Performance optimization of volume gratings with finite size through numerical simulation

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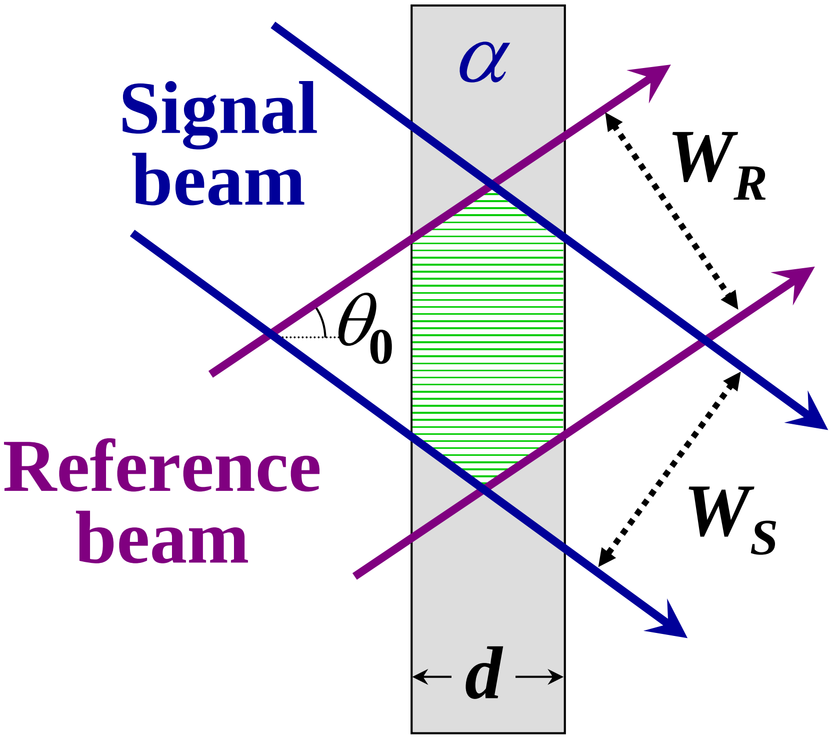
- **Introduction/motivation**
- **Simulation method**
  - **2-D coupled wave equation for "overlap gratings"**
- **Initial results**
  - **verify against Kogelnik**
  - **apodization of wavelength selectivity**
- **Conclusions**

"2-D restricted" volume gratings



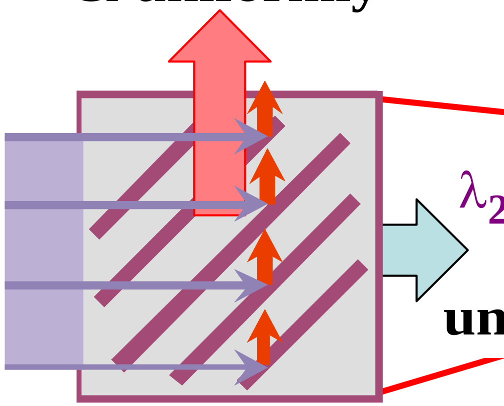
These can offer...

- the spatial- and spectral-shaping properties of volume gratings;
- 3-port devices easily cascaded at or near 90 degrees.

Applications of "2-D restricted" volume gratings

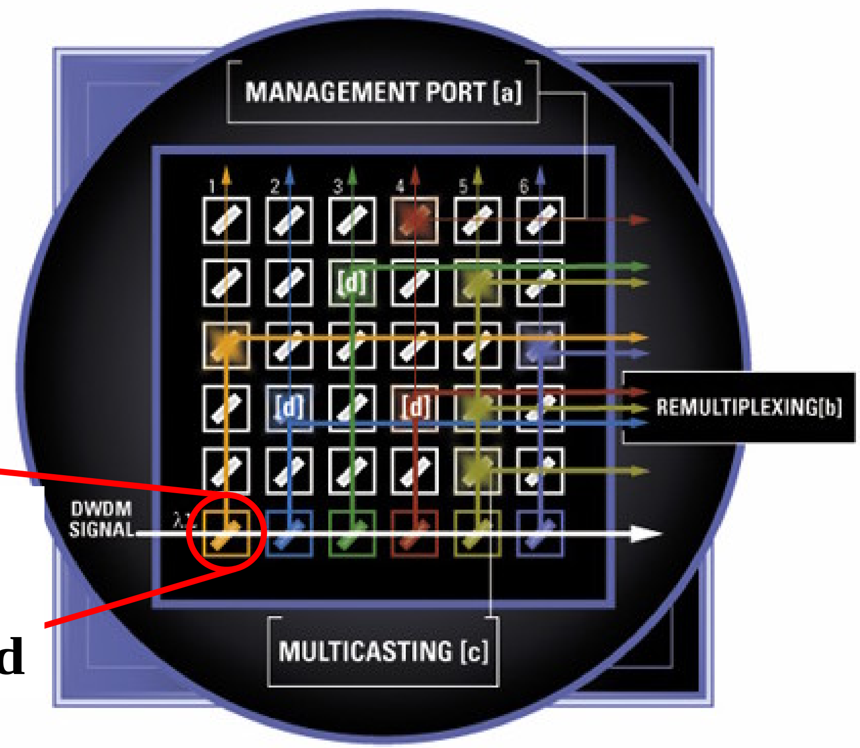
1) Electroholographic WDM switches

λ_1 **diffracts efficiently & uniformly**



input
λ_1, λ_2

λ_2 **passes thru unchanged**



trellis photonics
inherently different

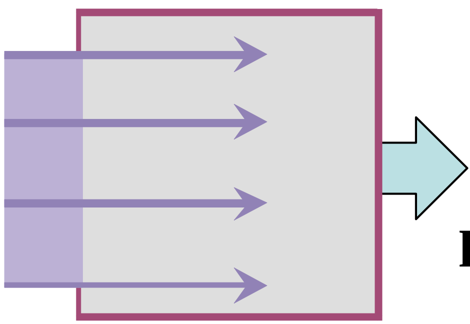
[1] B. Pesach, G. Bartal, E. Refaeli, A. J. Agranat, J. Krupnik, and D. Sadot, Applied Optics, **39**(5), 746 (2000).

Applications of "2-D restricted" volume gratings

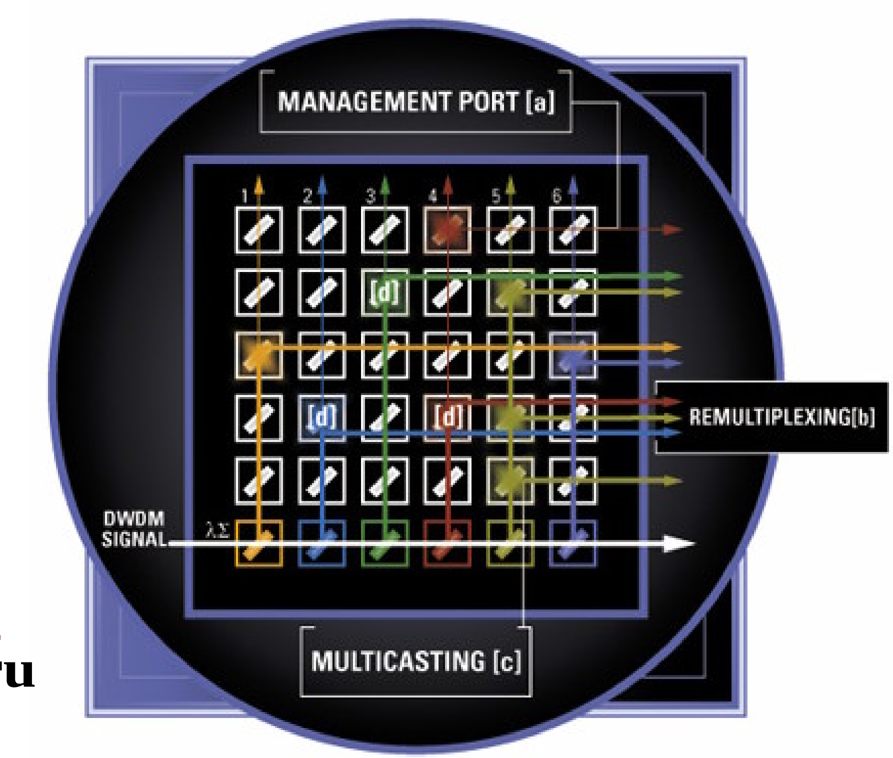
1) Electroholographic WDM switches

But if grating strength depends on applied DC field...

input
λ_1, λ_2



Both
λ_1 & λ_2
pass thru



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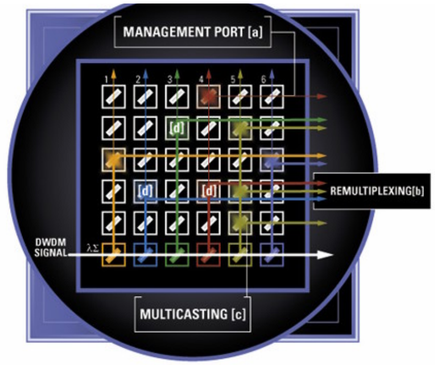
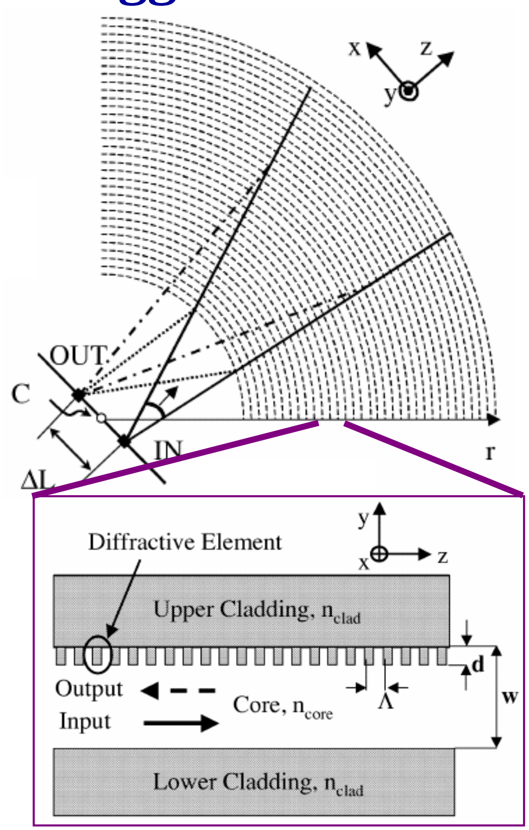
Applications of “2-D restricted” volume gratings

1) Electroholographic WDM switches

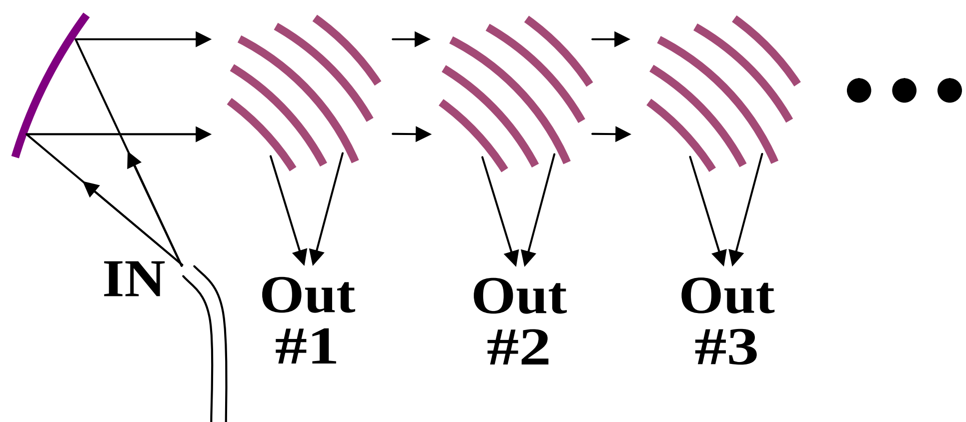


2) Planar holographic Bragg reflectors



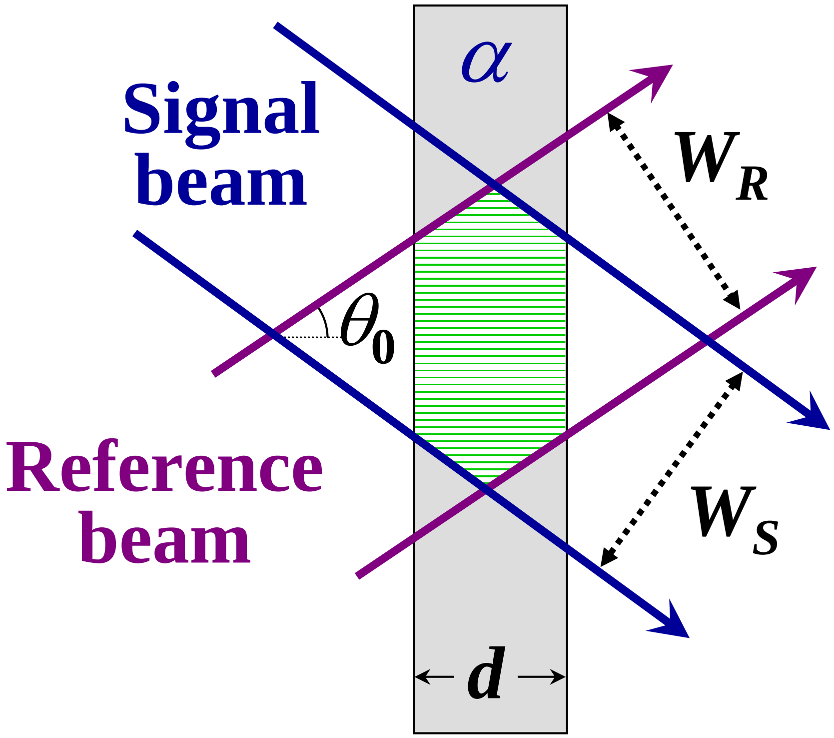
Possible extension:

cascading using the 90deg geometry?



[1] C. Greiner, D. Iazikov, and T. W. Mossberg, J. Lightwave Technology, **22**(1), 136 (2004).

"2-D restricted" volume gratings

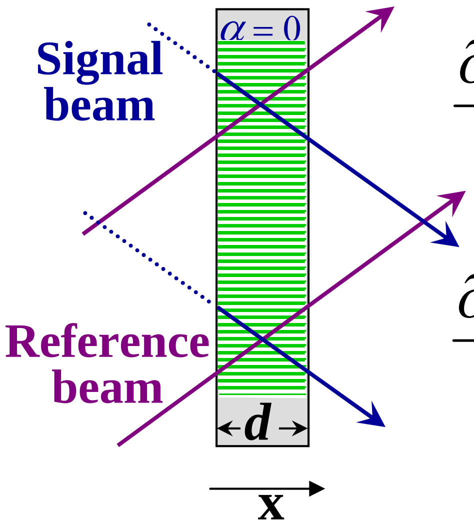


These can offer...

- the spatial- and spectral-shaping properties of volume gratings;
- 3-port devices easily cascaded at or near 90 degrees.
- technically neither a **transmission** nor a **reflection** grating
- must be analyzed by a **2-D coupled wave theory**

Coupled-wave theory

- **Transmission grating**

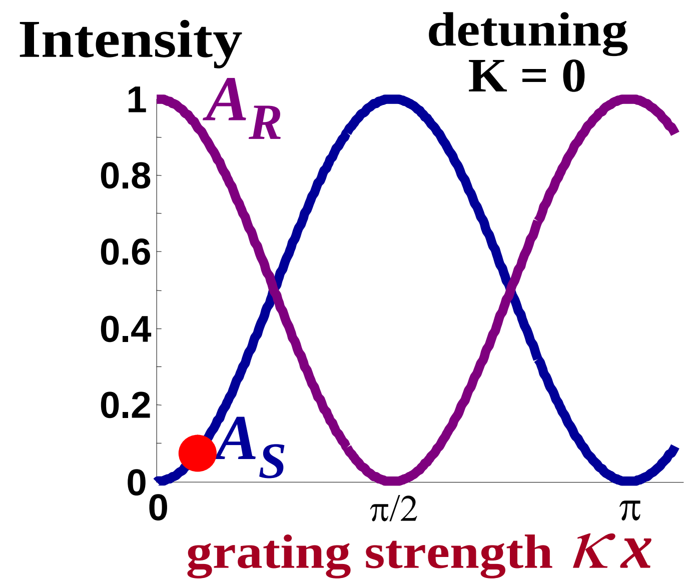


grating strength

$$\frac{\partial A_R}{\partial x} = -j\kappa \exp(-j\mathrm{K}x) A_S$$

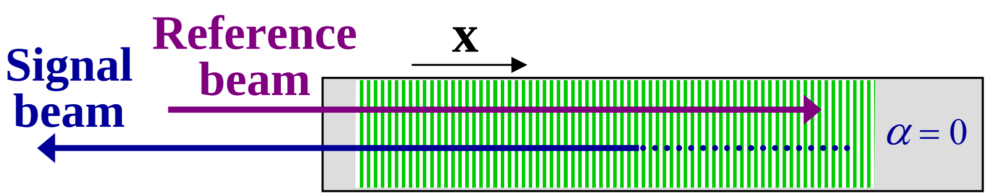
Detuning

$$\frac{\partial A_S}{\partial x} = -j\kappa \exp(j\mathrm{K}x) A_R$$



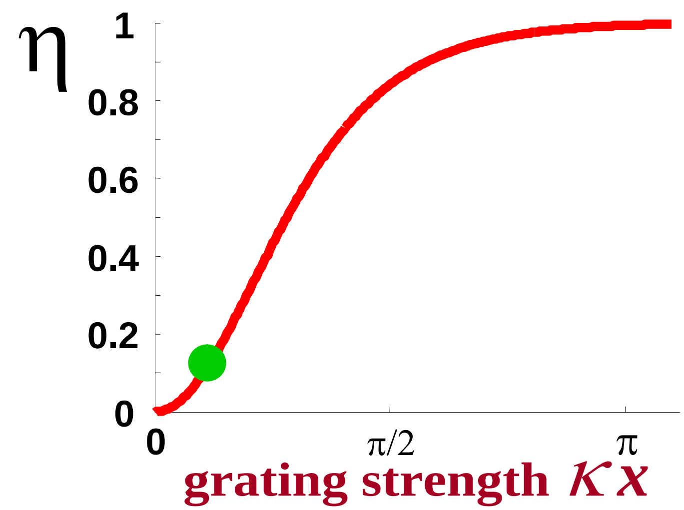
Diffraction efficiency η is <u>uncoupled</u> from output beam-shape!

- **Reflection grating**



$$\frac{\partial A_R}{\partial x} = -j\kappa \exp(-j\mathrm{K}x) A_S$$

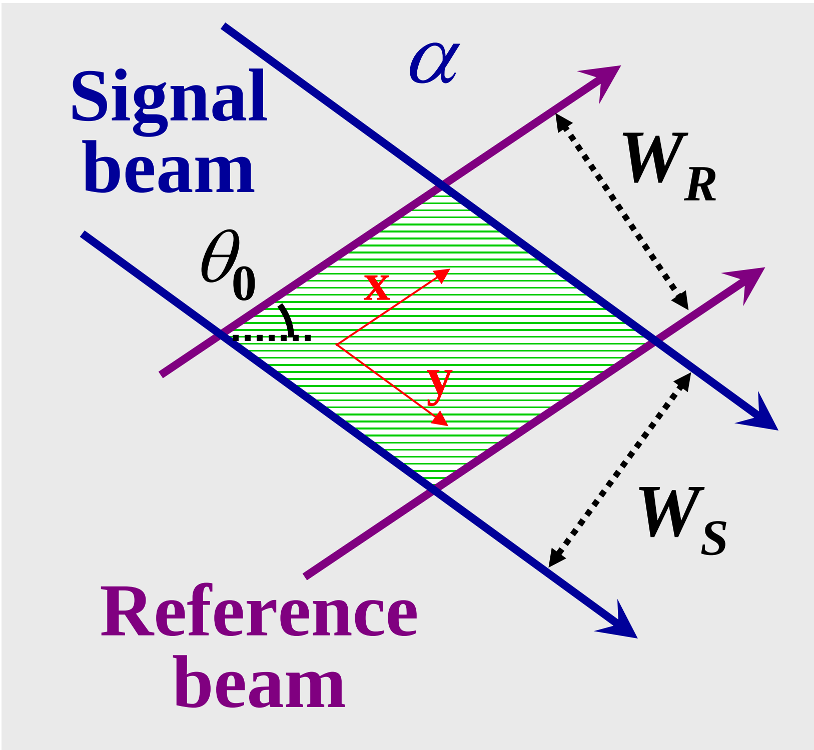
$$\frac{\partial A_S}{\partial x} = j\kappa \exp(j\mathrm{K}x) A_R$$



[1] H. Kogelnik, Bell Sys.Techn. Journal, **48**(9), 2909 (1969).
[2] P. Yeh, Introduction to Photorefractive Nonlinear Optics (1993).

2-D coupled-wave theory

- **“Overlap” grating**



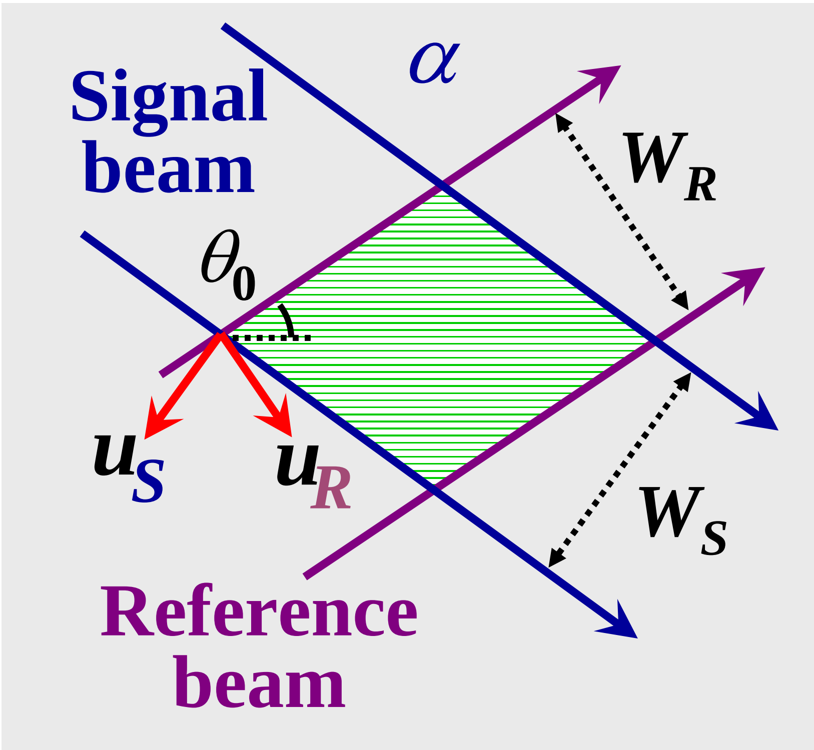
How to modify previous equations?

$$\frac{\partial A_R}{\partial x} = - \quad ???$$

$$\frac{\partial A_S}{\partial y} = \quad ???$$

2-D coupled-wave theory

- **"Overlap" grating**



grating strength

$$\frac{\partial A_R}{\partial u_S} = \frac{\alpha W_S}{\sin 2\theta_0} A_R + j\frac{\kappa W_S}{\sin 2\theta_0}\exp(-j\mathrm{K})A_S$$

Detuning

$$\frac{\partial A_S}{\partial u_R} = -\frac{\alpha W_S}{\sin 2\theta_0} A_S - j\frac{\kappa W_S}{\sin 2\theta_0}\exp(j\mathrm{K})A_R$$

$$0 > u_S > -1 \qquad 0 < u_R < \frac{W_R}{W_S}$$

A_1 and A_2 include all amplitude changes due to absorption and beam coupling.

Any Bragg mismatch (due to deviations in readout angle θ or wavelength λ) is described by the Bragg mismatch parameter, K:

$$\mathrm{K} = \frac{2\pi W_S}{\lambda_0}\left[\left(u_R + u_S \cos 2\theta_0\right)\Delta\theta + \left(u_R + u_S\right)\tan\theta_0 \frac{\Delta\lambda}{\lambda_0}\right]$$

[1] P. St. J. Russell, L. Solymar, Optica Acta **26**, 329 (1979).

Corrected analytical solution

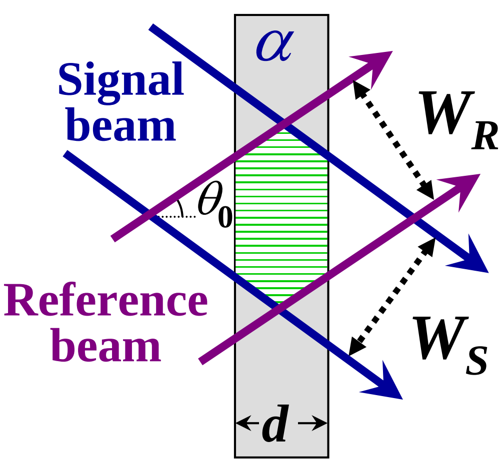
$$E_R = \exp\left[-\alpha' W_S \left(u_R \cos 2\theta_0 - u_S\right)\right] a_1(u_R) - \exp\left[-\alpha' W_S \left(u_R - u_S\right)\right] \exp\left(-j\delta W_S u_R\right)$$
$$\times a_{10}(u_R)\kappa' W_S \int_0^{u_R} a_{10}(\tau) a_1(\tau) \sqrt{\frac{M}{L}} J_1\left(2\kappa' W_S \sqrt{LM}\right) \exp\left[\left(2\alpha' \sin^2\theta_0 + j\delta\right) W_S \tau\right] d\tau$$

$$E_S = -j\kappa' W_S a_2(u_S) \exp\left[-\alpha' W_S \left(u_R - u_S\right)\right] \exp\left(j\delta W_S u_S\right)$$
$$\times \int_0^{u_R} a_{10}(\tau) a_1(\tau) J_0\left(2\kappa' W_S \sqrt{LM}\right) \exp\left[\left(2\alpha' \sin^2\theta_0 + j\delta\right) W_S \tau\right] d\tau$$

$$L = \int_\tau^{u_R} {a_{10}}^2(\xi) d\xi \quad M = \int_{u_S}^{0} {a_{20}}^2(\xi) d\xi$$

$$\delta = \frac{1}{2}\beta_0 \sec^2\theta_0 \Delta\theta + \beta_0 \frac{|\lambda_1 - \lambda_0|}{\lambda_0} \tan\theta_0$$

S. Tao, B. Wang, G. W. Burr, and J. Chen, "Diffraction efficiency of volume gratings with finite size: corrected analytical solution," to appear in *Journal of Modern Optics* (2004)

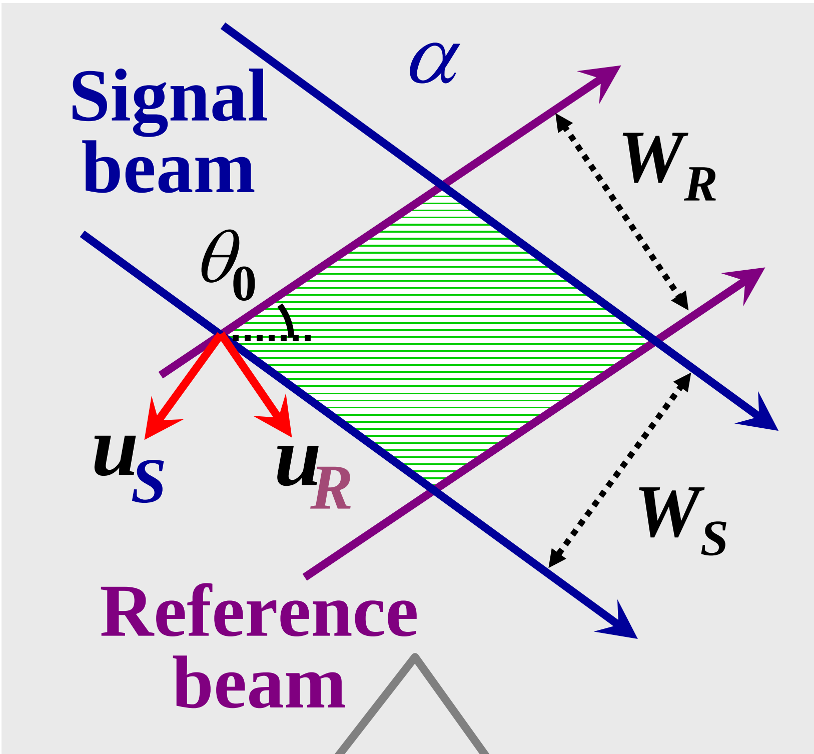


suitable only for uniform grating strength

...we need a numerical solution!

2-D coupled-wave theory: numerical solution

- **"Overlap" grating**

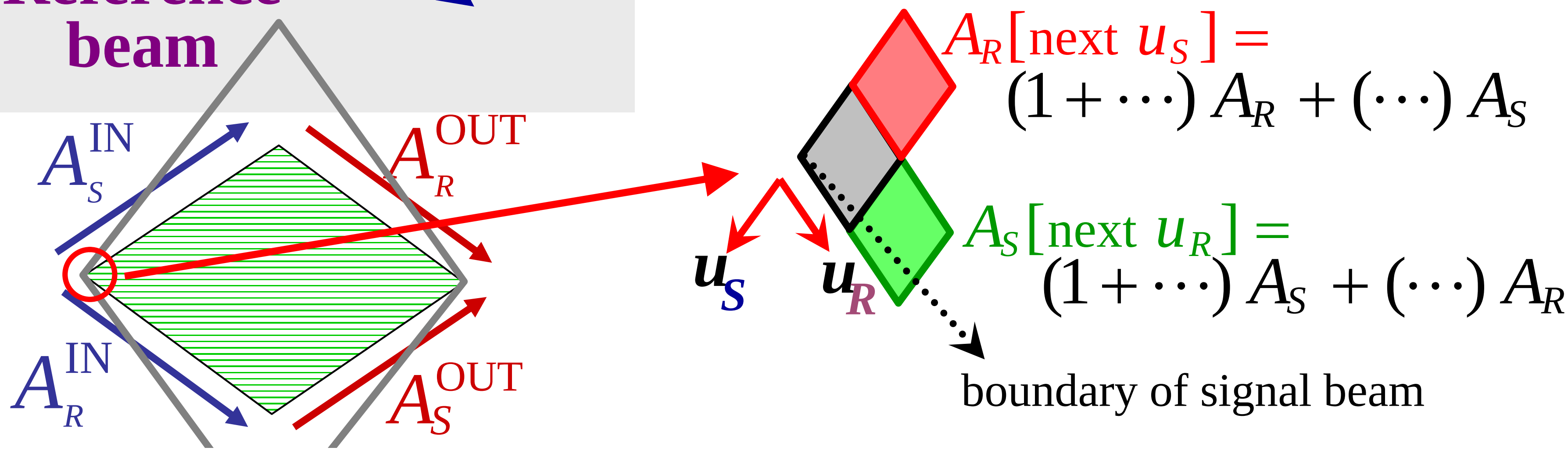


$$\frac{\partial A_R}{\partial u_S} = \frac{\alpha W_S}{\sin 2\theta_0} A_R + j\,\frac{\kappa W_S}{\sin 2\theta_0} \exp(-jK) A_S$$

$$\frac{\partial A_S}{\partial u_R} = -\frac{\alpha W_S}{\sin 2\theta_0} A_S - j\,\frac{\kappa W_S}{\sin 2\theta_0} \exp(jK) A_R$$

$$0 > u_S > -1 \qquad 0 < u_R < \frac{W_R}{W_S}$$

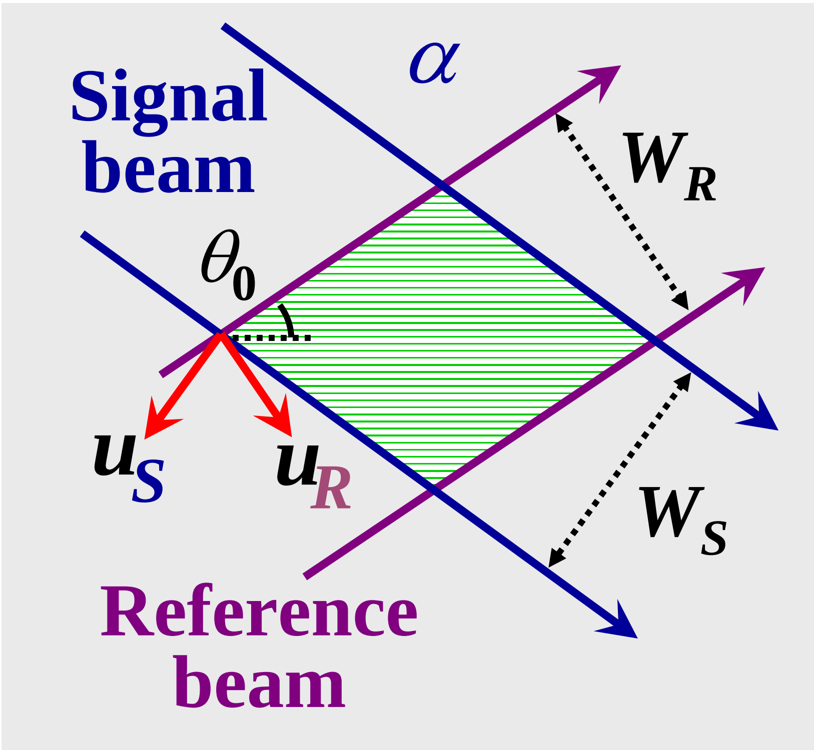
Compute by finite-difference...



also [1] Y. F. Bao, C. M. Verber, and R. P. Kenan, Optics Letters, **17**(8), 595 (1992).

2-D coupled-wave theory: numerical solution

- **"Overlap" grating**

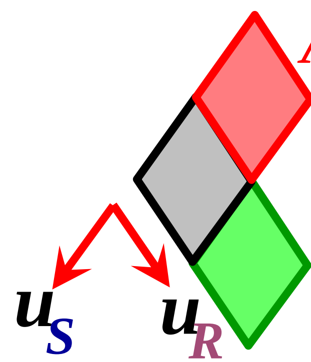


$$\frac{\partial A_R}{\partial u_S} = \qquad A_R + \qquad A_S$$

$$\frac{\partial A_S}{\partial u_R} = \qquad A_S - \qquad A_R$$

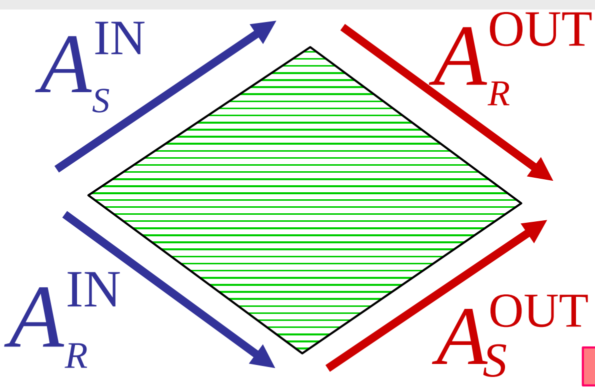
$$0 > u_S > -1 \qquad 0 < u_R < \frac{W_R}{W_S}$$

Compute by finite-difference...



$$A_R[\text{next } u_S] = (1 + \cdots)\, A_R + (\cdots)\, A_S$$

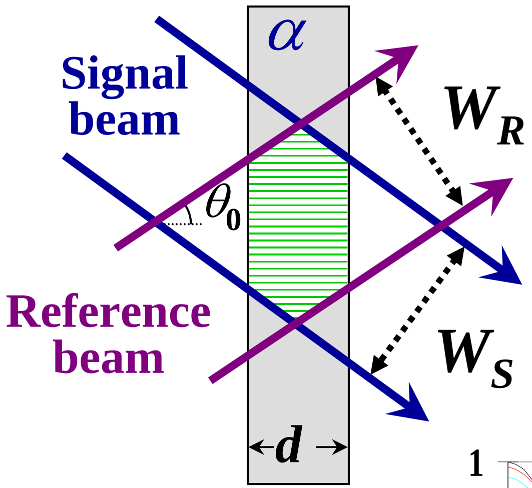
$$A_S[\text{next } u_R] = (1 + \cdots)\, A_S + (\cdots)\, A_R$$



η, selectivity, & beam-shape

also [1] Y. F. Bao, C. M. Verber, and R. P. Kenan, Optics Letters, **17**(8), 595 (1992).

Initial results: comparison against Kogelnik's theory

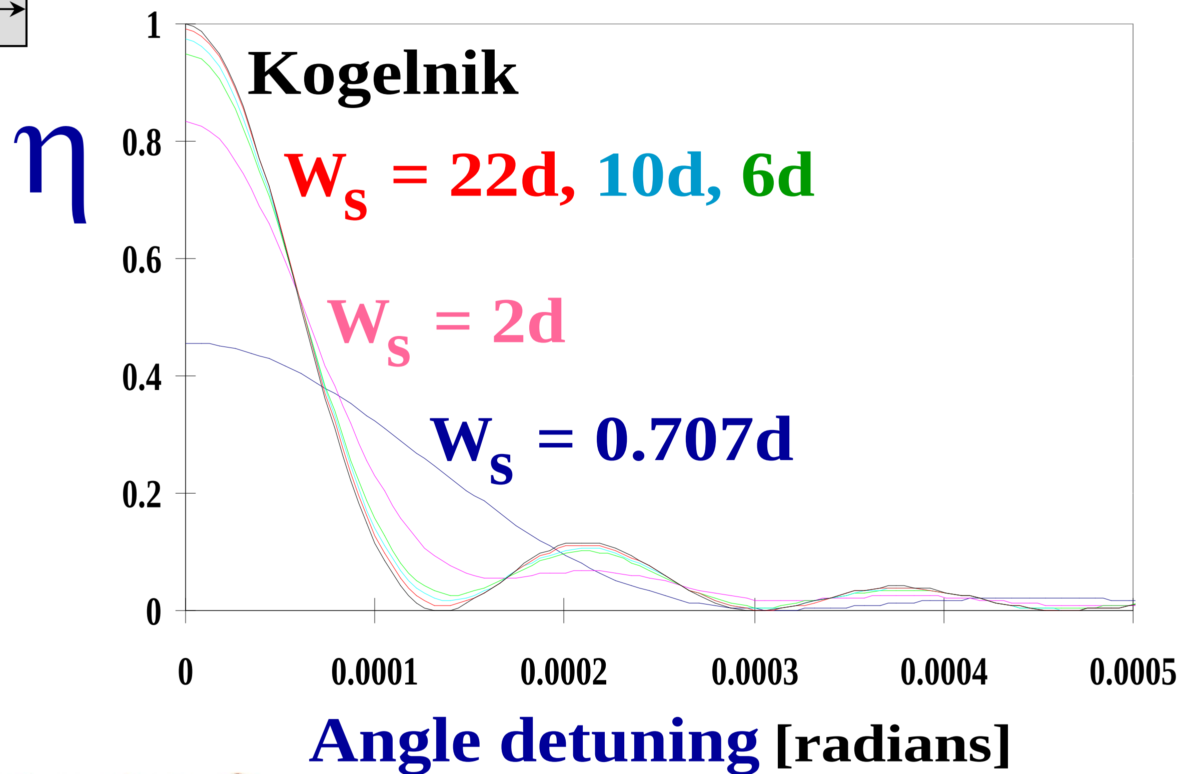


κ = 3.7 cm^{-1} within the shaded area
= 0 otherwise

$W_S = W_R$ θ_0 = 45 degrees

d = 3 mm λ = 1.55 μm

α = 0



..also verified match with reflection gratings

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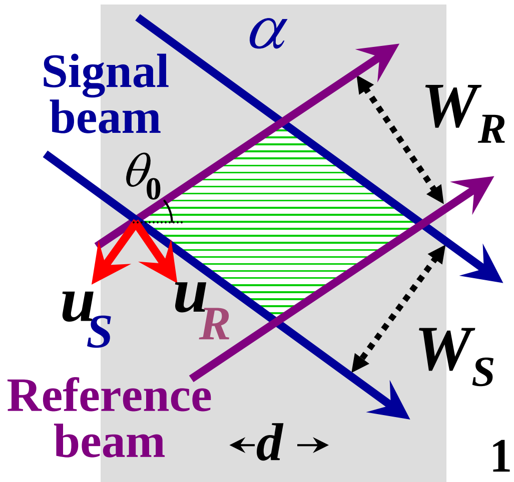
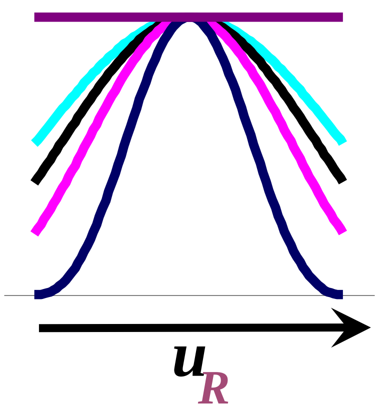
Initial results: apodization of wavelength response

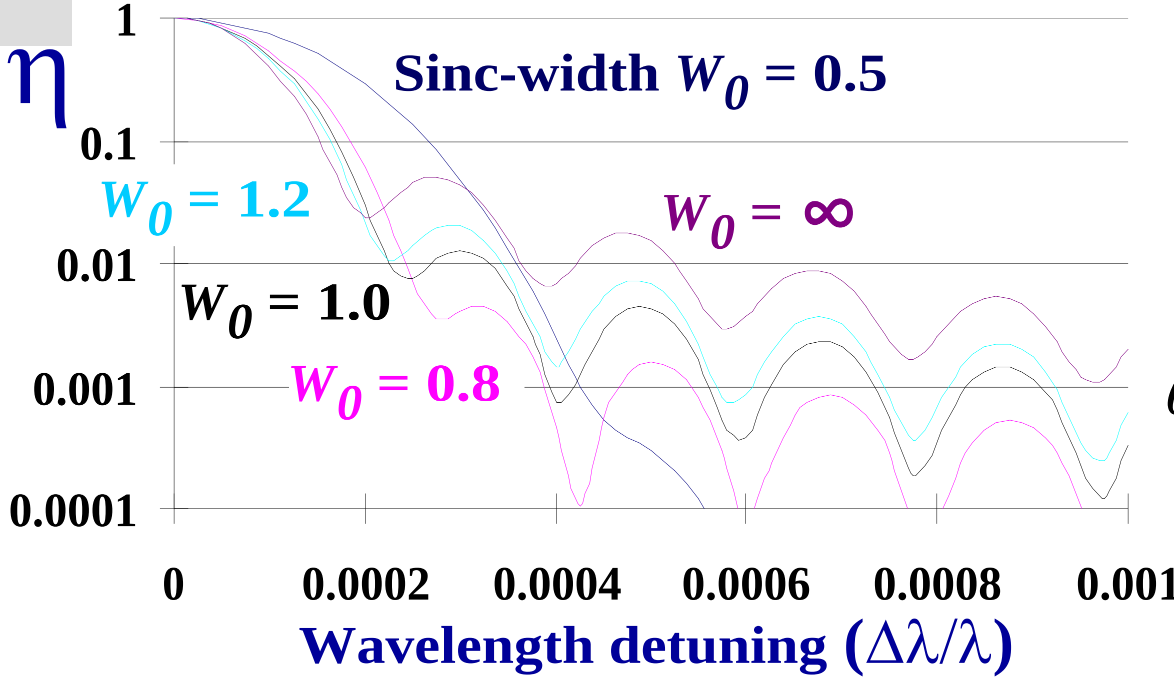


Using a coupling strength that varies as

$$\kappa\,(u_R,,u_S) = \kappa_0\,\mathrm{sinc}^2\left(\pi\,\frac{u_R - W_R/2W_S}{W_0}\right)$$

The resulting detuning curves show a suppression of the side-lobes for narrow sinc functions ($W_0 <$ 0.8), at a slight cost in the filter bandwidth.





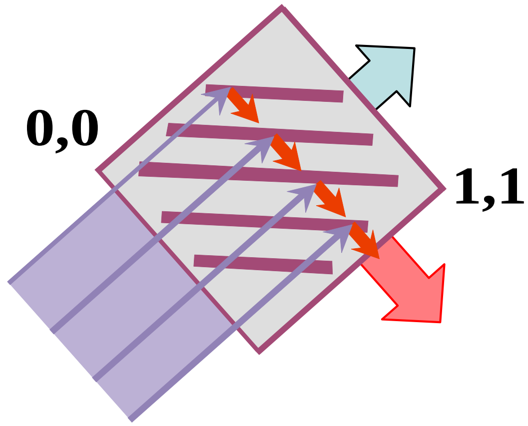
α= 0

$W_S = W_R$ = 5200λ

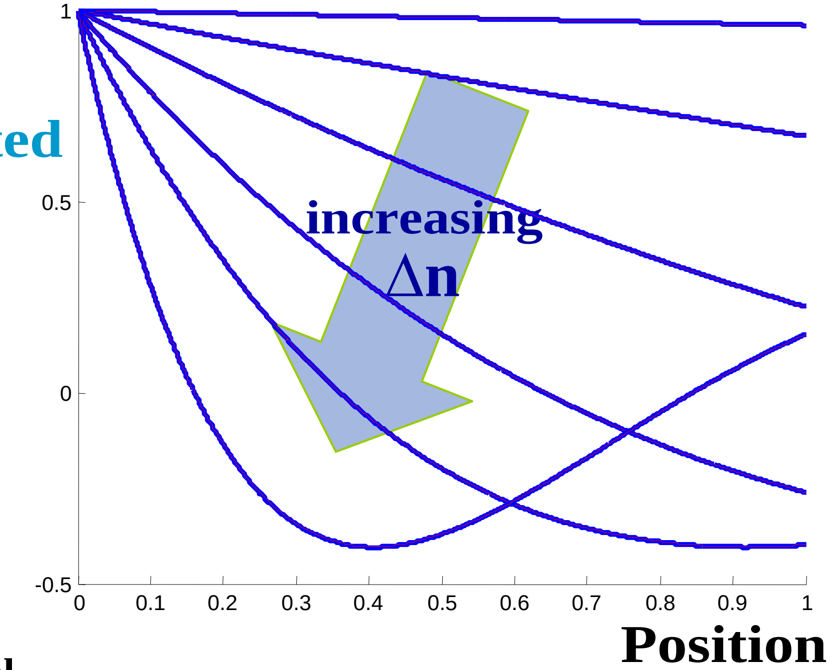
θ_0 = 45 deg.

Such an apodization of wavelength response could be quite useful for cascaded wavelength filtering devices...

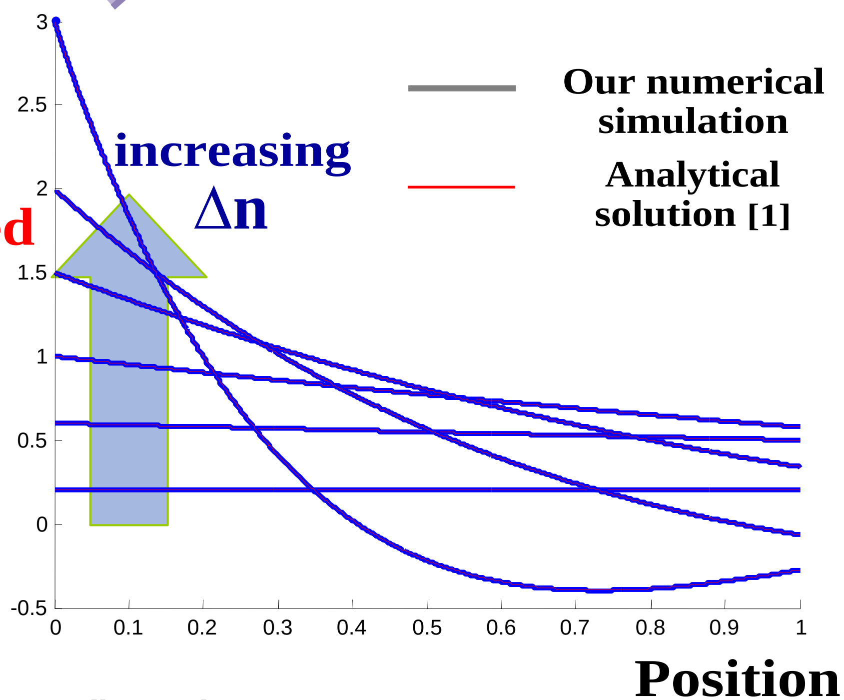
Trade-off between η & beam-profile



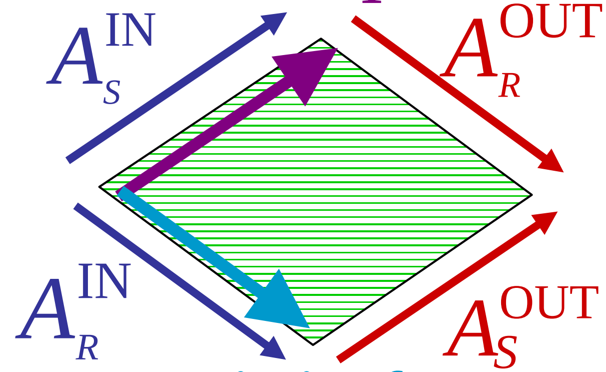
Transmitted field



Diffracted field



optimize for λ_1 extinction?



optimize for beam uniformity?

[1] P. St. J. Russell, L. Solymar, Optica Acta **26**, 329 (1979).

Conclusions

2-D restricted volume gratings offer

- **the spatial & spectral filtering capabilities of volume holograms**
- **the potential for cascading multiple 3-port devices**

We have implemented a numerical simulation of the 2-D coupled-wave equations for such volume gratings, and

- **verified it against Kogelnik theory**
- **used it to investigate apodization of wavelength selectivity**

By allowing researchers to study the effects of spatial variations in grating strength, performance optimization of these gratings should now be possible.