Low-loss Grating for Coupling to a High-Finesse Cavity

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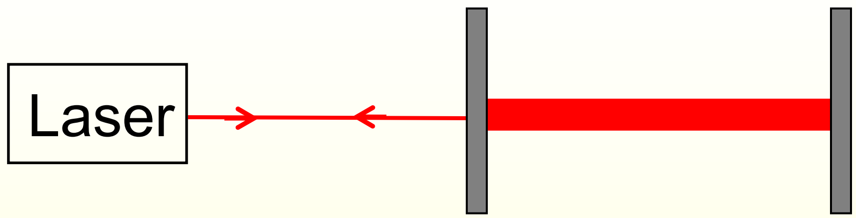
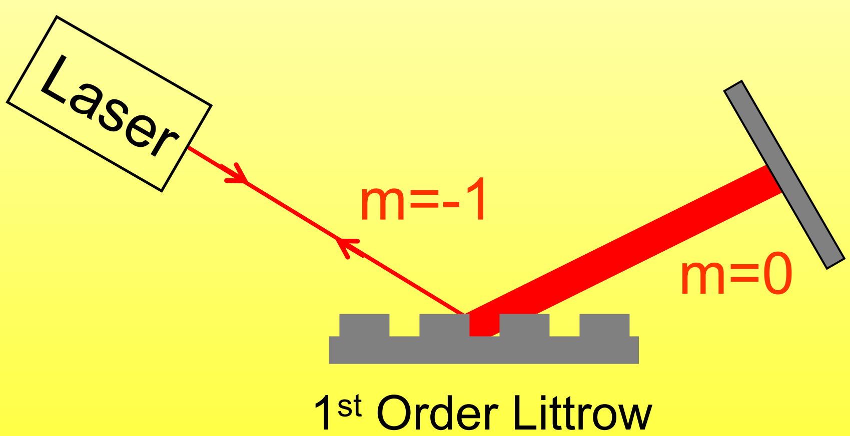
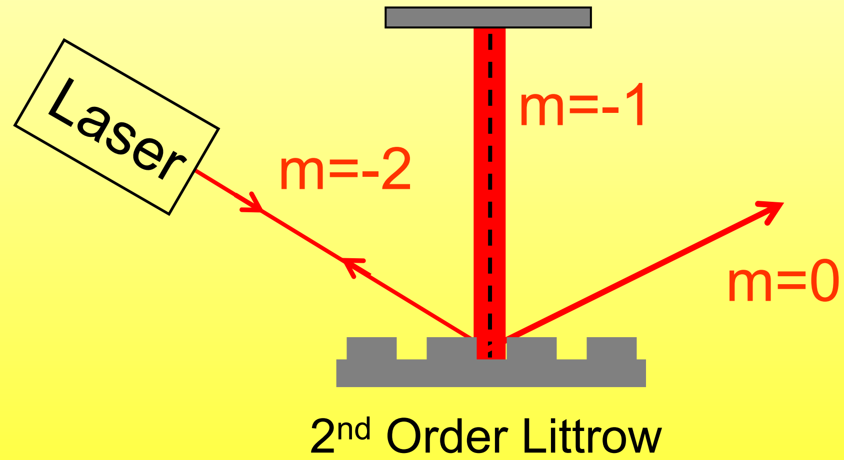


Is it possible to couple light to a cavity without transmission?





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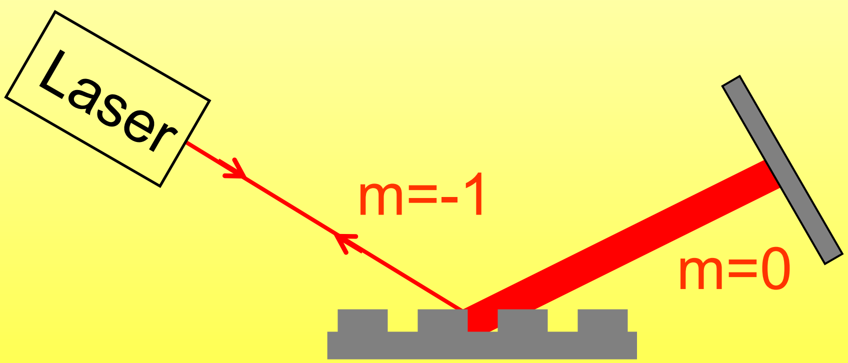
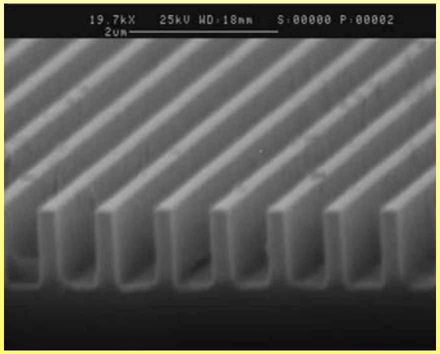


1st Order Littrow

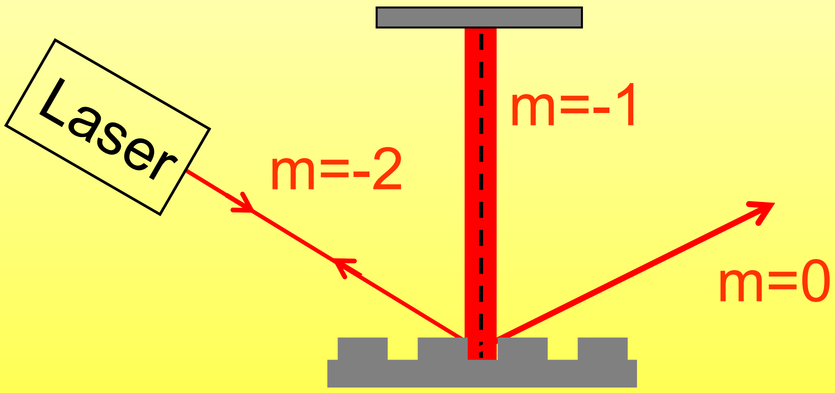


Deep grating structure for high diffraction efficiencies

Is it possible to couple light to a cavity without transmission?

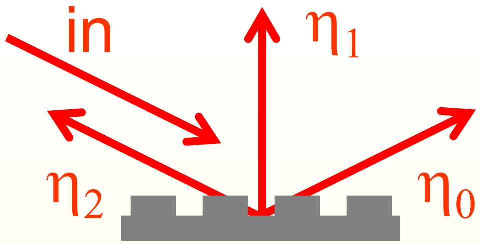
Advantage:

- Cavity finesse is limited by specular reflectivity (>99.99% seems possible)
- Low diffraction efficiency
- Shallow structures
- Low scattering loss



2nd Order Littrow

Coupler / 2nd Order Littrow



Grating equation:

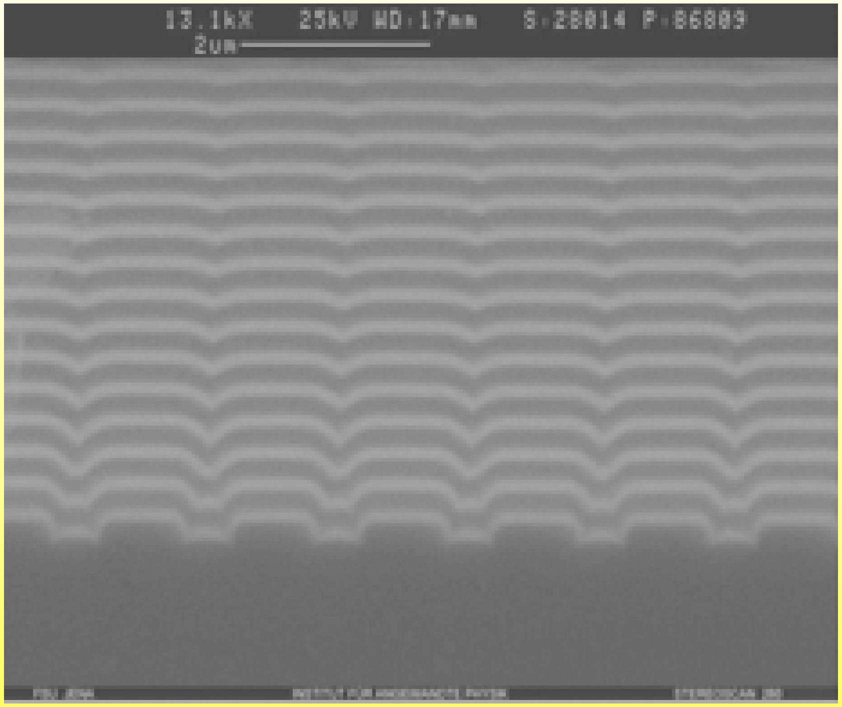
$$\sin\theta_{in} + \sin\theta_m = \frac{m\lambda}{d}$$

$$\Rightarrow \qquad \theta_{in,Litt} = 47.2°$$

for d=1450 nm (grating period),
λ =1064 nm, |m|=2.

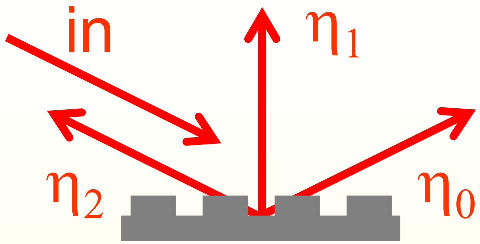
<u>Suggested design values for coupling amplitudes:</u>

$\eta_0{}^2$=99%,
$\eta_1{}^2$=1%,
$\eta_2{}^2$ as small as possible,
ρ^2 (0°)=98%,
no transmission at all, low loss



Shallow grating (40 to 50nm) structure with HR stack on top

Coupler / 2nd Order Littrow



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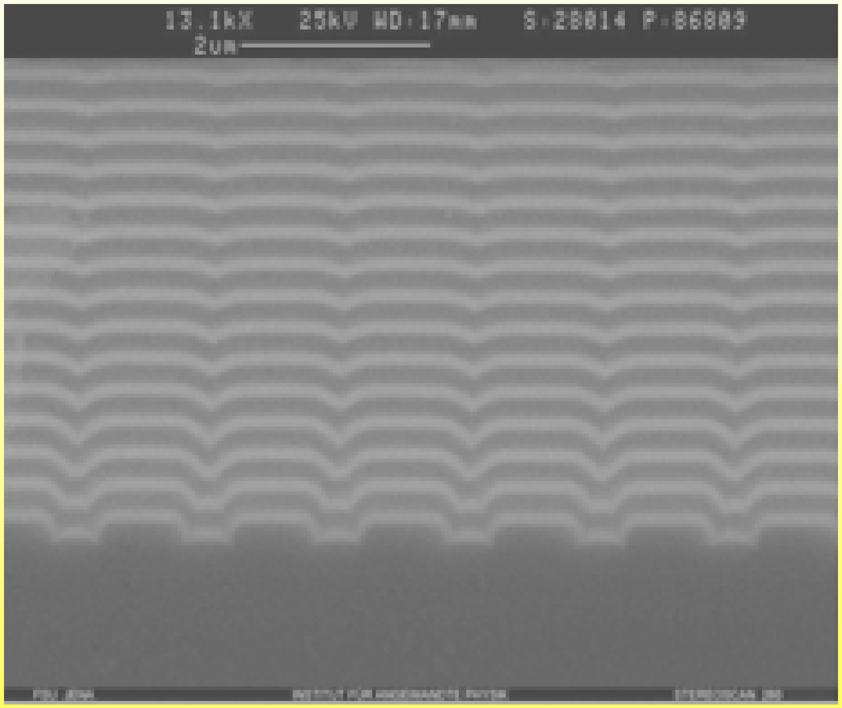
<u>Measured (+measurement inferred) values for coupling amplitudes:</u>

$\eta_0^2 \approx 99.4\%$,
$\eta_1^2 \approx 0.58\%$,
$\eta_2^2 \approx 0.005\%$,
ρ^2 (0°) $\approx 98.8\%$,
Overall loss@0° ≈0.04%



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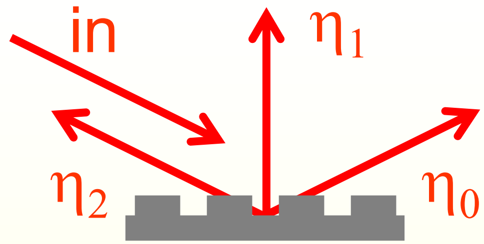

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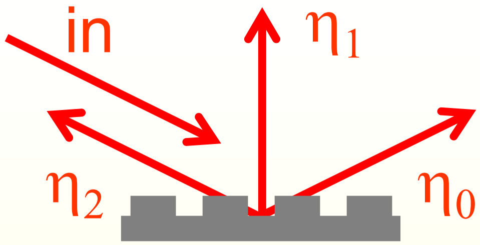

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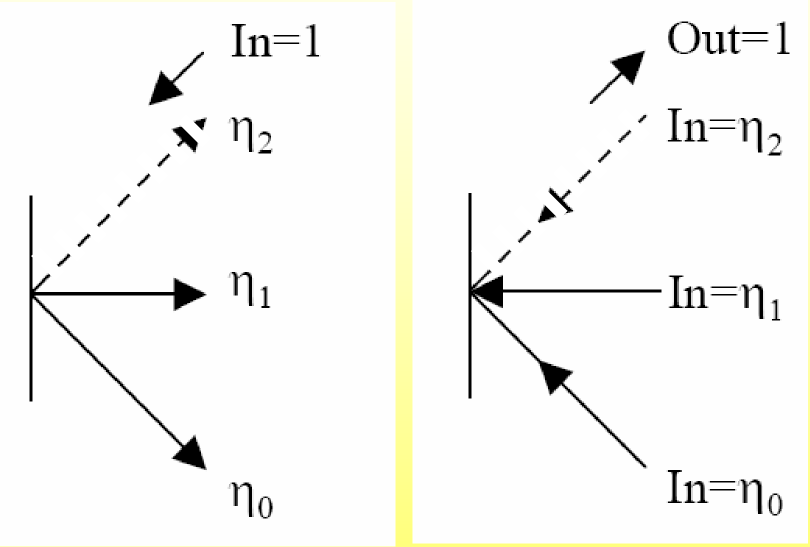
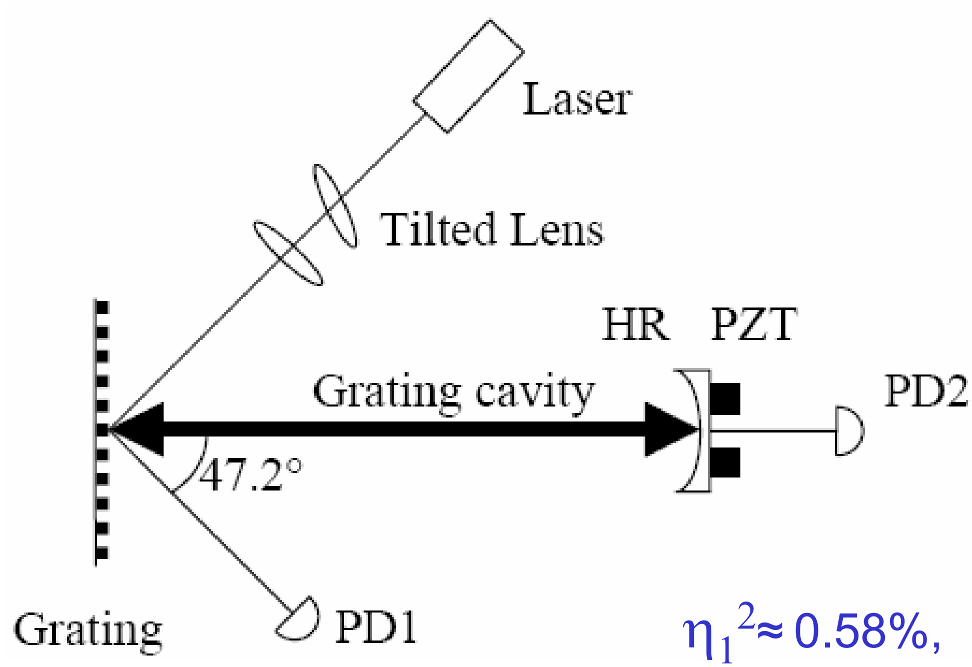


From η_1>0, η_{-1}>0 and time reversal consideration one can deduce η_2>0!
What is the lowest η_2 possible?

FP-Cavity: Coupled 2nd Order Littrow



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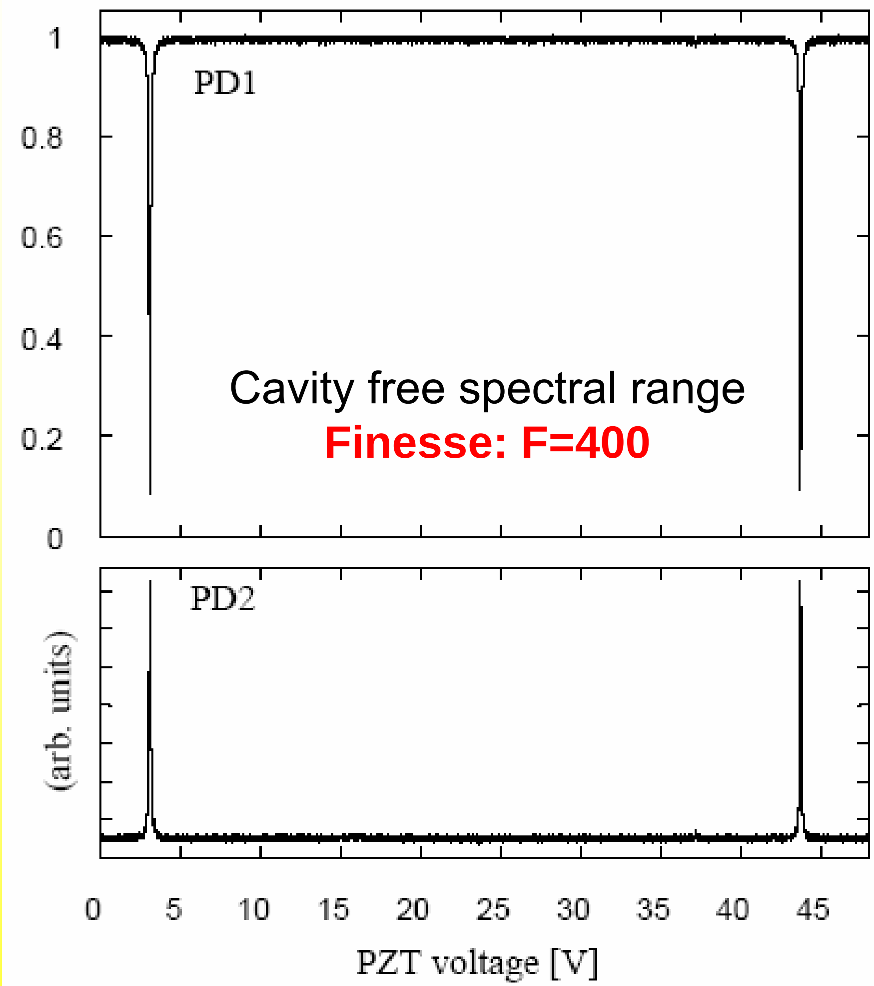
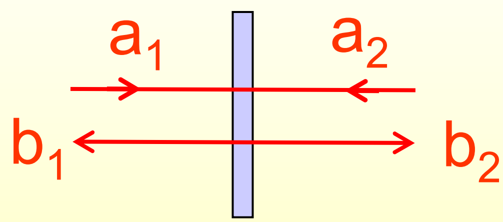


A. Bunkowski *et al.*, Opt. Lett. 29, 2342, (2004)

Coupling Relations of the 2-Port (transmissive) Beamsplitter

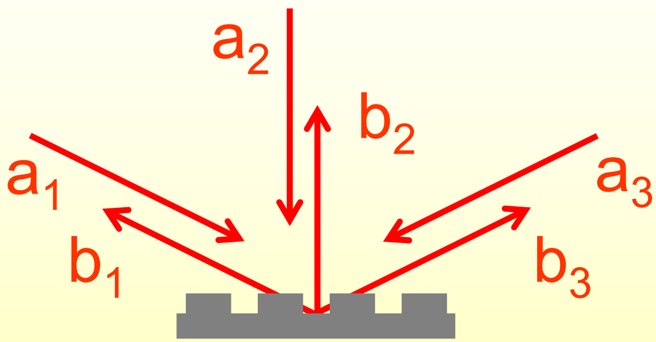


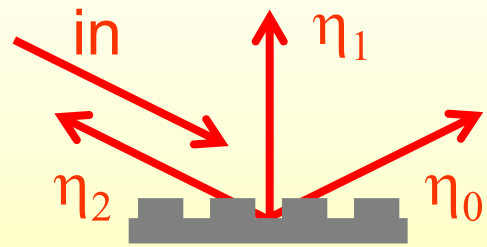
a_i ,b_i : complex field amplitudes

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \times \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \;, \quad \overset{\mathbb{T}}{S}{}^{*}_{2p} \overset{\mathbb{T}}{S}_{2p} = \mathrm{I}$$

$$\Rightarrow \quad \overset{\mathbb{T}}{S}_{2p} = \begin{pmatrix} \rho & \tau \\ \tau & -\rho \end{pmatrix} \qquad \text{or} \qquad \overset{\mathbb{T}}{S}_{2p} = \begin{pmatrix} \rho & i\tau \\ i\tau & \rho \end{pmatrix}$$

Coupling Relations of the 3-Port (reflective) Beamsplitter





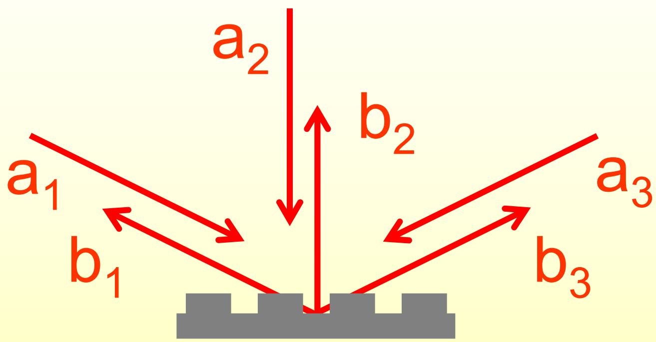
$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} \eta_2 e^{i\phi_2} & \eta_1 e^{i\phi_2} & \eta_0 e^{i\phi_0} \\ \eta_1 e^{i\phi_1} & \rho_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} \\ \eta_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} & \eta_2 e^{i\phi_2} \end{pmatrix} \times \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}, \quad \overset{\mathbf{T}}{S}{}^{*}_{3p} \overset{\mathbf{T}}{S}_{3p} = \mathrm{I}$$

$$\Rightarrow \quad \begin{matrix} \rho_0^2 + 2\eta_1^2 = 1 \\ \eta_0^2 + \eta_1^2 + \eta_2^2 = 1 \end{matrix}$$

and

$$\frac{(1-\rho_0)}{2} \le \eta_2 \le \frac{(1+\rho_0)}{2}$$

Coupling Relations of the 3-Port (reflective) Beamsplitter



$$\phi_0 = 0$$

$$\phi_1 = -(1/2)\arccos\left[\left(\eta_1^2 - 2\eta_0^2\right)/\left(2\rho_0\eta_0\right)\right]$$

$$\phi_2 = \arccos\left[-\eta_1^2/\left(2\eta_2\eta_0\right)\right]$$

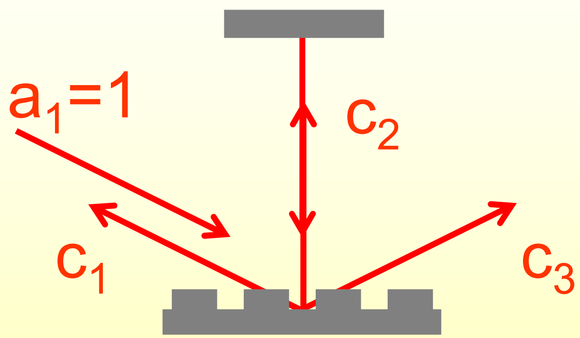
$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} \eta_2 e^{i\phi_2} & \eta_1 e^{i\phi_2} & \eta_0 e^{i\phi_0} \\ \eta_1 e^{i\phi_1} & \rho_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} \\ \eta_0 e^{i\phi_0} & \eta_1 e^{i\phi_1} & \eta_2 e^{i\phi_2} \end{pmatrix} \times \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}, \quad \overset{\mathrm{T}}{S}{}^{*}_{3p} \overset{\mathrm{T}}{S}_{3p} = \mathrm{I}$$

$$\Rightarrow \quad \boxed{\begin{aligned} \rho_0^2 + 2\eta_1^2 &= 1 \\ \eta_0^2 + \eta_1^2 + \eta_2^2 &= 1 \end{aligned}}$$

and

$$\boxed{\frac{(1-\rho_0)}{2} \le \eta_2 \le \frac{(1+\rho_0)}{2}}$$

3-Port Coupled FP Cavity



$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \mathbf{S}_{3p}^{\mathbf{T}} \times \begin{pmatrix} 1 \\ c_2 \exp(2i\phi) \\ 0 \end{pmatrix} ,$$

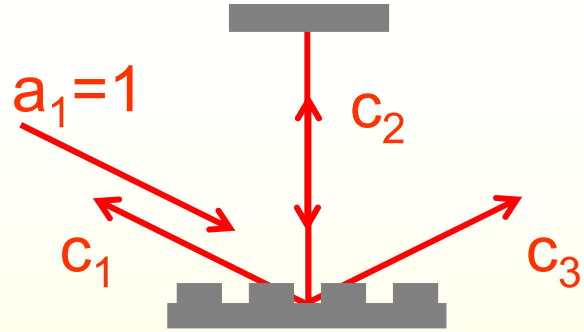
$$c_1 = \eta_2 \exp(i\phi_2) + \eta_1^2 \exp[2i(\phi_1 + \phi)]d$$

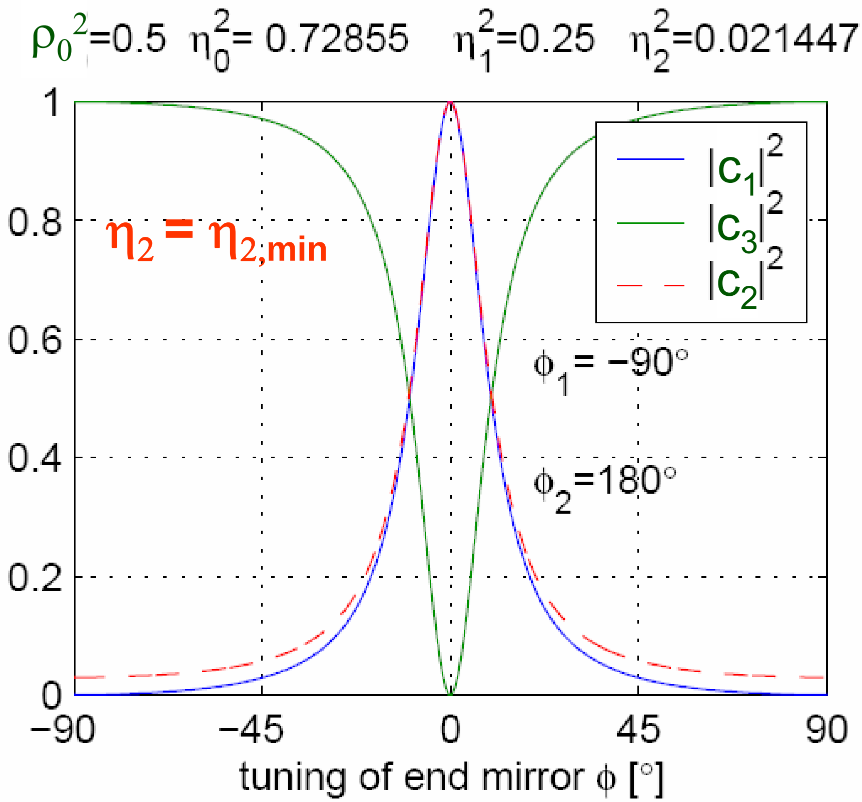
$$\Rightarrow \quad c_2 = \eta_1 \exp(i\phi_1)d$$

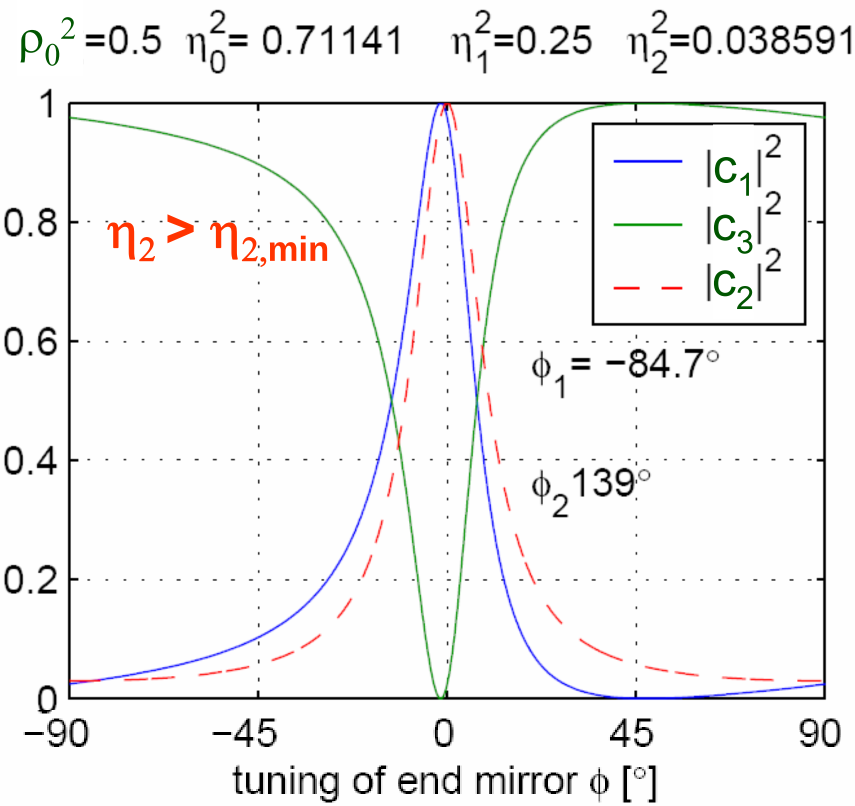
$$c_3 = \eta_0 + \eta_1^2 \exp[2i(\phi_1 + \phi)]d$$

$$d = \frac{1}{\rho_0 \exp(2i\phi)}$$

3-Port Coupled FP Cavity







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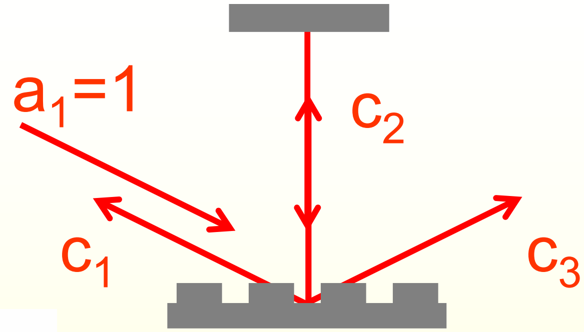
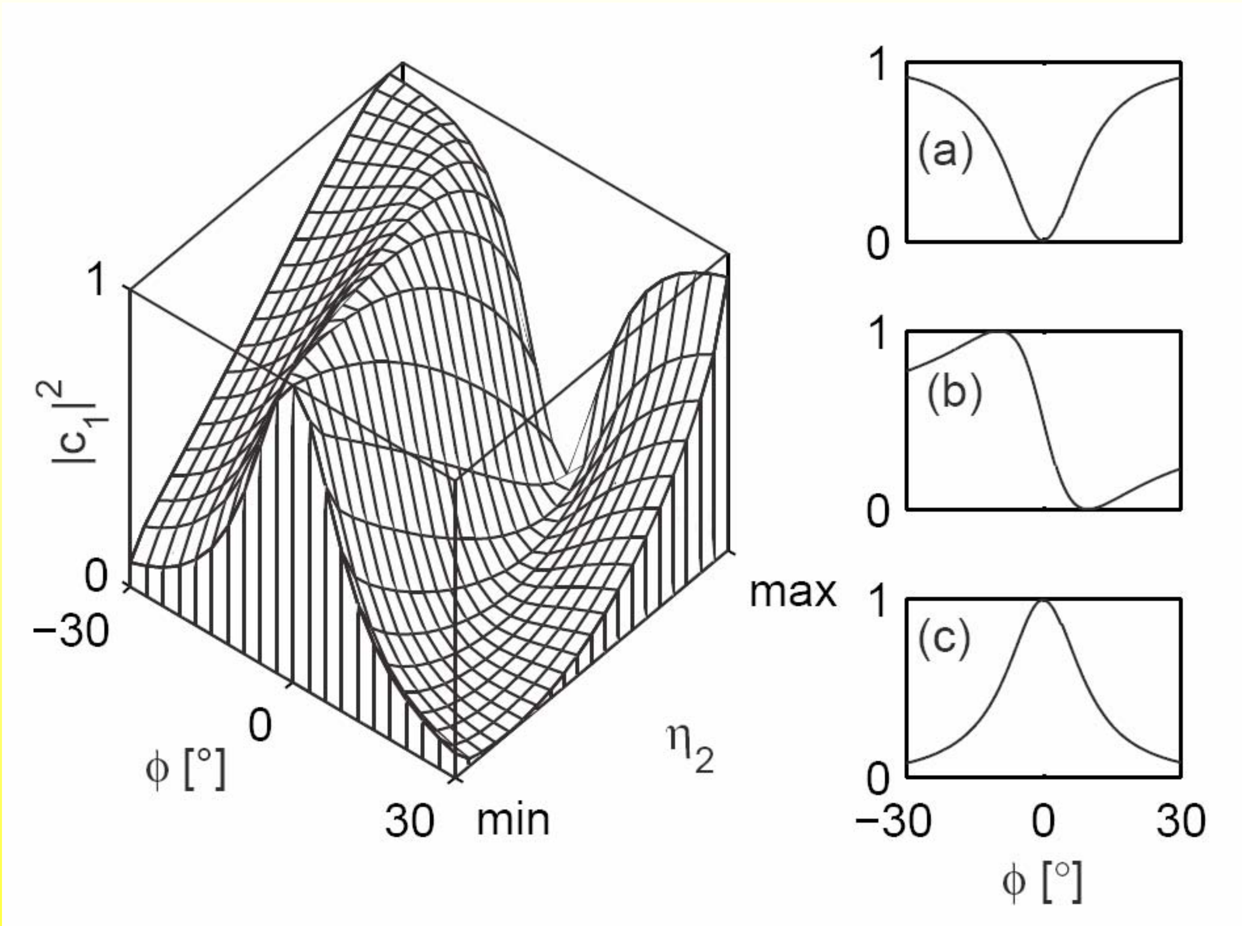


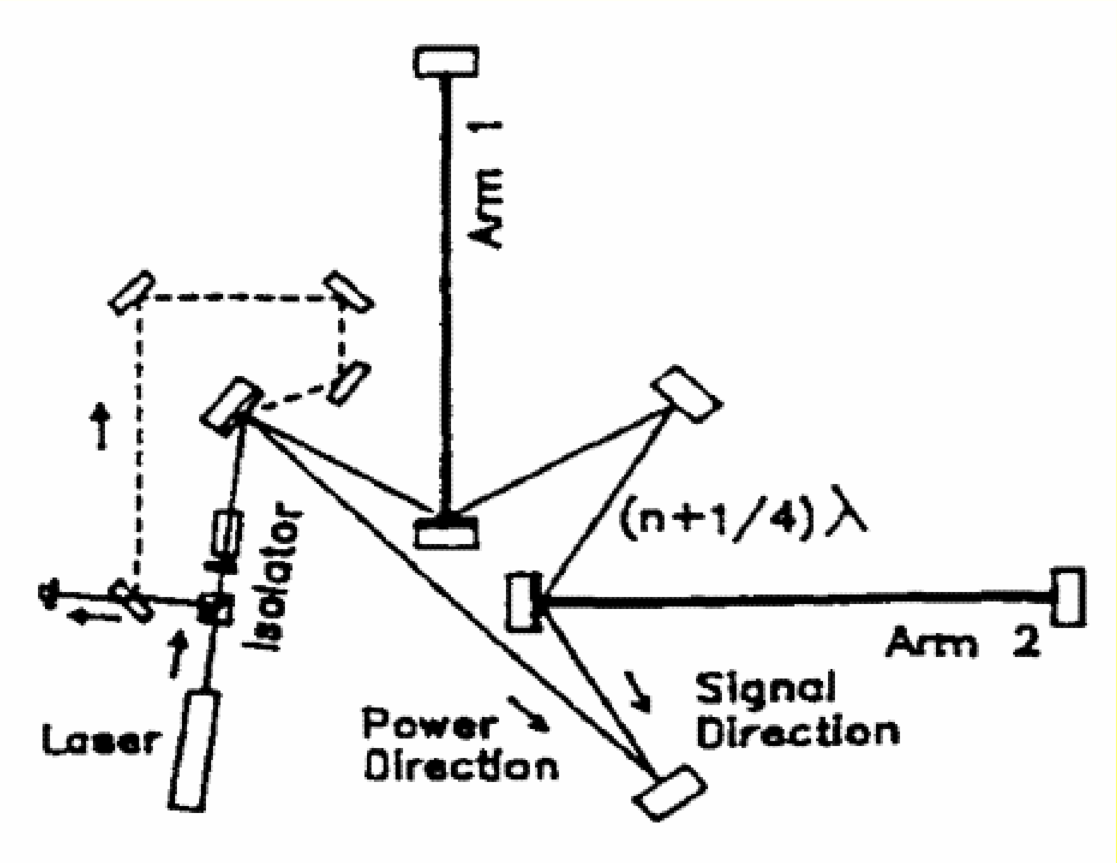


Gratings with minimum η_2 provide a dark port (c_3=0) for a tuned cavity and enables power recycling.

Summary

- A low loss reflective coupler to a cavity of Finesse 400 has been demonstrated.
- Phase relations of the three-port coupler are understood.
- Our results show that low efficiency, 3-port gratings are very promising for high power interferometers.

All-reflective Grating IFO



Proposed by R. Drever

3-Port Coupled FP Cavity