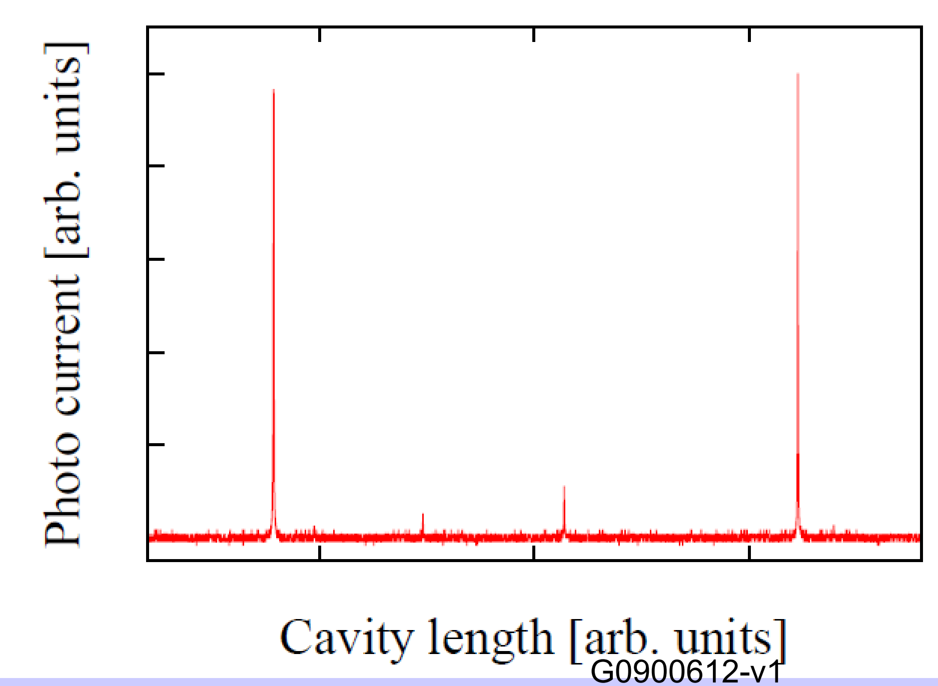
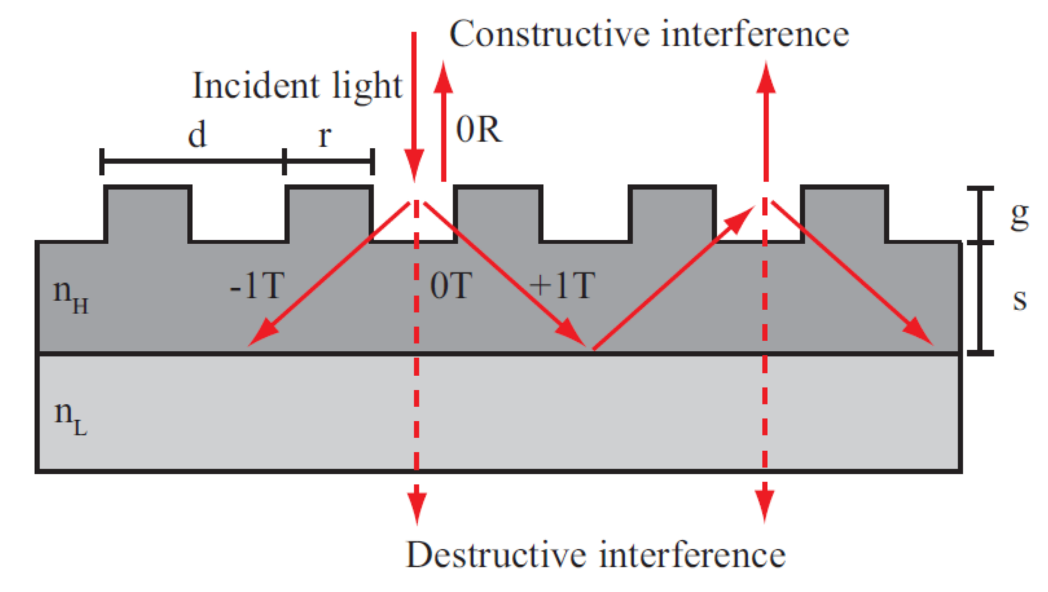
Grating BS Experiment





Finesse PRC ~880
Intra cavity losses 0.46%

Waveguide coatings



$$\begin{aligned} d &< \lambda \quad \text{(to permit only zeroth order in air)}, \\ \lambda/n_H &< d \quad \text{(first orders in high-index layer)}, \\ d &< \lambda/n_L \quad \text{(only zeroth order in the substrate)} \end{aligned}$$

Brückner *et al.*, OPTICS EXPRESS, **17**, No. 1, pp. 163-, (2009)

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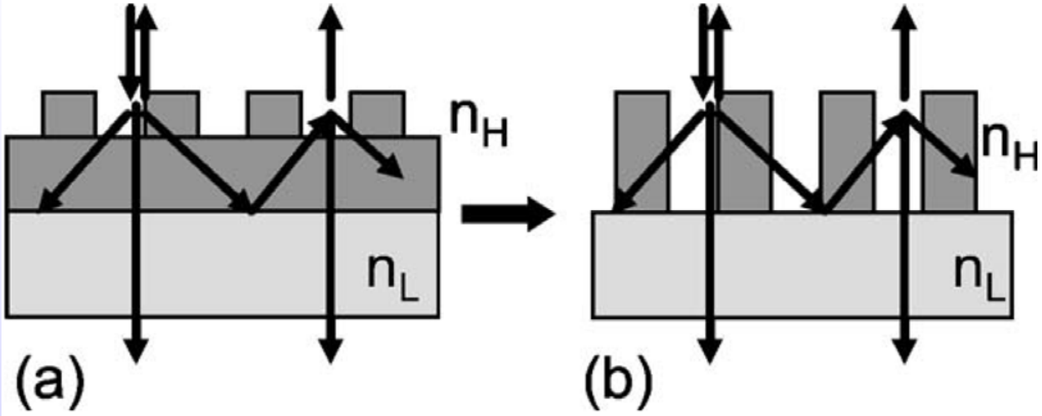
Nanostructured Surfaces

•Reduce the waveguide to the grating itself and still fullfil conditions for waveguiding
•Replace intuition by solving Maxwell equations for optimization



Monolithic 100% reflection “coating”
[Brückner *et al.*, Opt. Lett., 33, 264 (2008)]

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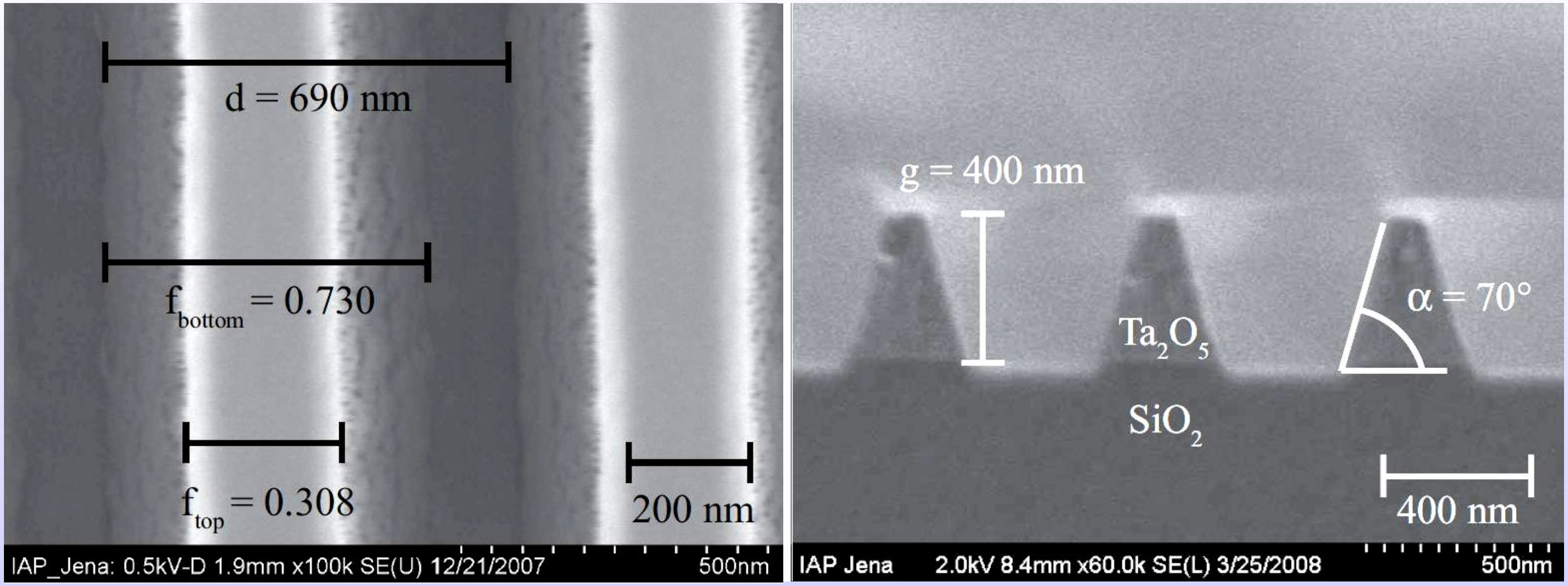
Experimental realization

Compound structure SIO_2 / Ta_2O_5



99.1% reflectivity realized:

Brückner *et al.*, OPTICS EXPRESS, **17**, No. 1, pp. 163--, (2009)

Contrast enhanced for better visibility

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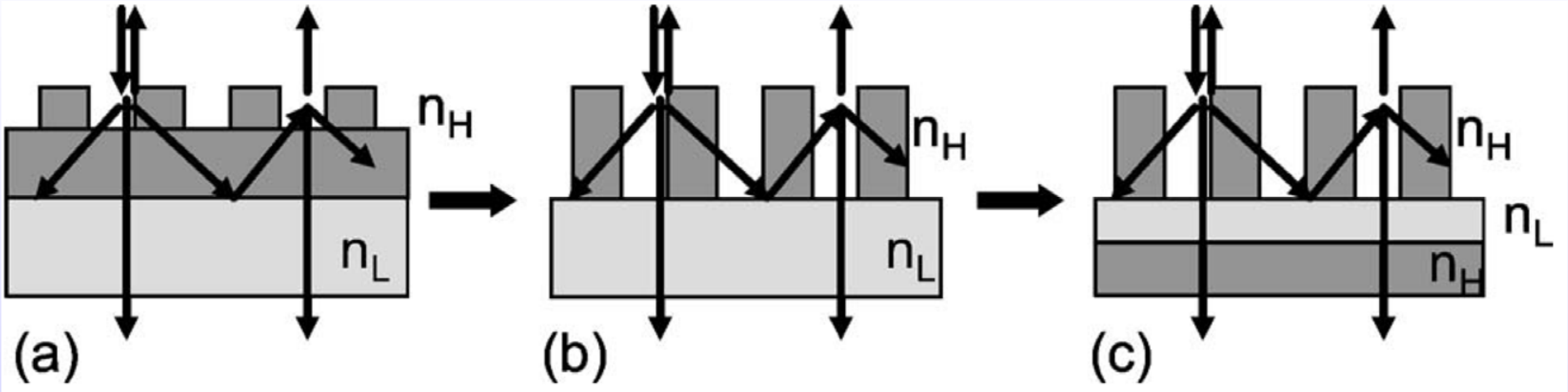
Nanostructured Surfaces



Monolithic 100% reflection “coating”

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

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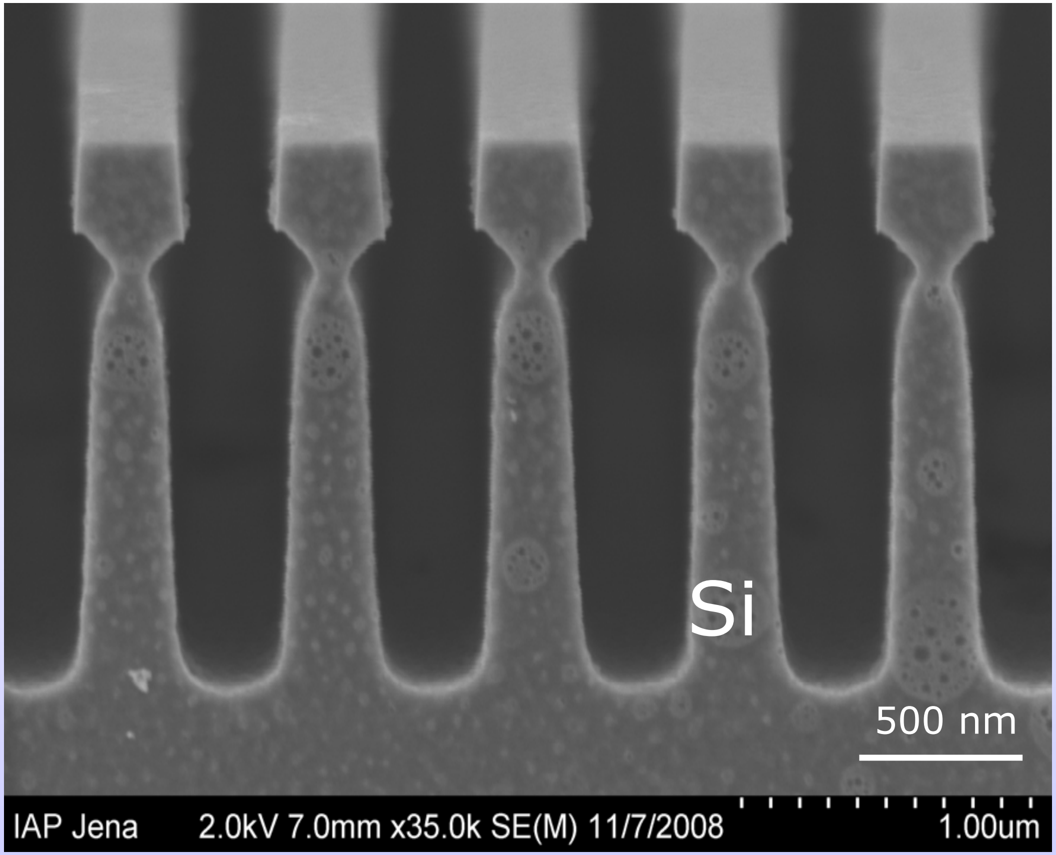
Promising new results



R > 99.8%, private communication, Brückner via Schnabel

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Numbers

Application	Performance
Littrow 1st order	Efficiency 99.6%
Littrow 2nd order	Finesse 1580
BS	Losses 0.46%
Wave-guide coating	Reflectivity >99.8%

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Lateral motion of the wave-guide structure

The arguments:

- Symmetry of the problem
- rigorous calculation shows no phase change
- Diffraction order changes sign

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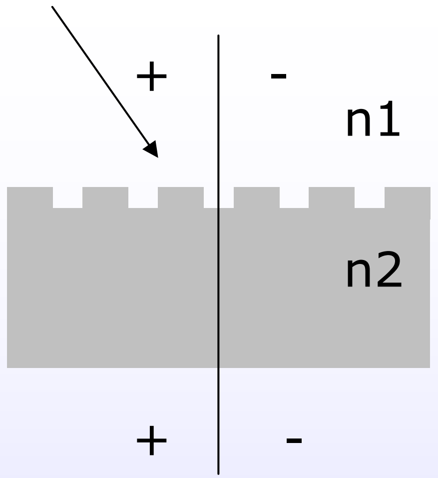
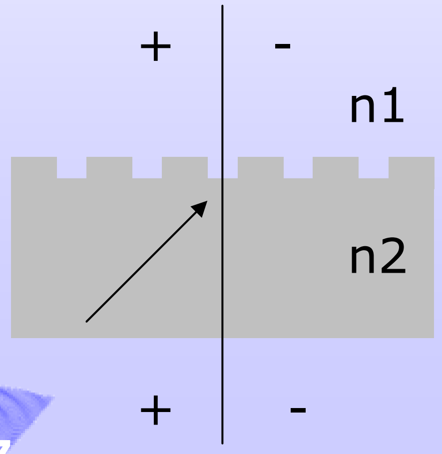
Sign convention and corresponding grating equation



Light coming from Superstrate

Refl.: n1*sin(out)+n1*sin(in)=mL/d

Trans.: n2*sin(out)+n1*sin(in)=mL/d



Light coming from Substrate

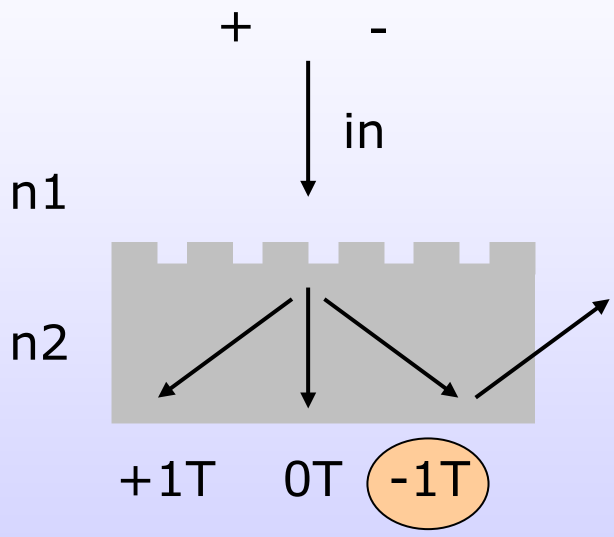
Refl.: n2*sin(out)+n2*sin(in)=mL/d

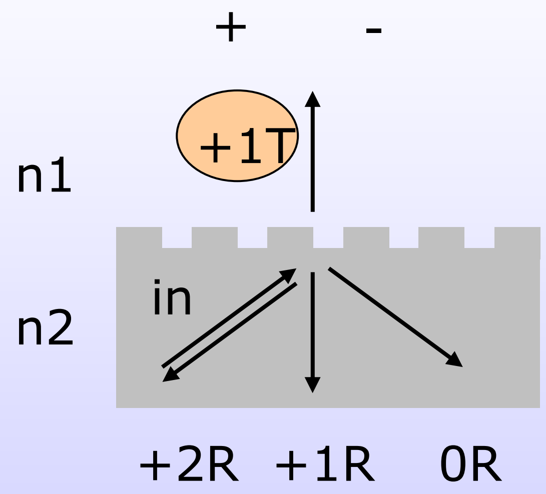
Trans.: n1*sin(out)+n2*sin(in)=mL/d

Refl.: n2*sin(out)+n2*sin(in)=m

Trans.: n2*sin(out)+n1*sin(in)=mL/d

Trans.: n1*sin(out)+n2*sin(in)=m





-> Between coupling in and out the sign of the diffraction order switches

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