

# Selected Topics in Advanced Optics

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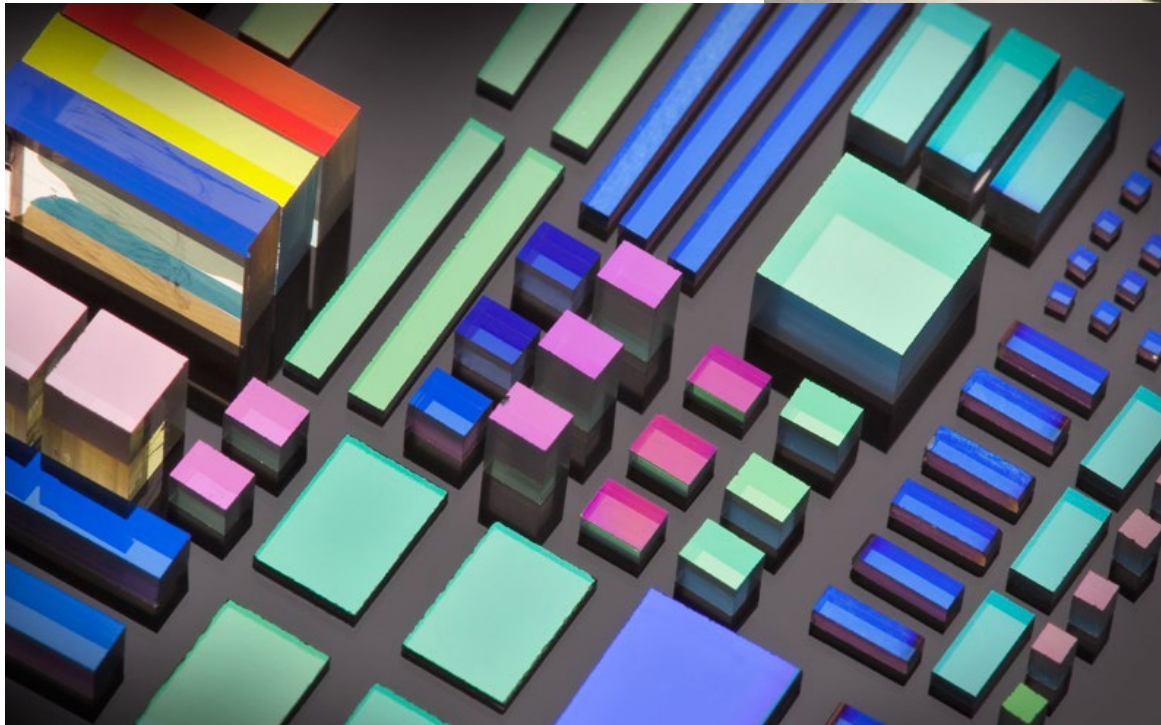
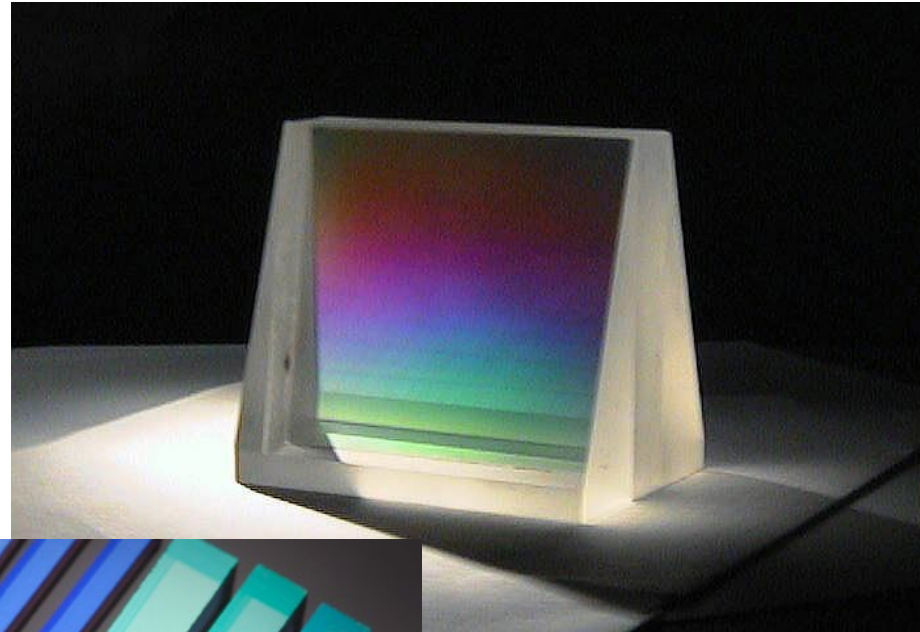
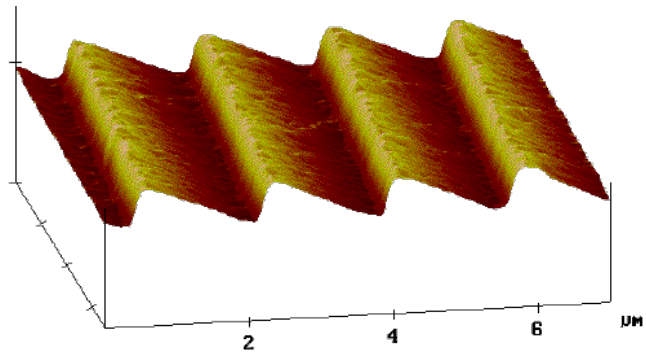
## Week 8 – part 1

Olivier J.F. Martin  
Nanophotonics and Metrology Laboratory

**EPFL**

# Gratings, stratified media and photonic crystals

## Part I – Gratings



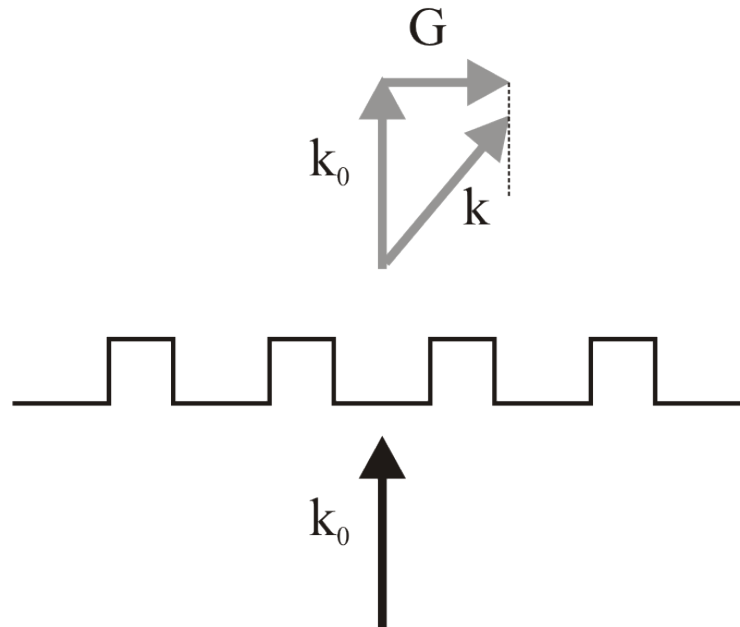
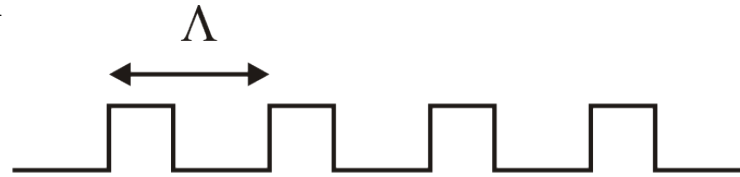
## Some references

- B.E.A. Saleh & M.C. Teich, Fundamental of photonics 2<sup>nd</sup> Ed. (Wiley, Hoboken, 2007), Chapter 7.
- C. Palmer and E. Loewen, Diffraction grating handbook 6<sup>th</sup> Ed. (Newport Corporation, Rochester), available at [gratings.newport.com](http://gratings.newport.com) and on Moodle.

## Bragg grating on a surface – Transmission

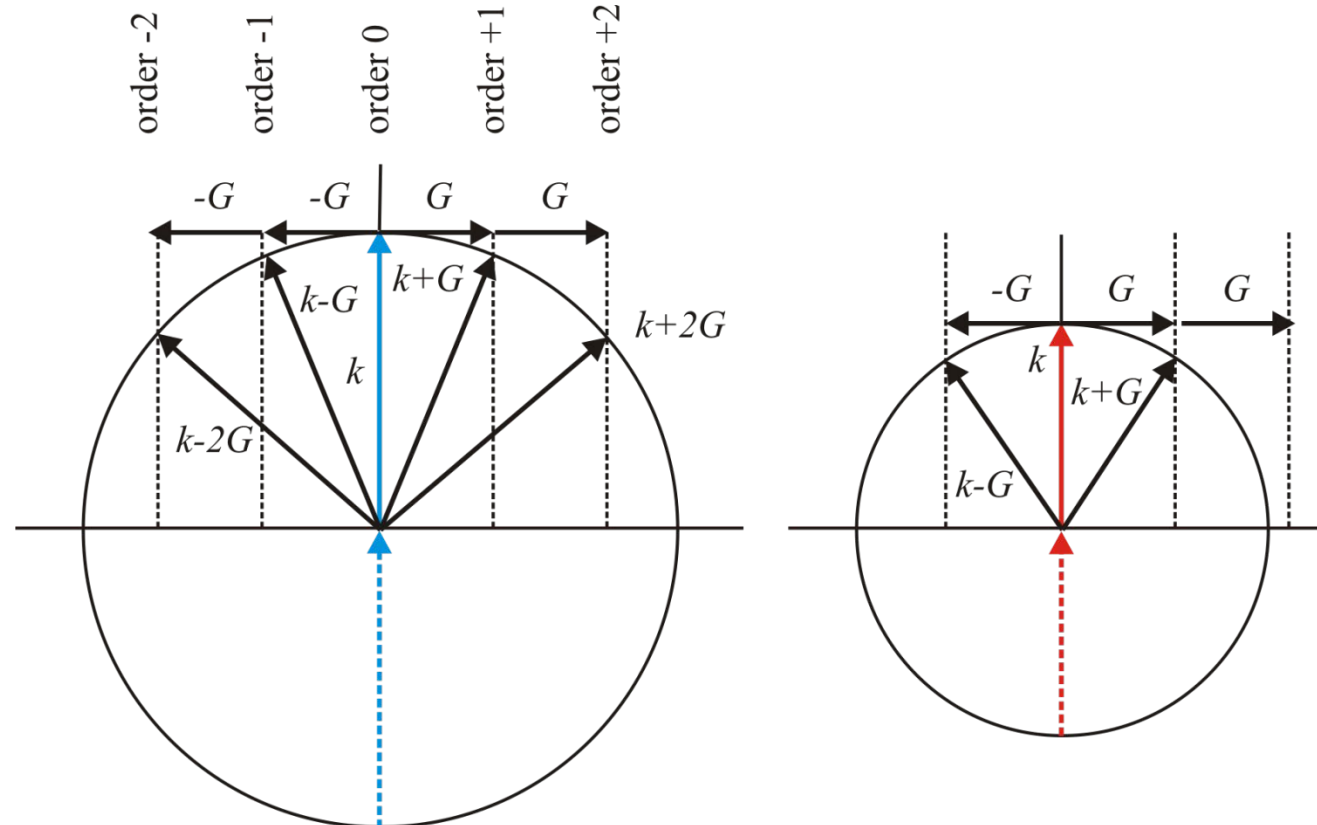
- The grating periodicity provides additional momentum parallel to the surface in multiples of the reciprocal lattice vector:

$$G = g = 2\pi / \Lambda$$



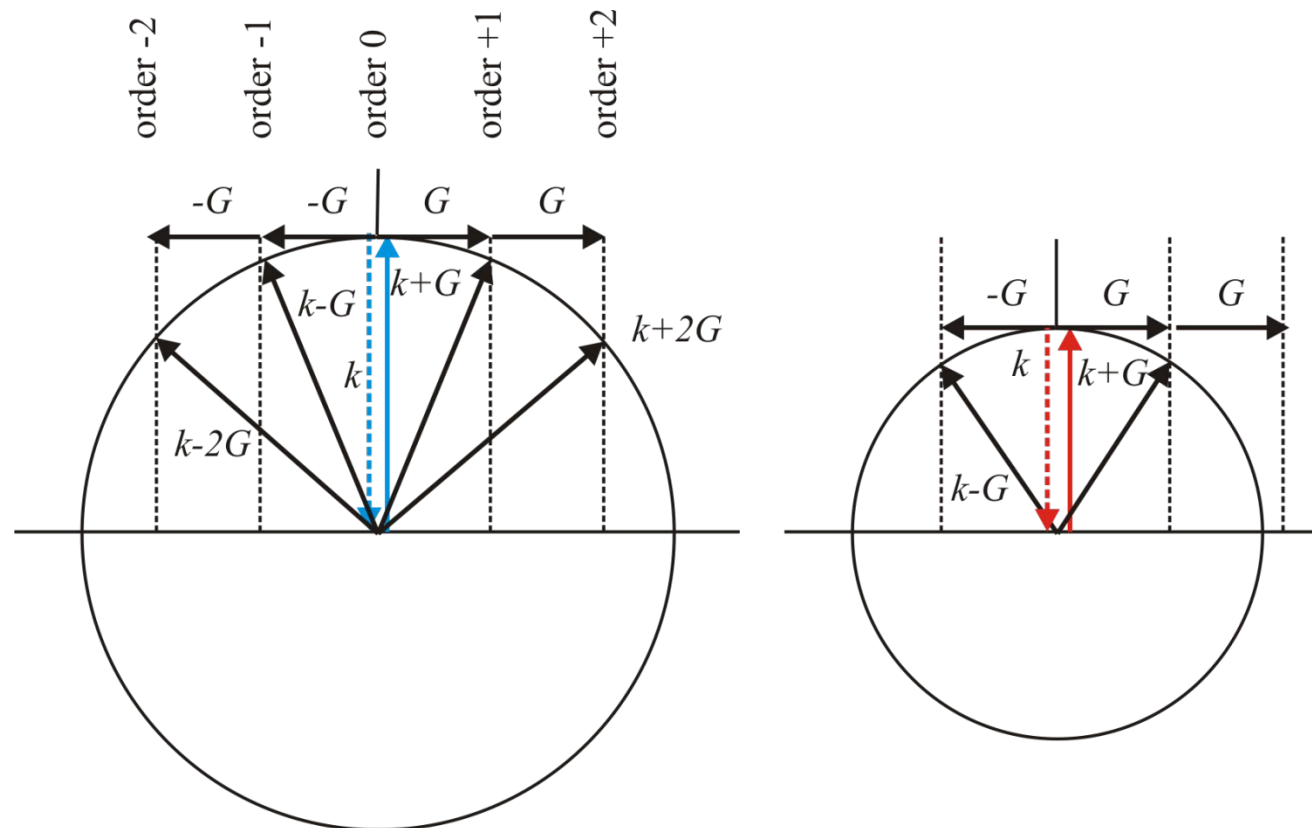
## Bragg grating on a surface – Transmission

- The direction of the wave scattered by the grating depends on the periodicity and on the frequency
- Not all the orders exist for all frequencies; there are cases where no orders exist



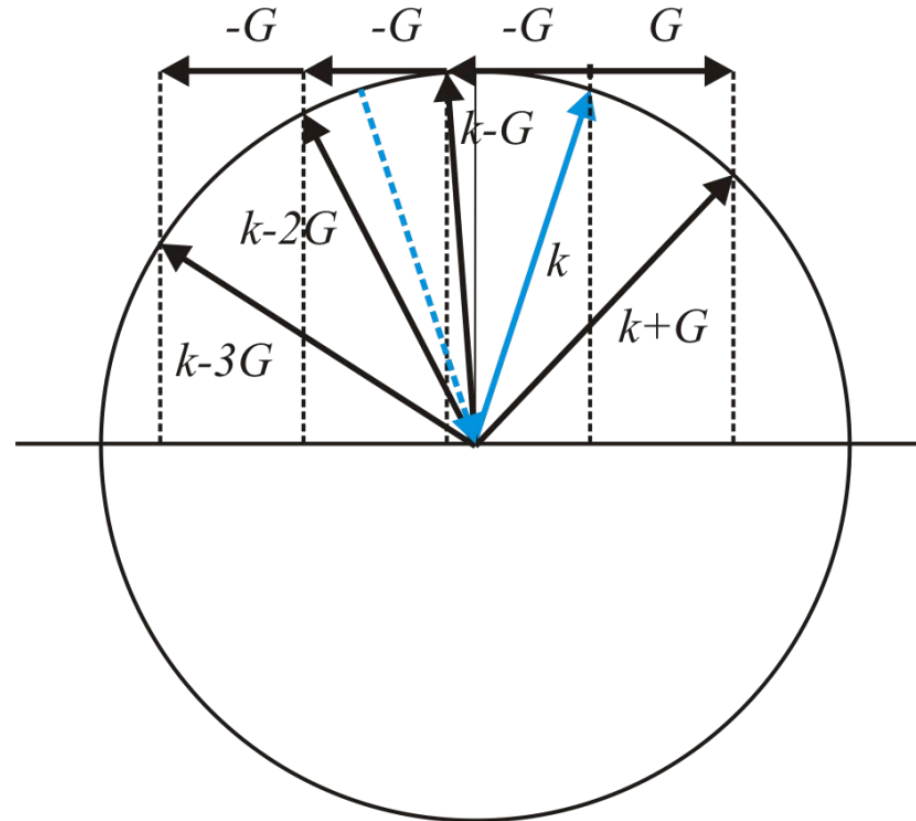
## Bragg grating on a surface – Reflection

- The principle is the same in reflection as it is in transmission
- Many gratings, however are not transparent and must be used in reflection



## Bragg grating on a surface – Non-normal incidence

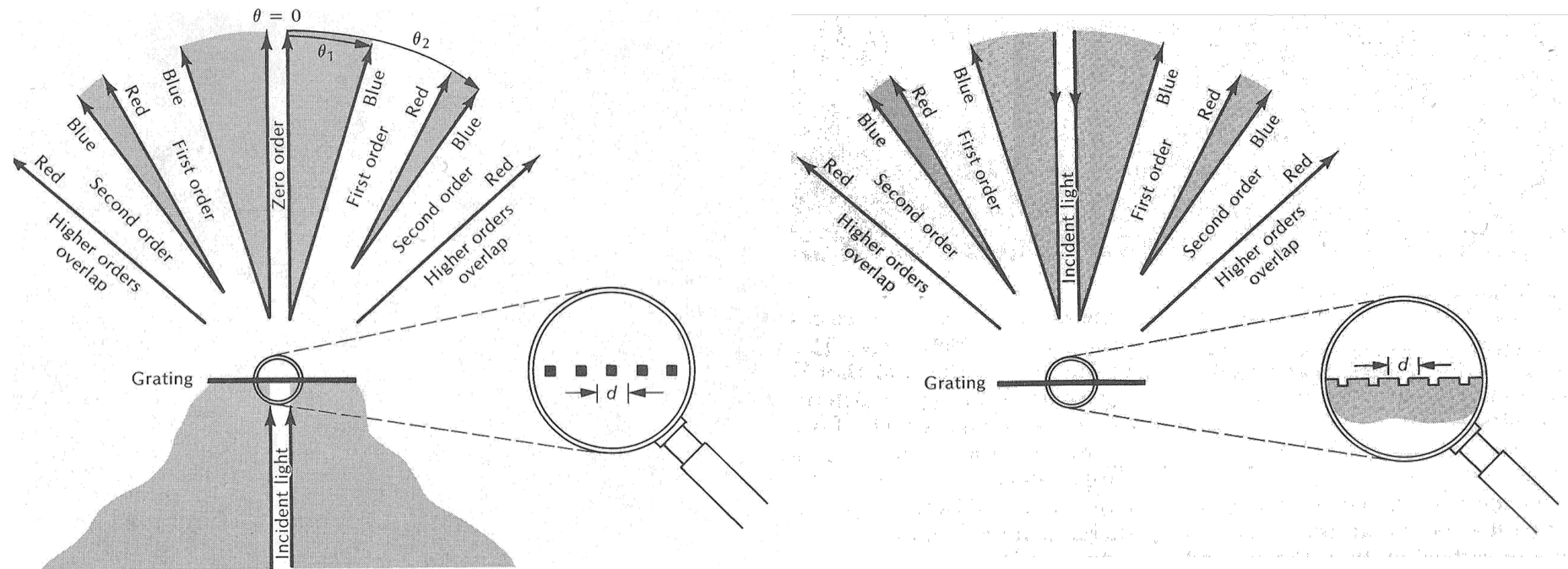
- In that case, the 0<sup>th</sup> order is just the normal reflection and all superior orders are deviated from the 0<sup>th</sup> order
- The number of positive and negative orders can be different





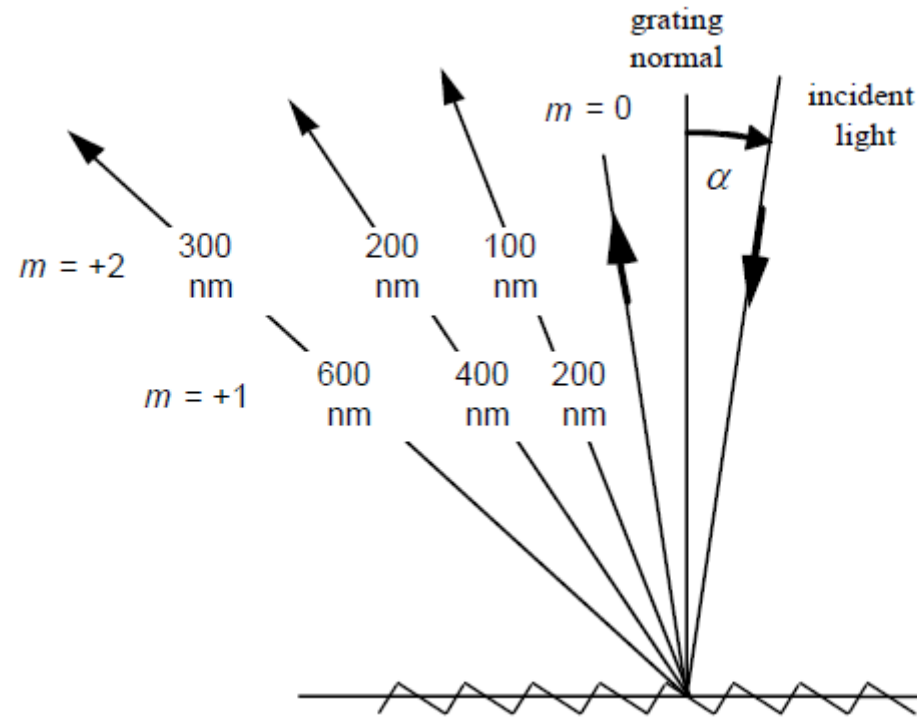
# Bragg grating on a surface – Spectral spread

- A grating can work in reflection or transmission; the orders are the same
- The spatial spread increases with the order (i.e. red and blue are **more** separated in a high order, and can even overlap between orders)



## Bragg grating on a surface – Spectral spread

- One must be careful that for specific conditions, the colours associated with different orders can be mixed up:

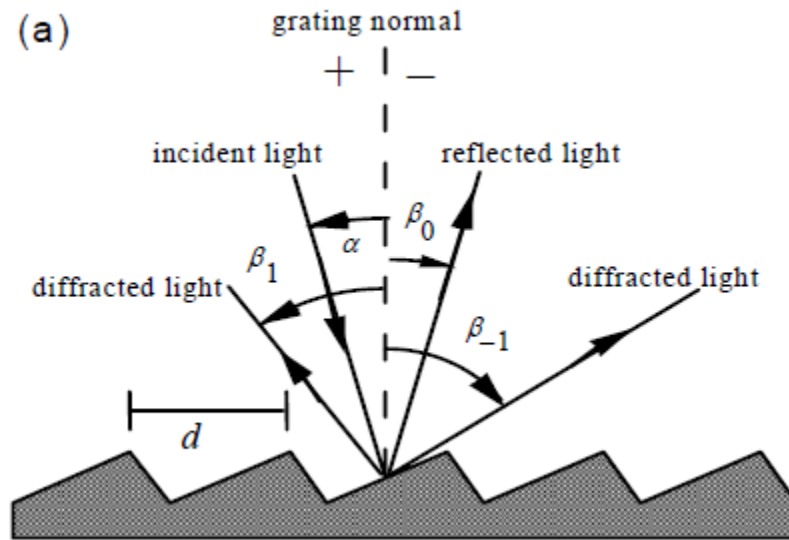


- The resolving power  $R$  of a grating is a measure of its ability to separate adjacent spectral lines of average wavelength  $\lambda$ :  $R = \lambda / \Delta\lambda$
- For example Sodium D-line doublet:  $\lambda=589.00$  nm and  $589.59 \rightarrow R=1000$

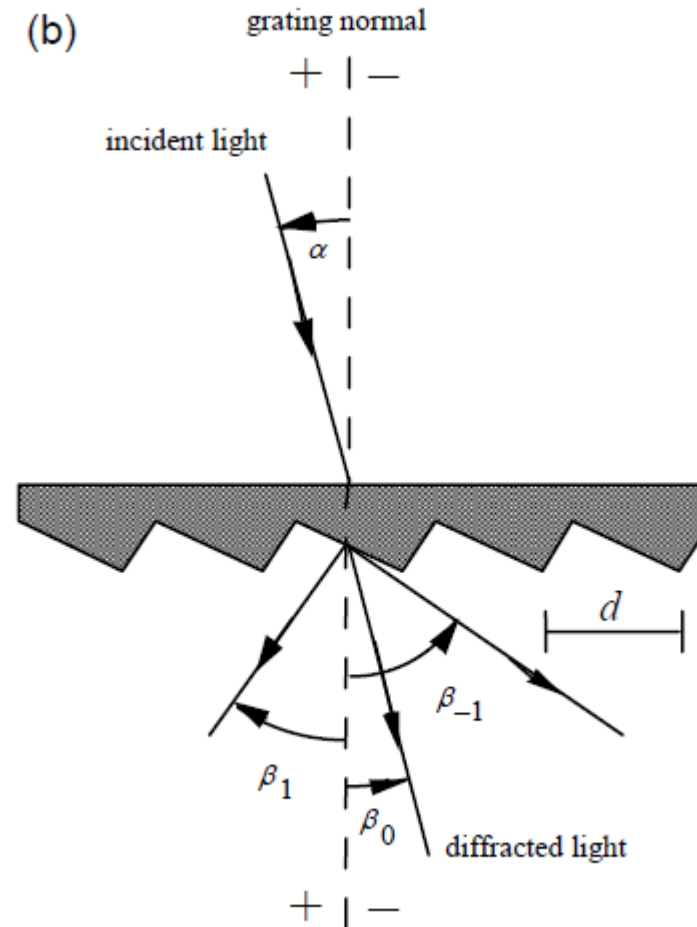
## Grating equation – Sign convention for the orders

- The angles are measured from the normal to the grating to the beam ( $\rightarrow$  different signs for the different  $\beta$  below)

Reflection grating:

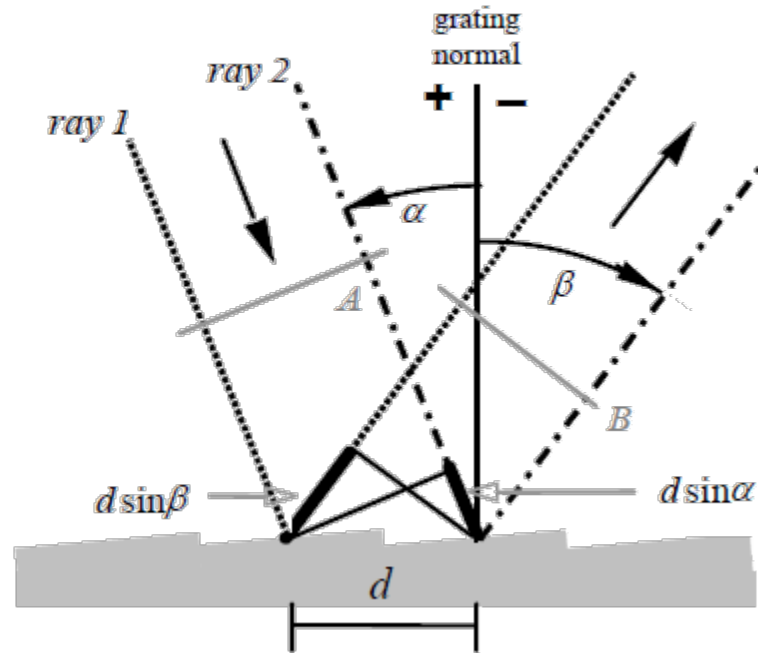


Transmission grating:



## Grating equation – Incidence in the normal plane

- The light diffracted by a grating can be understood in a similar way as in an experiment with an array of slits



- Constructive interference if the path is a multiple of  $\lambda$ :

$$d(\sin \alpha + \sin \beta) = m\lambda$$

$$(\sin \alpha + \sin \beta) = Gm\lambda \quad G = 1/d$$

## Existence of the different diffraction orders

- Assuming normal incidence ( $\alpha=0$ ):  $\sin \beta = m \frac{\lambda}{d}$
- The first diffracted orders appear for  $m = \pm 1$
- The cutoff for the first order modes appears when  $\beta = 90^\circ$   
$$\sin \beta = m \frac{\lambda}{d} \rightarrow d = \lambda$$
- No diffraction order if  $d < \lambda$  (a period smaller than the wavelength does not produce any diffraction orders); this condition is very important for experiments with periodic samples
- Total number of possible modes ( $0, \pm 1, \pm 2, \dots$ ):  $M = \frac{2d}{\lambda} + 1$
- For small angles, one sometimes uses  $\beta = m \frac{\lambda}{d}$

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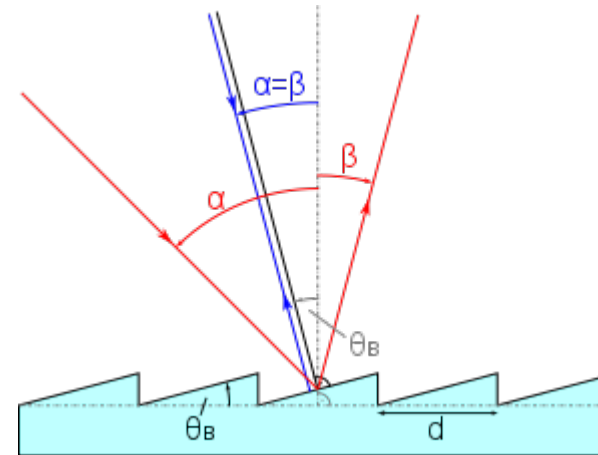
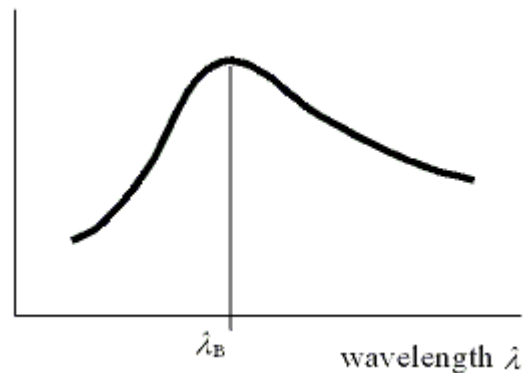
## Week 8 – part 2

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## Blazed grating

- Blazed gratings provide strong diffraction for a specific wavelength (blazed wavelength) and in a specific order  $m$
- They are often used in the Littrow configuration:  $\alpha = \beta$  (by extension, the normal to the facet bisects the incident/diffracted angle)



$$d(\sin \alpha + \sin \beta) = m\lambda \quad \rightarrow \quad 2d \sin \alpha = m\lambda$$

## Resolving power, spectral resolution and bandpass

- The resolving power is the ability to separate adjacent spectral lines of average wavelength  $\lambda$ :

$$R = \frac{\lambda}{\Delta\lambda} \quad \Delta\lambda: \text{minimal spectral range that can still be detected}$$

- Theoretical resolving power for a planar grating:

$$R = mN \quad N: \text{total number of illuminated grooves}$$

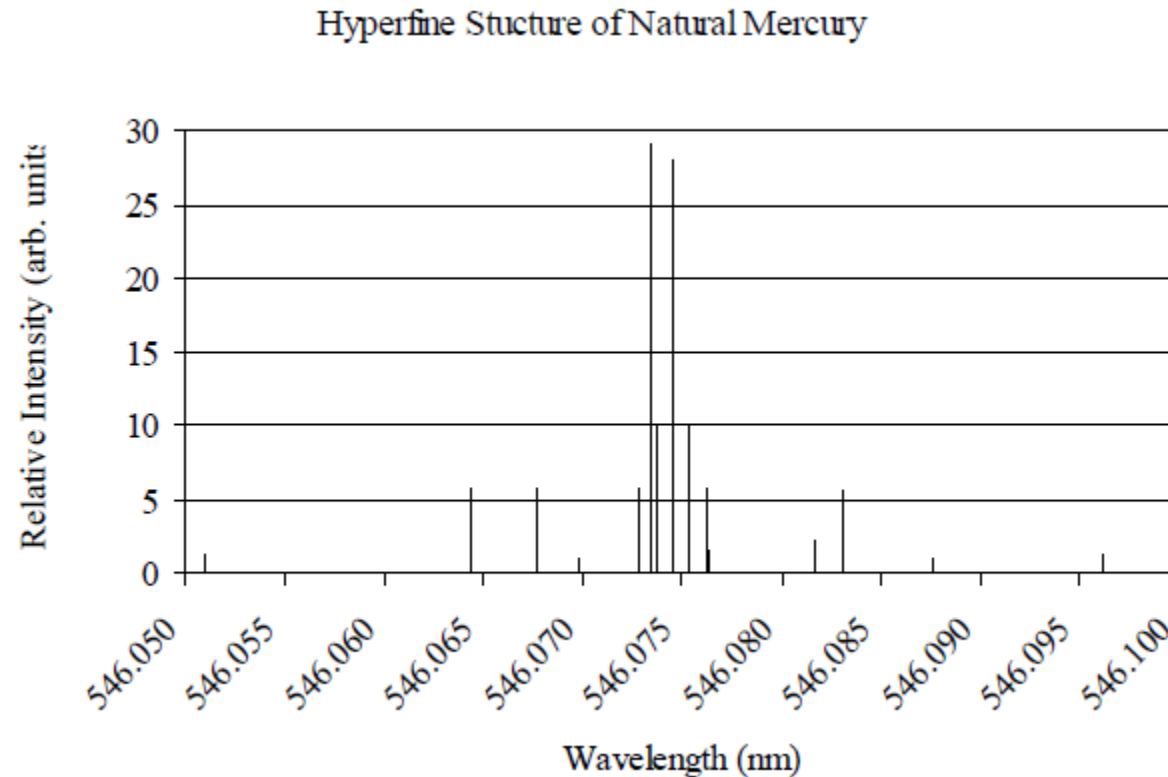
$$R = \frac{Nd(\sin \alpha + \sin \beta)}{\lambda} = \frac{W(\sin \alpha + \sin \beta)}{\lambda}$$

$W$ : grating width (illuminated)

- A large grating has a larger resolution power, unfortunately, a large grating can be more difficult to use since the incident light must be spread over a large surface

## Resolving power, spectral resolution and bandpass

- The resolving power is one of the key parameters for a grating. It can be tested by using a Mercury lamp and trying to resolve the hyperfine structure:



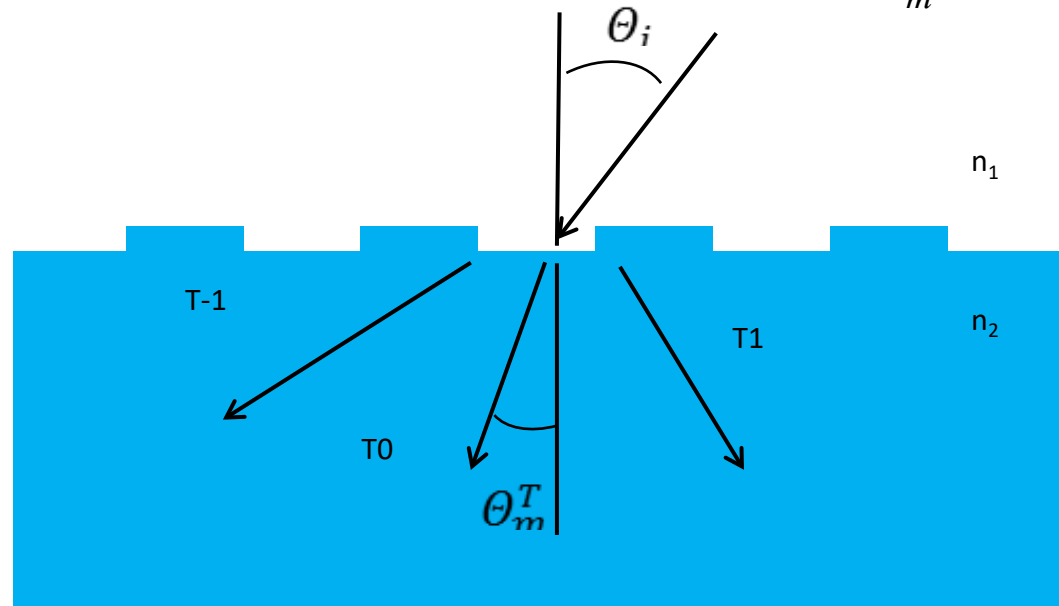
## Grating equation across two different media

- Grating equation (based on Snell's law):

$$n_2 \sin \theta_m^T = n_1 \sin \theta_i + m \frac{\lambda}{\Lambda} \quad m = 0, \pm 1, \pm 2, \dots$$

- Equation for the different diffraction orders:

$$\theta_m^T = \sin^{-1} \left( \frac{n_1 \sin \theta_i + m \frac{\lambda}{\Lambda}}{n_2} \right)$$

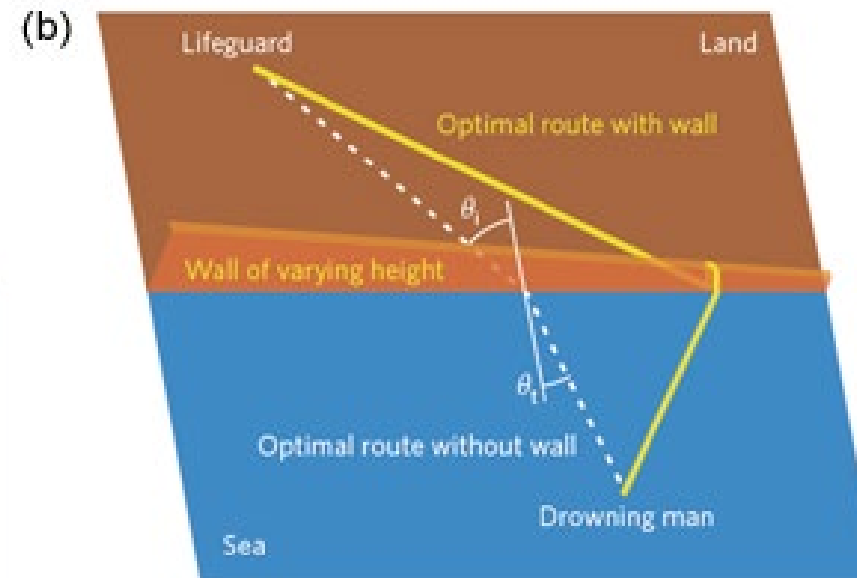
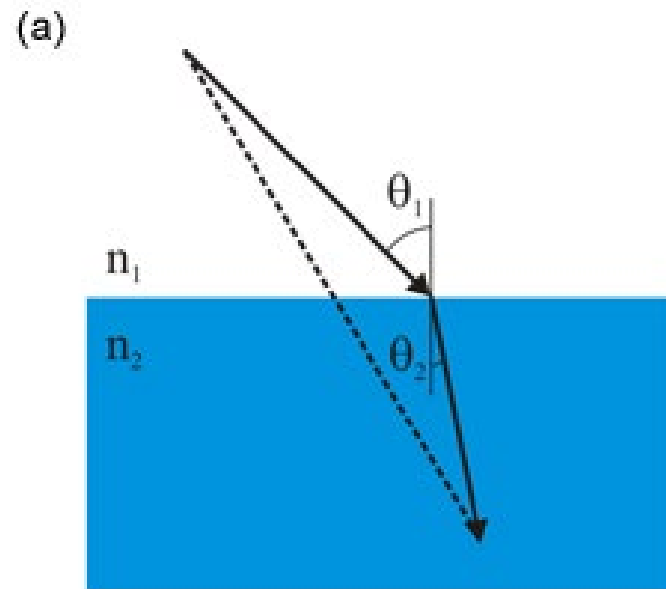


## Grating equation: Generalized Snell's law

- The grating adds some phase gradient to the refracted wave:

$$n_1 \sin \theta_1 - n_2 \sin \theta_2 = 0$$

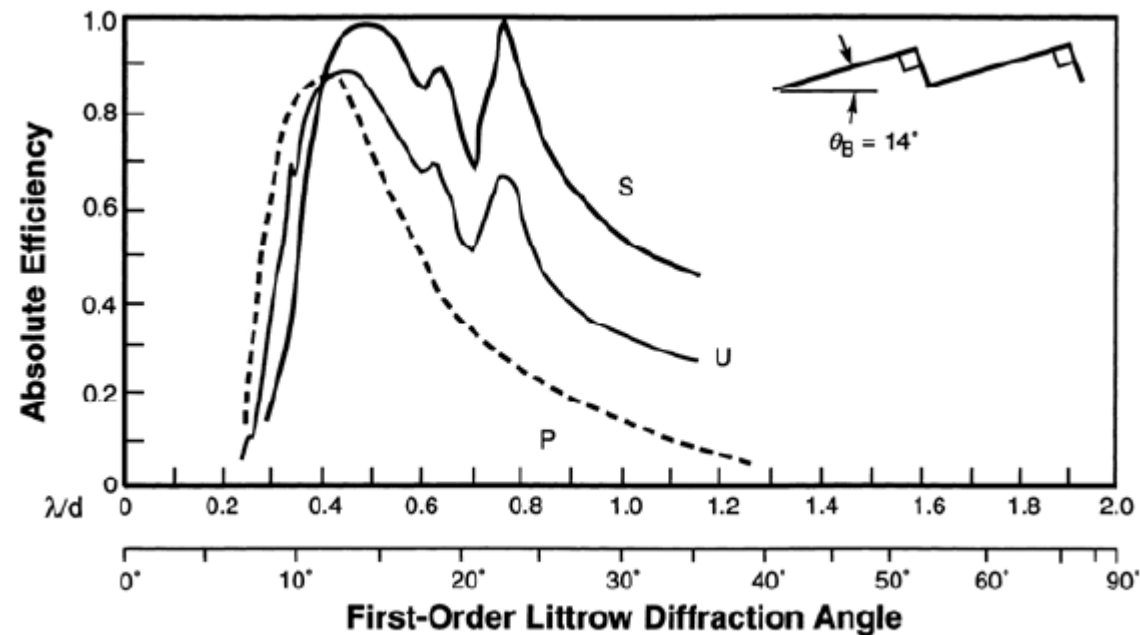
$$n_1 \sin \theta_1 - n_2 \sin \theta_2 = \frac{\lambda}{2\pi} \frac{d\phi}{dx}$$



*N. Yu, Nature Materials vol. 13, p. 139 (2014)*

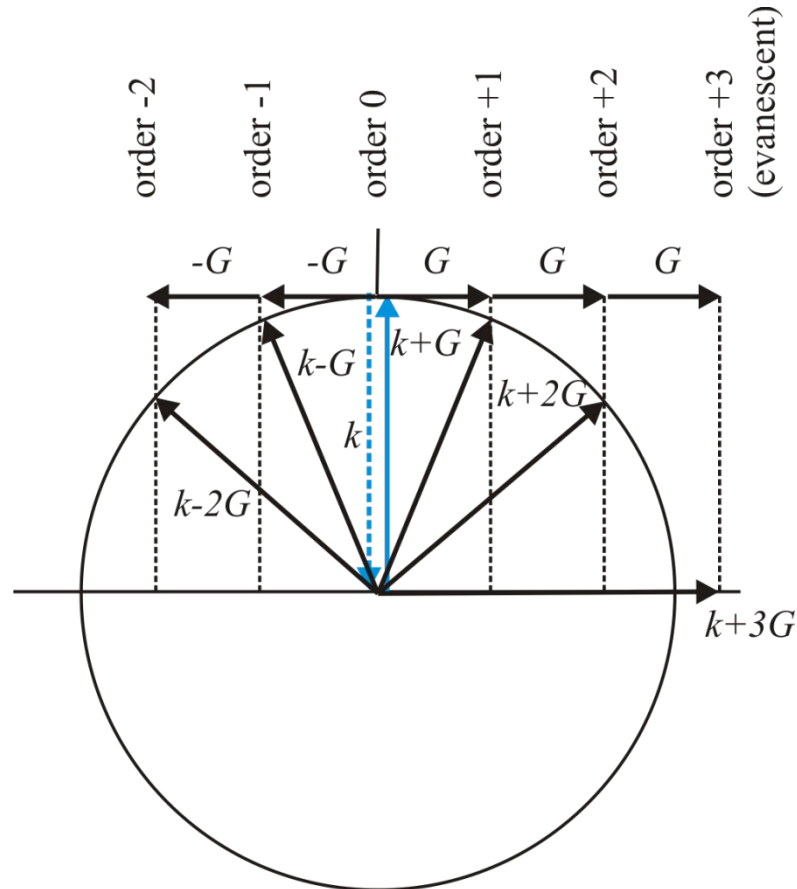
## Polarization effects

- For a very small profile (or blazed angle), polarization effects are negligible
- As soon as the profile becomes important (or the blazed angle larger than about  $10^\circ$ ), polarization effects can be significant, leading to a different response magnitude for both polarizations



## Bragg grating on a surface – Evanescent orders

- Non-existing orders are often called evanescent, because they have a propagation vector parallel to the interface which is larger than the free space wave vector

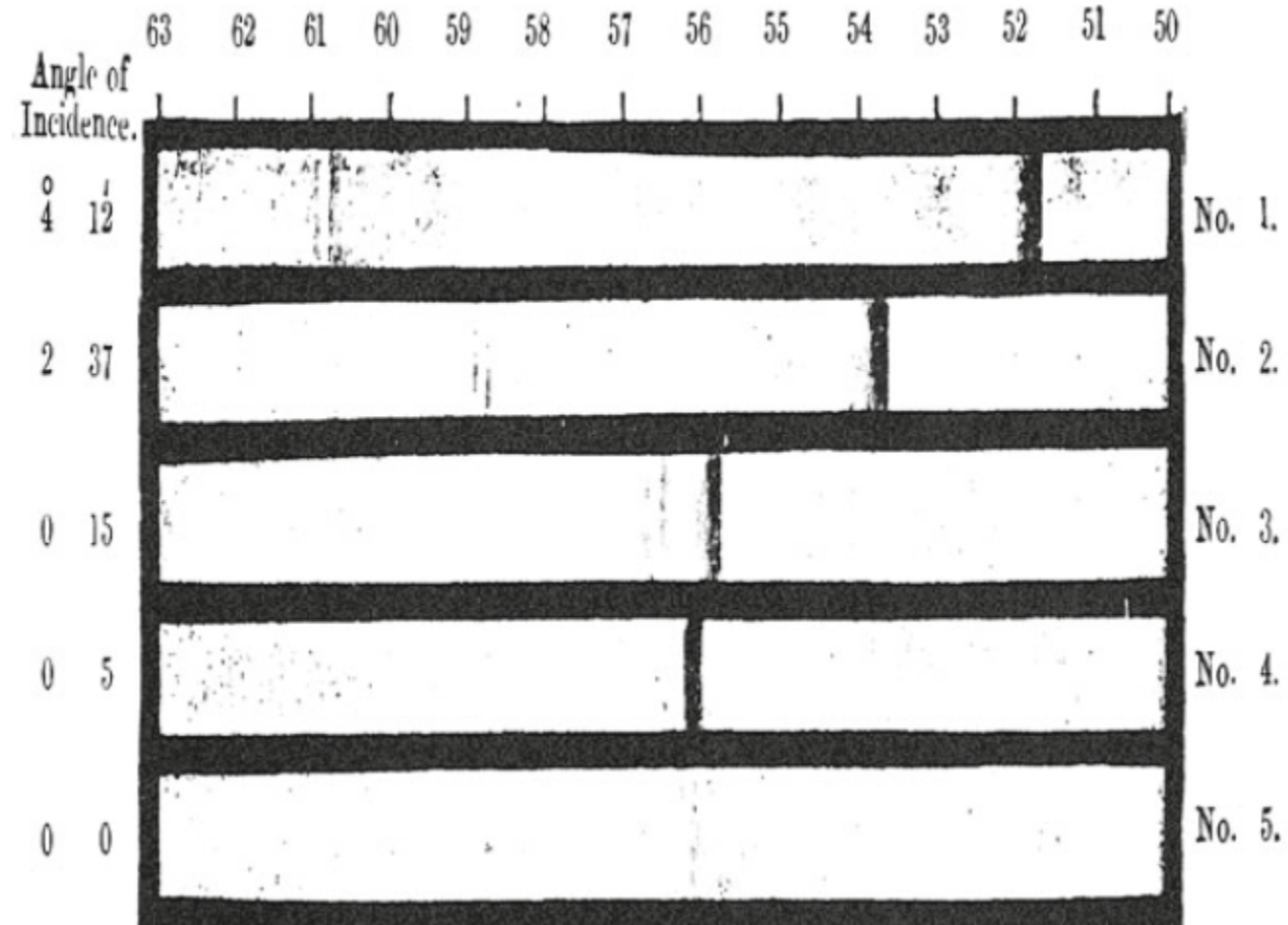


## Rayleigh and Wood anomalies

- These anomalies are observed in the spectral response of gratings, they usually correspond to the condition when:
  - Light of a given wavelength  $\lambda'$  and spectral order  $m'$  is diffracted at an angle  $|\beta| = 90^\circ$ , so for  $\lambda < \lambda'$  propagation is possible in order  $m'$  (and all lower orders), but it is not possible for  $\lambda > \lambda'$
  - Light excites a resonance in the system, like a surface plasmon

# Rayleigh and Wood anomalies

- Spectra of a continuous source



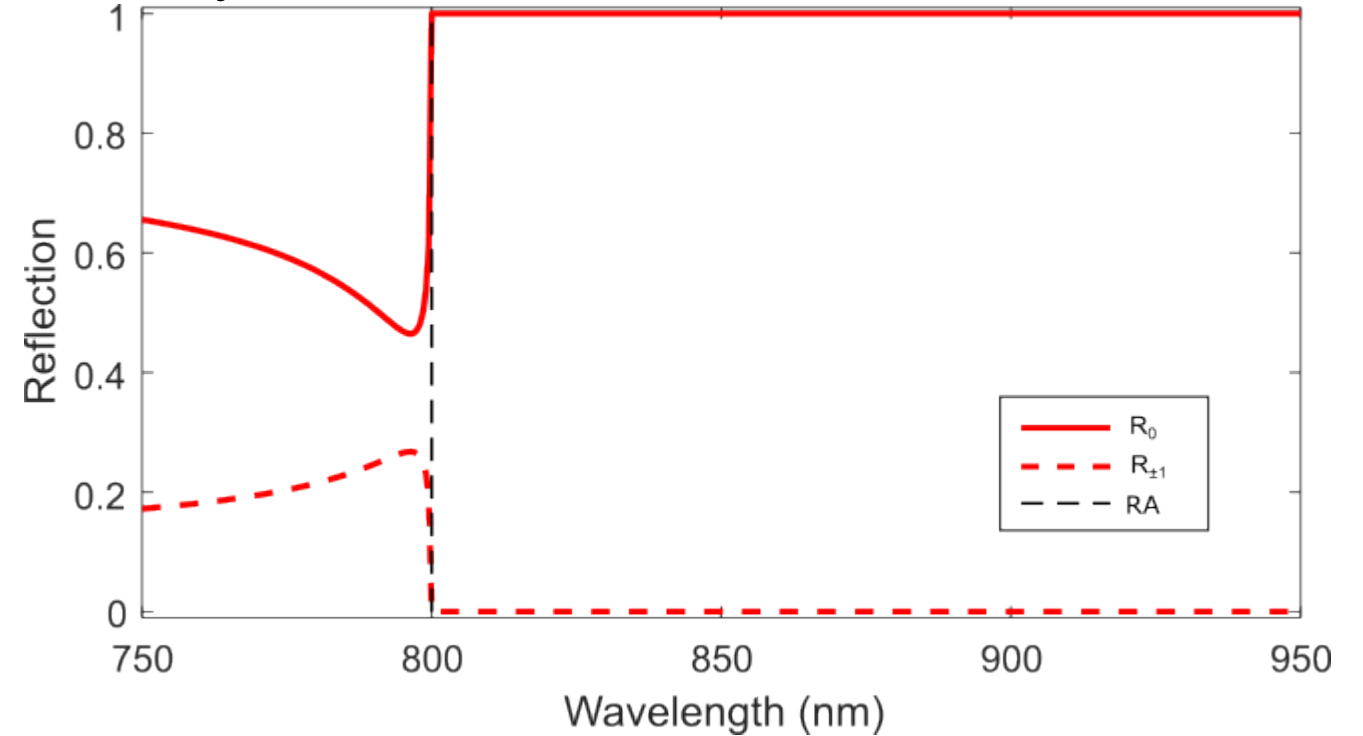
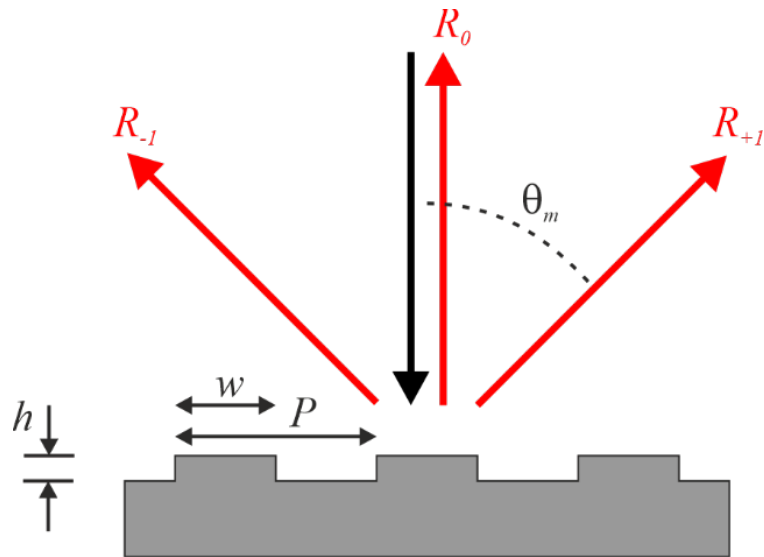
*R.W. Wood, Philos. Mag. vol. 4, p. 396 (1902)*

# Rayleigh and Wood anomalies

- Perfect electric conductor: Rayleigh anomaly

Grating equation:  
(normal incidence)

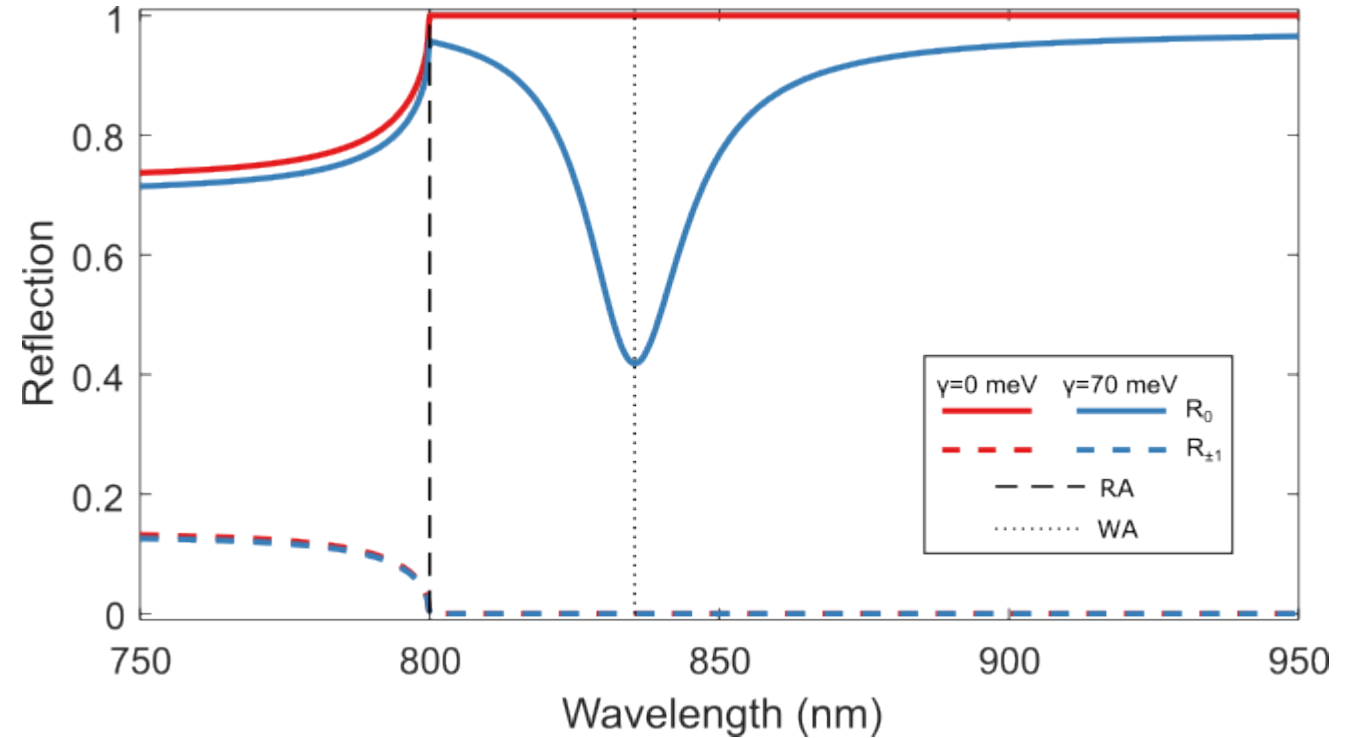
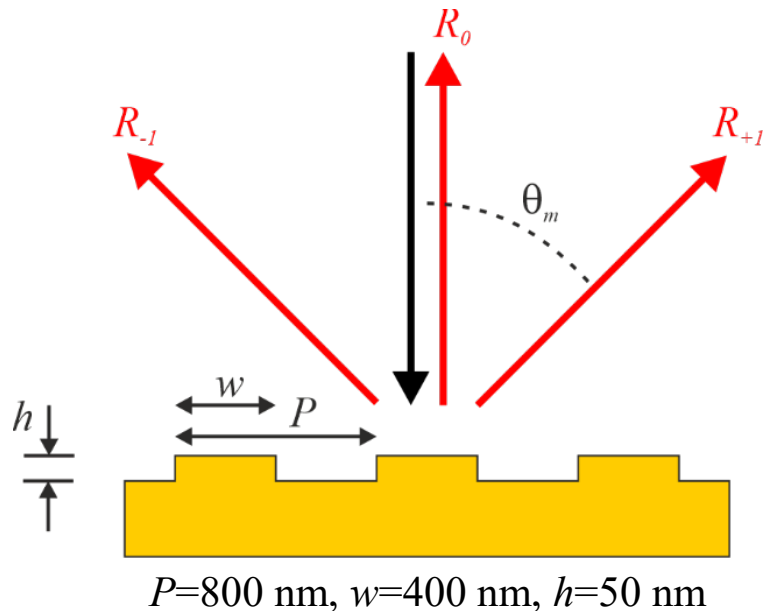
$$\sin(\theta_m) = \frac{m\lambda}{P}$$



Rayleigh anomaly: onset of diffraction,  $\lambda = P$

# Rayleigh and Wood anomalies

- Drude material grating: Rayleigh and Wood anomalies
- Very close to each other
- Wood anomaly requires losses

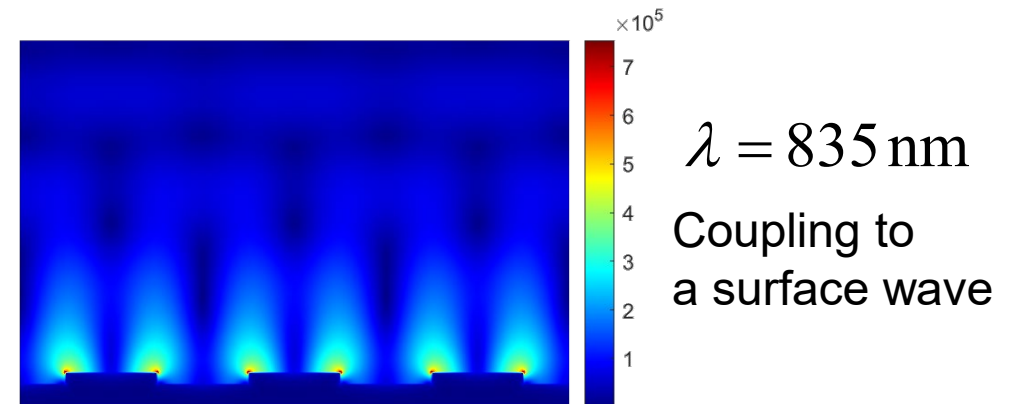
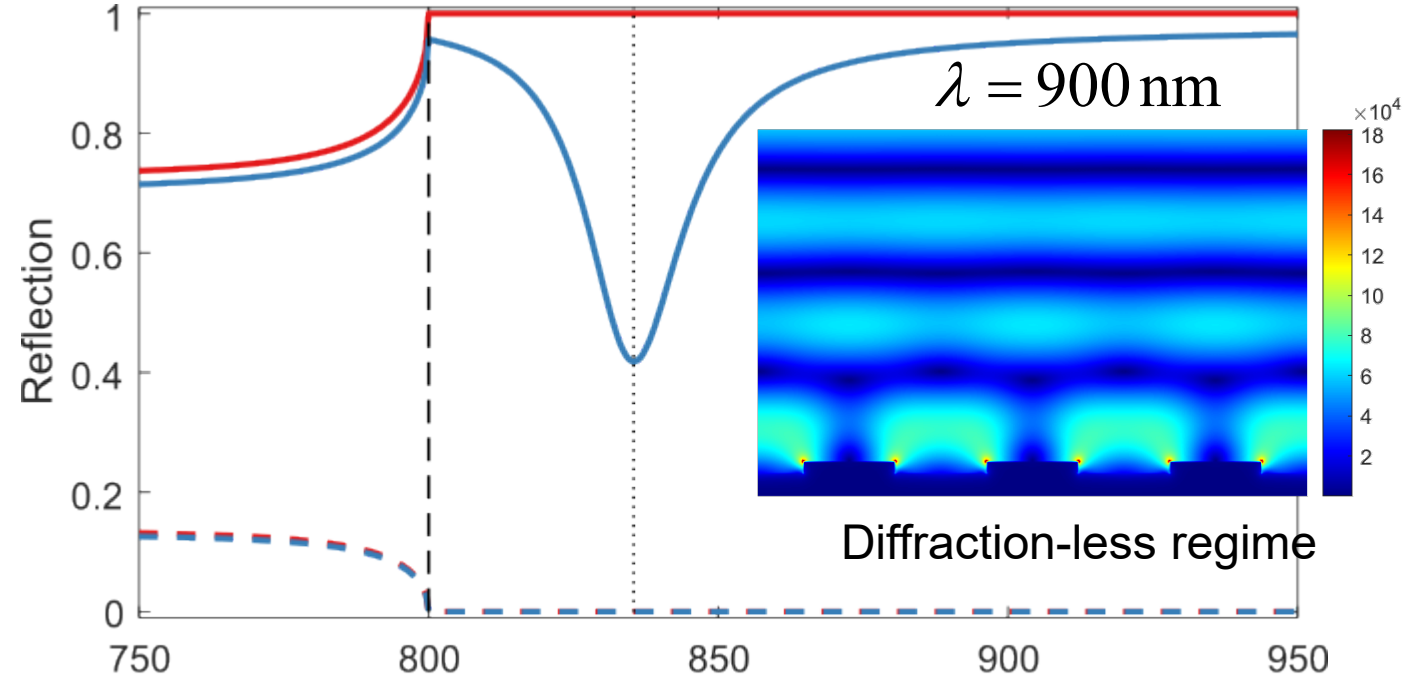
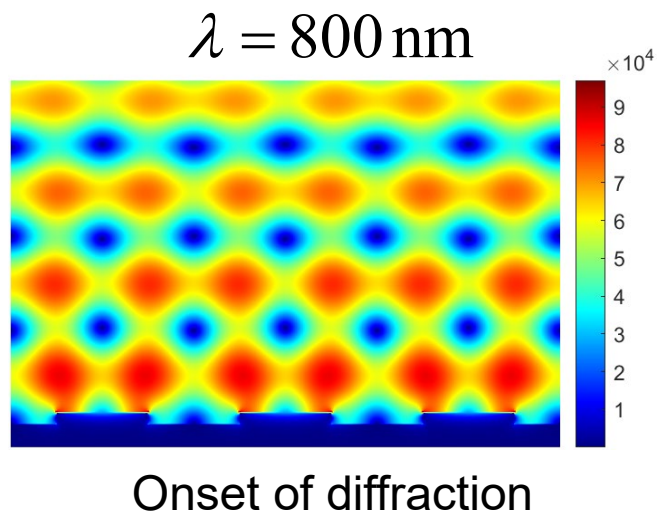
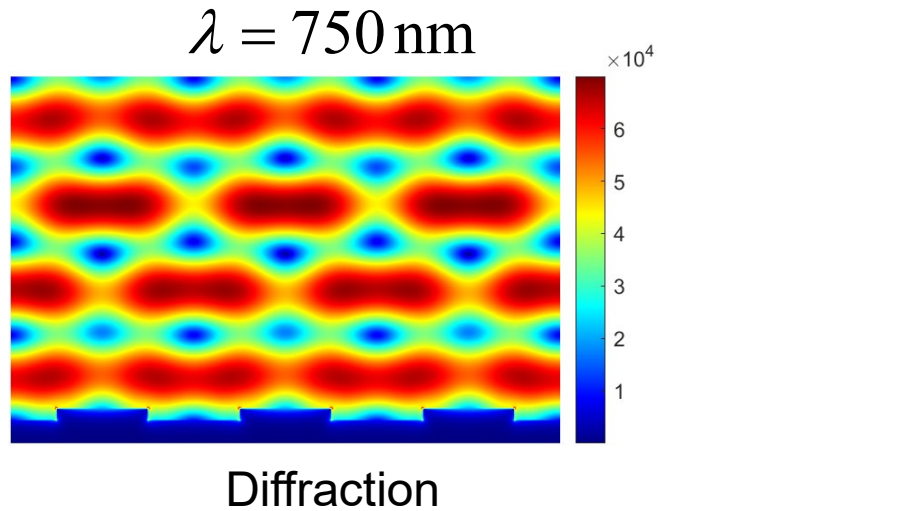


$$\epsilon = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

$$\epsilon_{\infty} = 10 \text{ eV} \quad \omega_p = 8.95 \text{ eV}$$

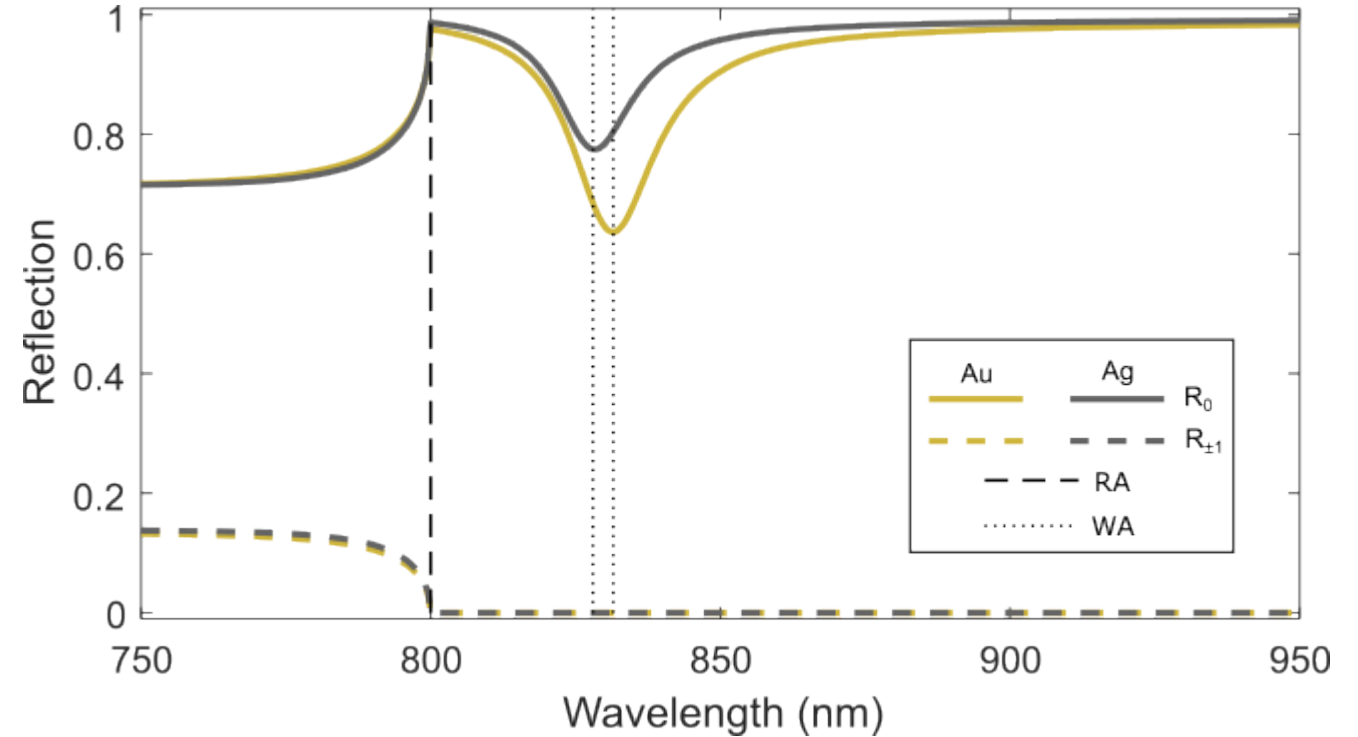
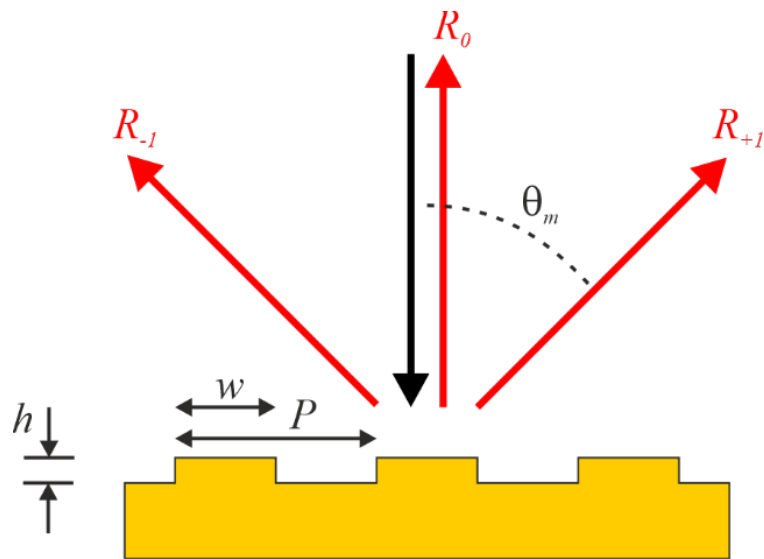
# Rayleigh and Wood anomalies

- Drude material grating: Rayleigh and Wood anomalies



# Rayleigh and Wood anomalies

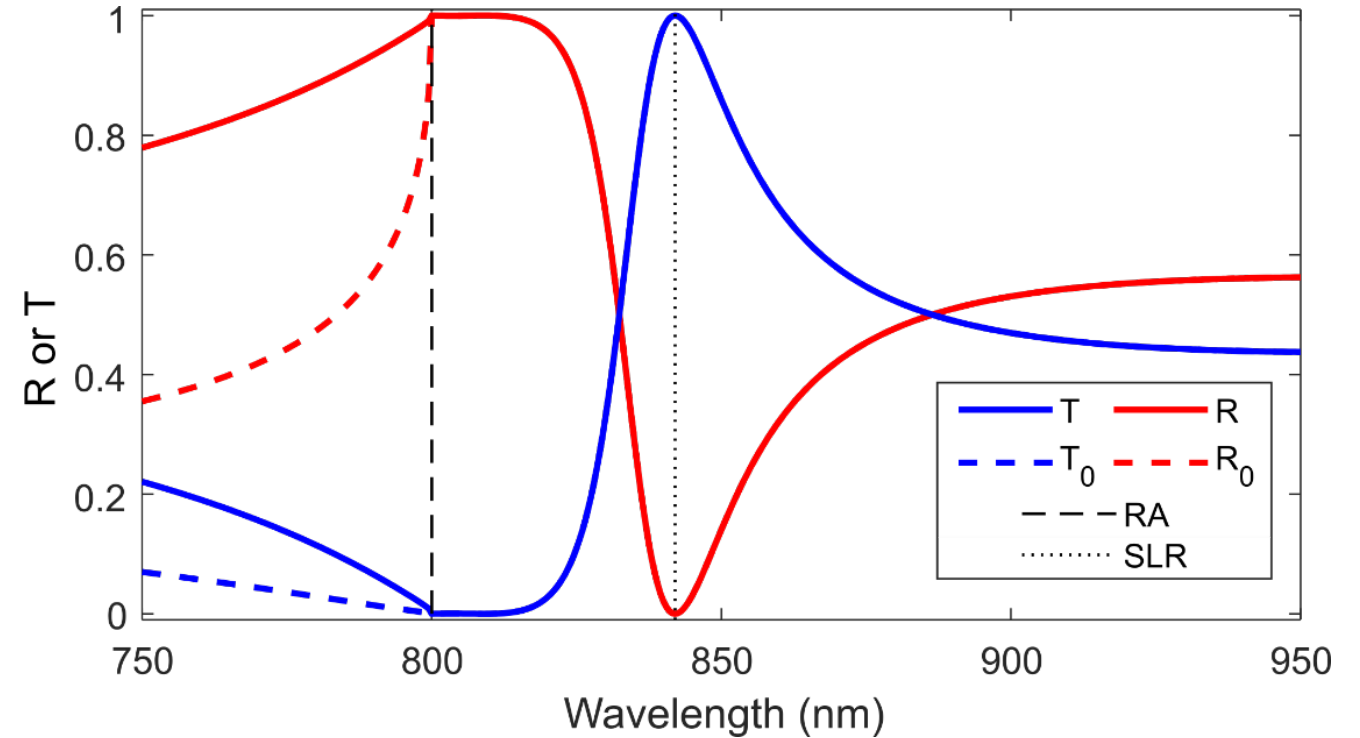
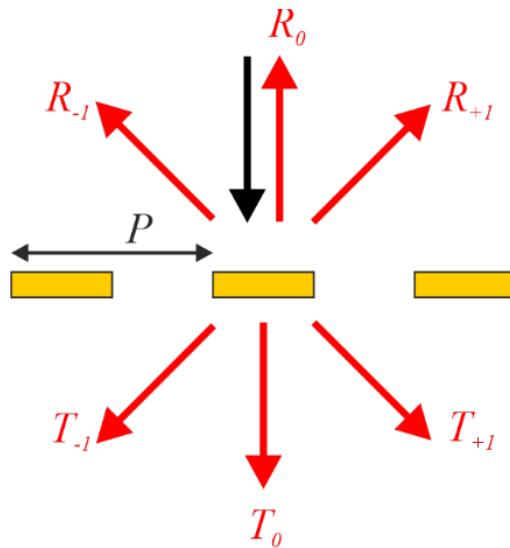
- Au or Ag gratings: Rayleigh and Wood anomalies
- Wood anomaly depends on the excitation of the surface plasmon-polariton



$$k_{\parallel} = k_{\text{SPP}} + \frac{2\pi}{\lambda}$$

# Rayleigh and Wood anomalies

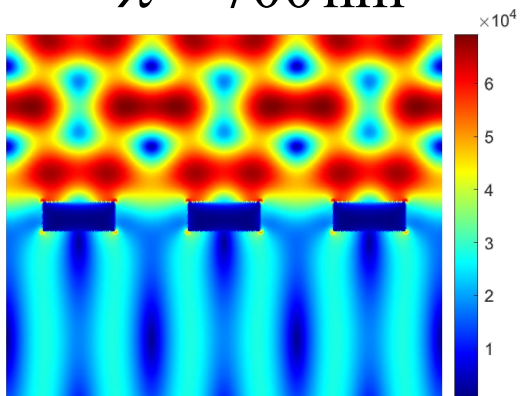
- Drude grating: Rayleigh and Wood anomalies
- Wood anomaly:
  - Full transmission
  - Wood anomaly = Surface lattice resonance



$$\epsilon = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \quad \epsilon_{\infty} = 10 \text{ eV} \quad \omega_p = 8.95 \text{ eV}$$

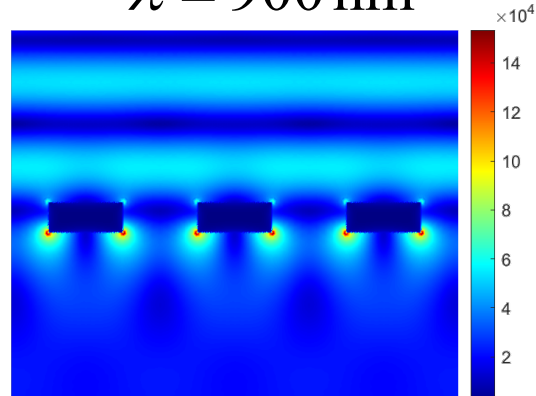
# Rayleigh and Wood anomalies

$\lambda = 700 \text{ nm}$



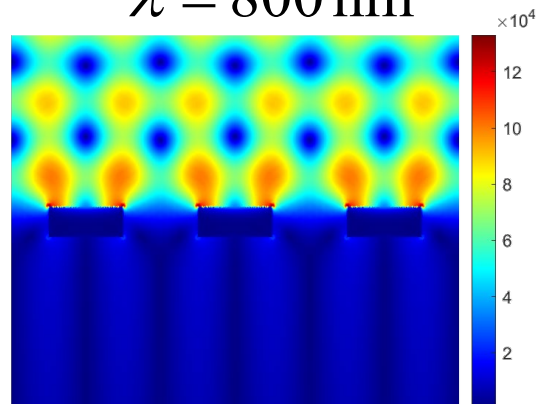
Diffraction

$\lambda = 900 \text{ nm}$



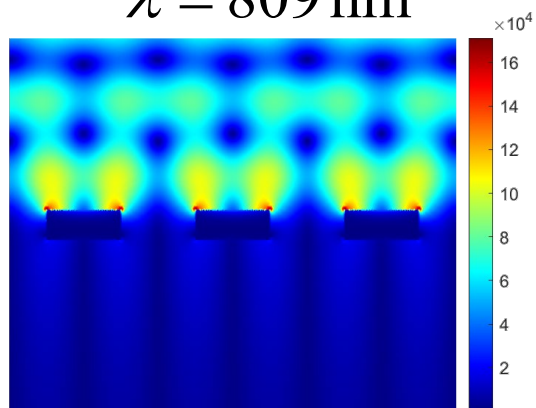
Diffraction-less regime

$\lambda = 800 \text{ nm}$

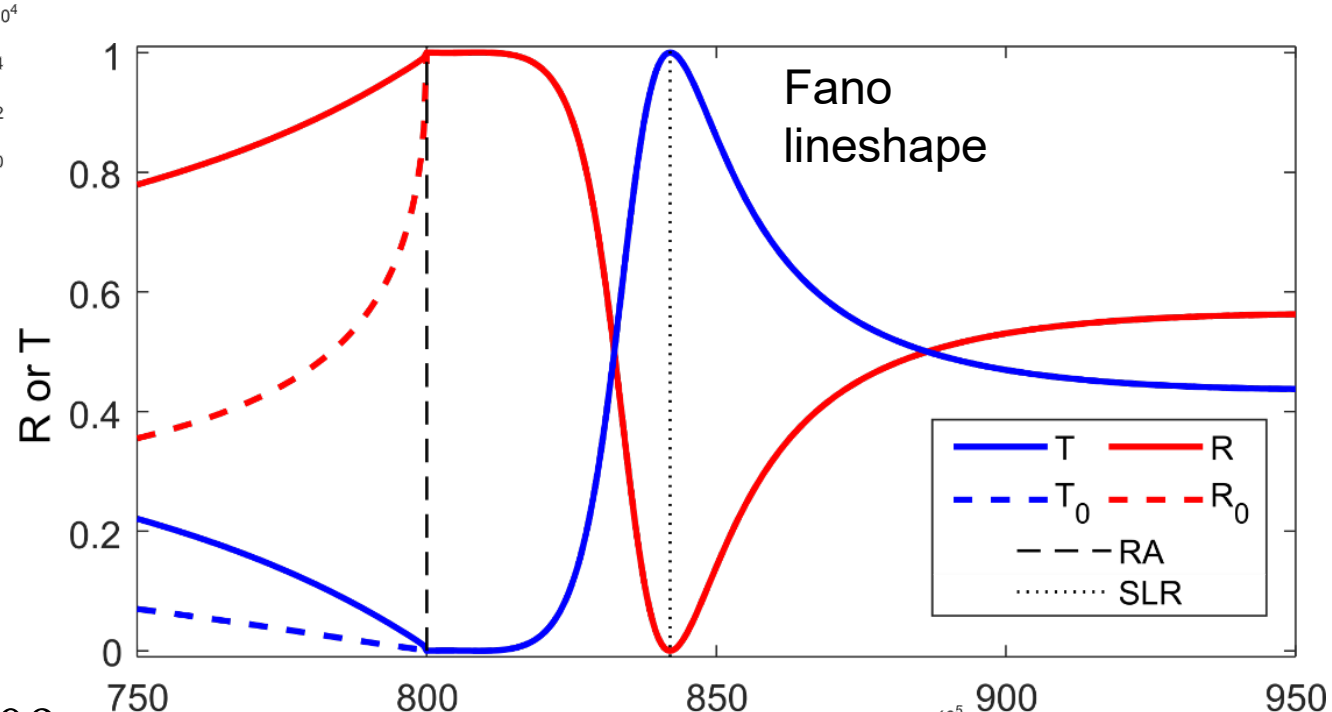


Onset of diffraction

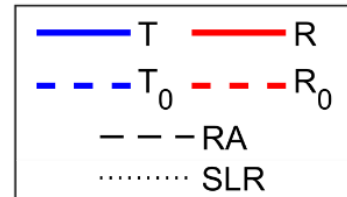
$\lambda = 809 \text{ nm}$



Maximum  $R$

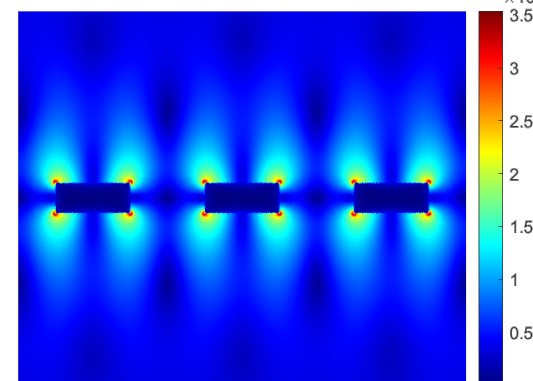


Fano lineshape



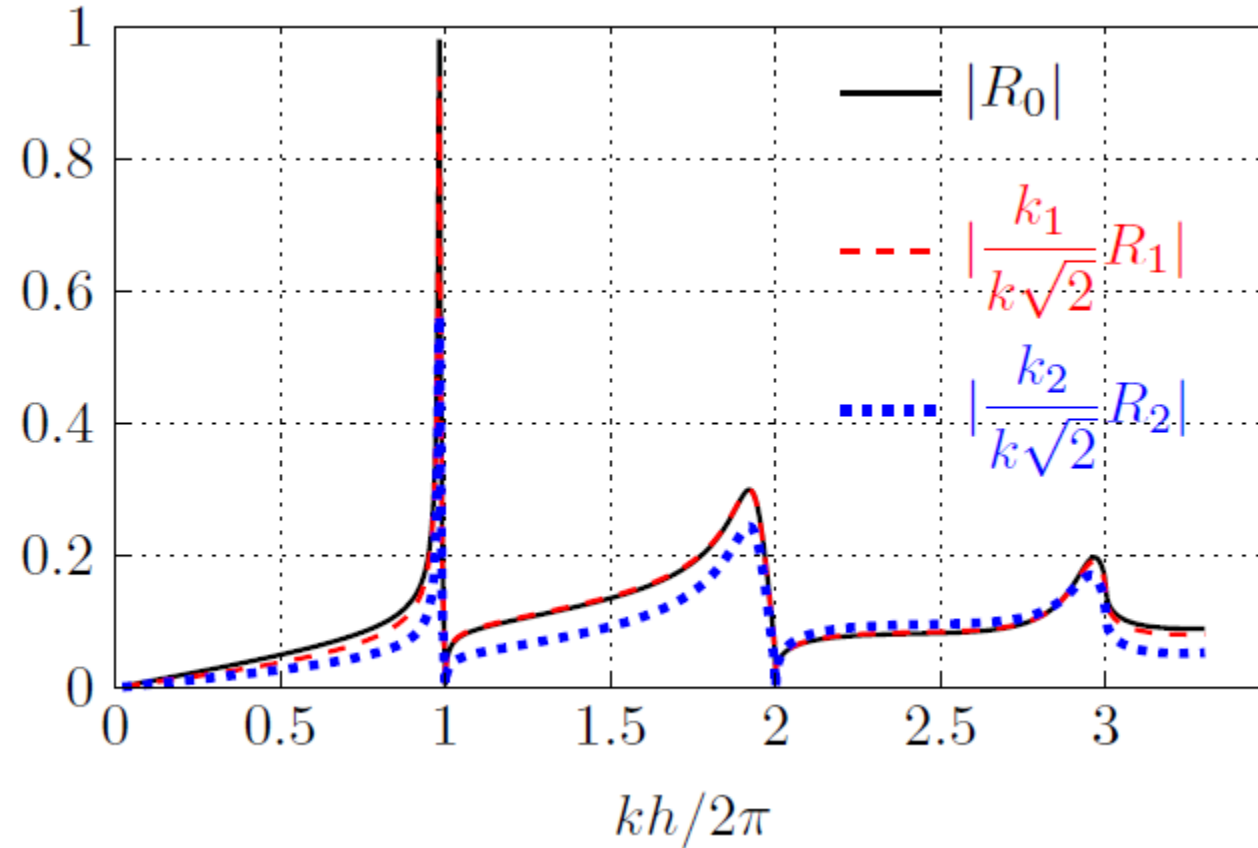
$\lambda = 843 \text{ nm}$

Surface lattice resonance



## Rayleigh and Wood anomalies

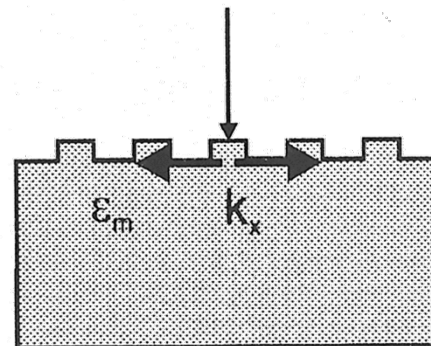
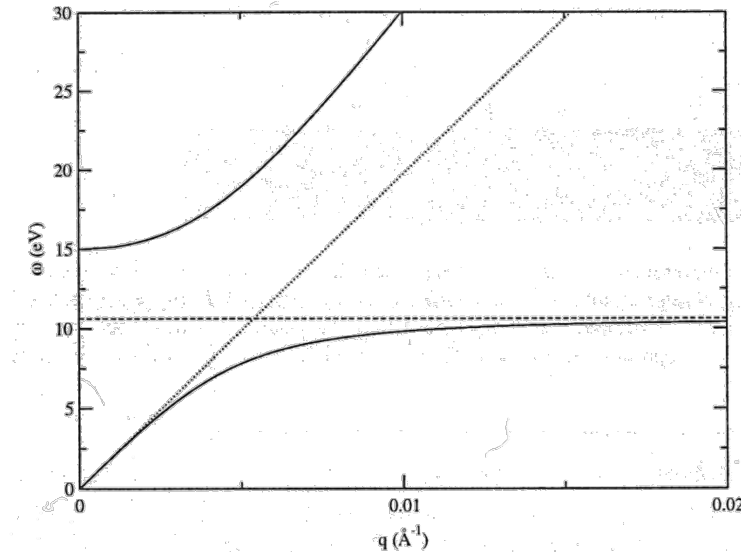
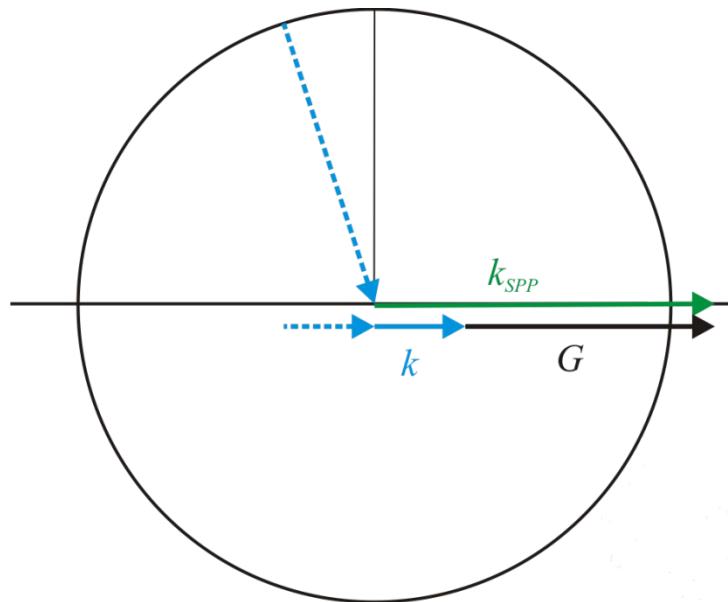
- At specific points, the reflection goes to zero, but just before there are strong scattering peaks



A. Maurel, *J. Europ. Opt. Soc. Rap. Public.* 9, 14001 (2014)

# Excitation of surface plasmon-polariton with a grating

- SPP cannot be excited directly since their wave vector is larger than the free space one; a grating can provide the required additional momentum



# Selected Topics in Advanced Optics

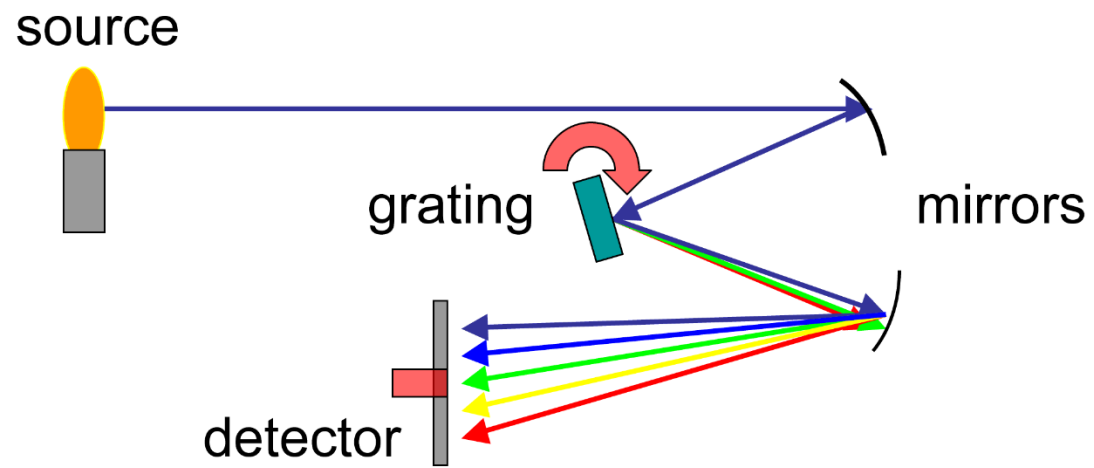
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## Week 8 – part 3

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Nanophotonics and Metrology Laboratory

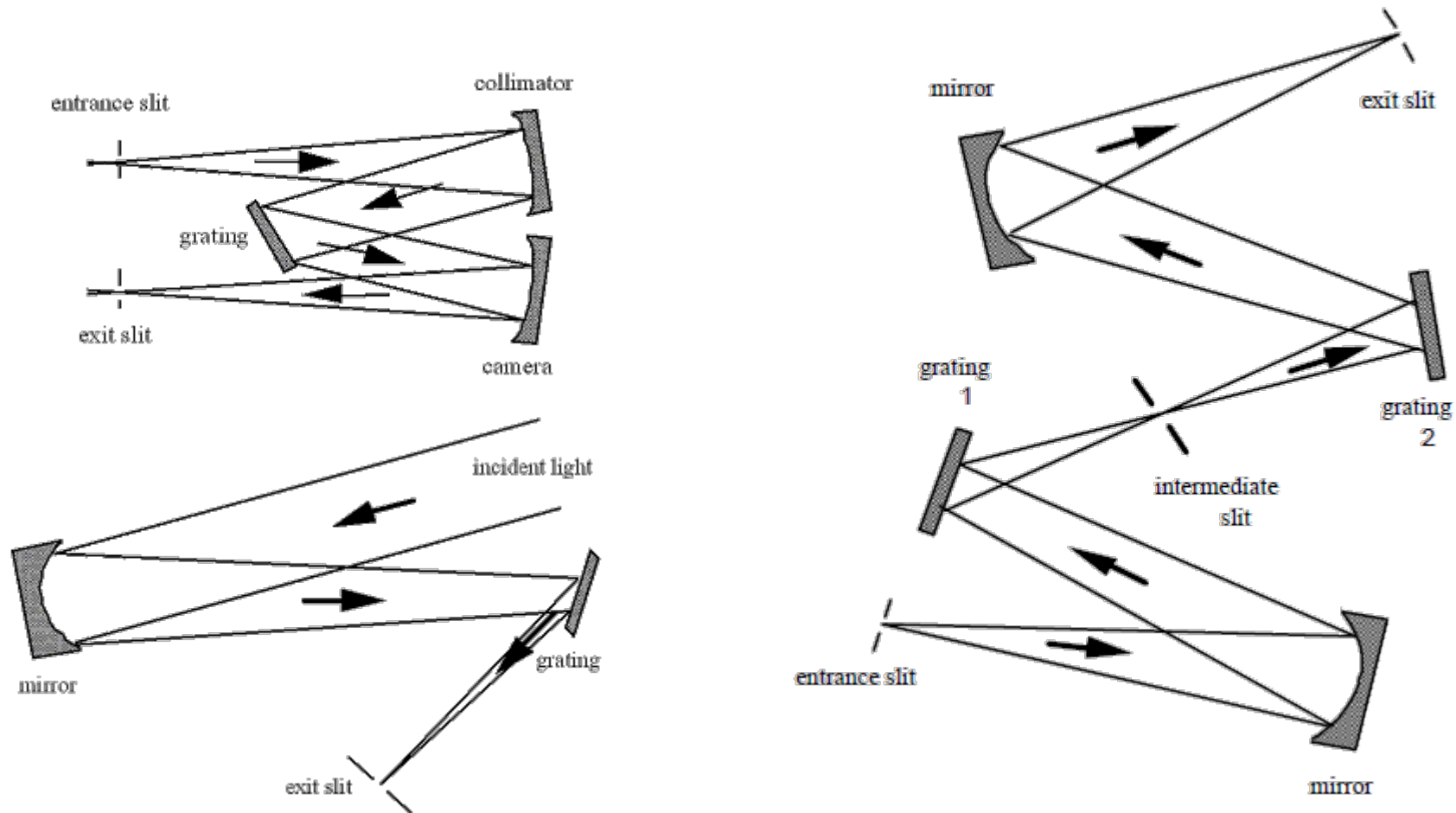
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# Spectrometer - monochromator



# Spectrometer – monochromator

- Different configurations exist, but the principle is always the same
- Some elements (grating, mirror) can rotate, or an extended camera can be used to record the spectrum



# Spectrometer – monochromator

ASTRONOMY & ASTROPHYSICS

OCTOBER II 1996, PAGE 373

SUPPLEMENT SERIES

*Astron. Astrophys. Suppl. Ser.* **119**, 373-390 (1996)

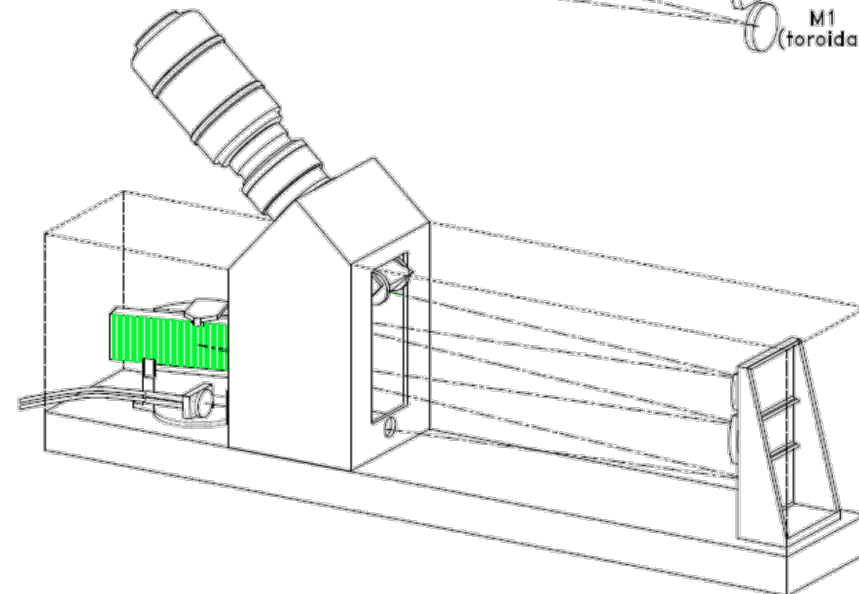
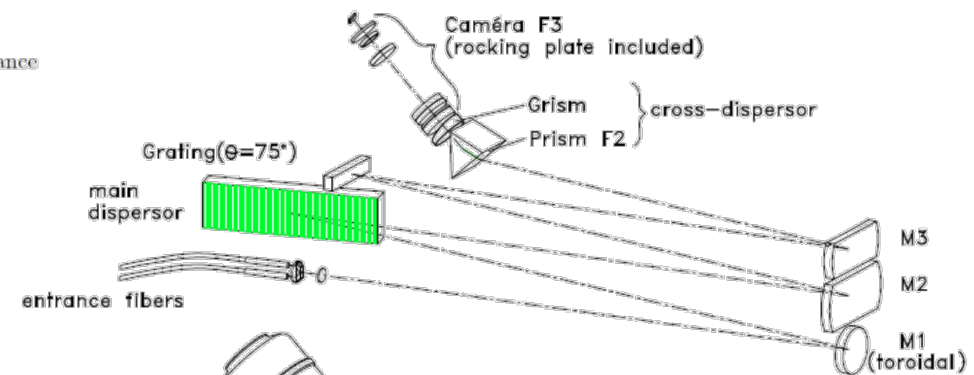
## ELODIE: A spectrograph for accurate radial velocity measurements

A. Barame<sup>1</sup>, D. Queloz<sup>2</sup>, M. Mayor<sup>2</sup>, G. Adrianszyk<sup>3</sup>, G. Knispel<sup>3</sup>, D. Kohler<sup>3</sup>, D. Lacroix<sup>3</sup>, J.-P. Meunier<sup>3</sup>,  
G. Rimbaud<sup>3</sup> and A. Vin<sup>3</sup>

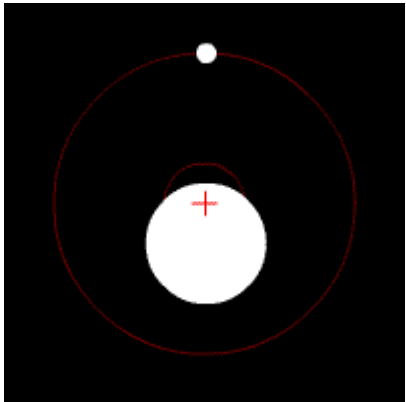
<sup>1</sup> Observatoire de Marseille, 2 Place Le Verrier, F-13248 Marseille, France

<sup>2</sup> Observatoire de Genève, CH-1290 Sauverny, Switzerland

<sup>3</sup> Observatoire de Haute-Provence, F-04870 Saint Michel l'Observatoire, France

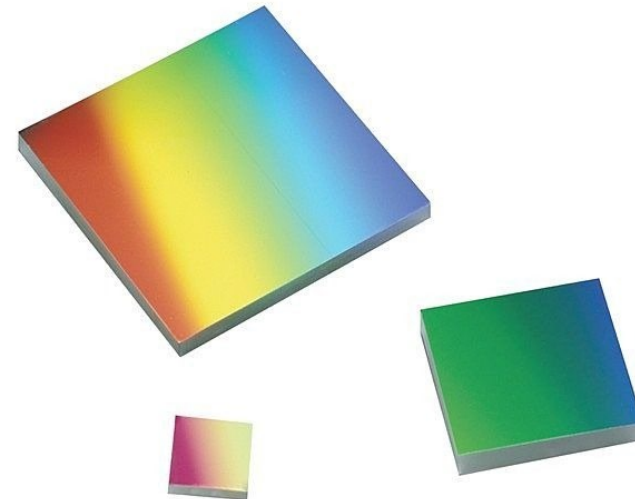
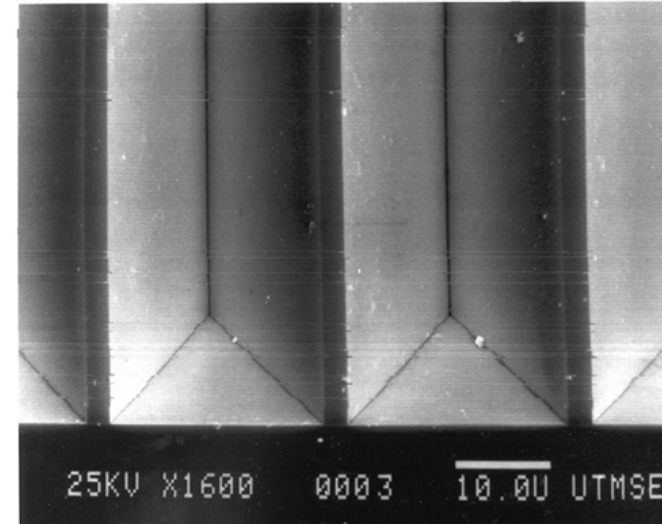
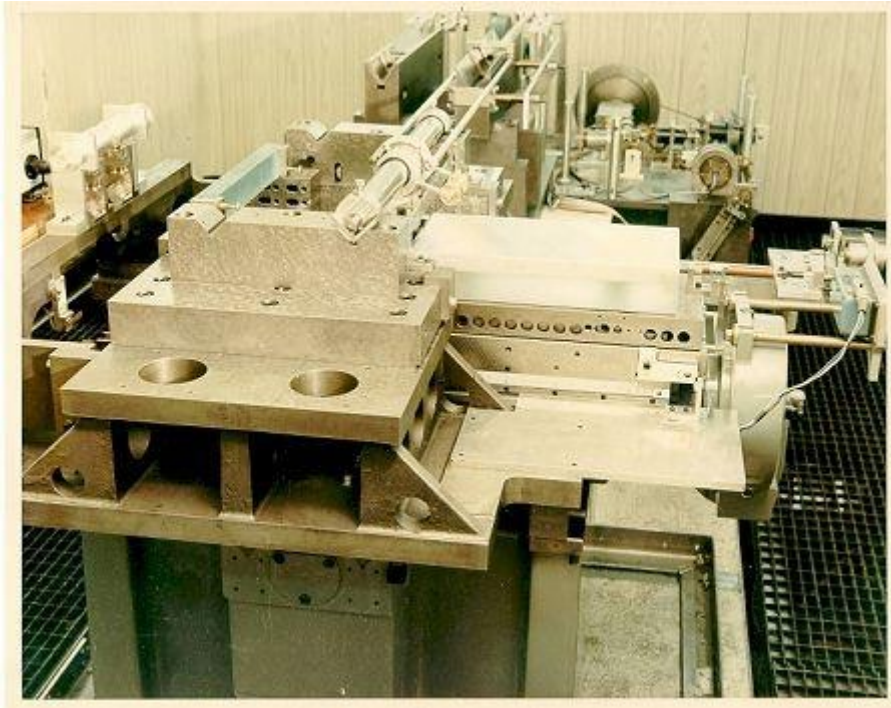


Olivier J.F. Martin



## Grating fabrication – Ruled grating

- The grating is mechanically "inscribed" into a glass or metal substrate



Newport

# Grating fabrication – Holographic grating (interference)

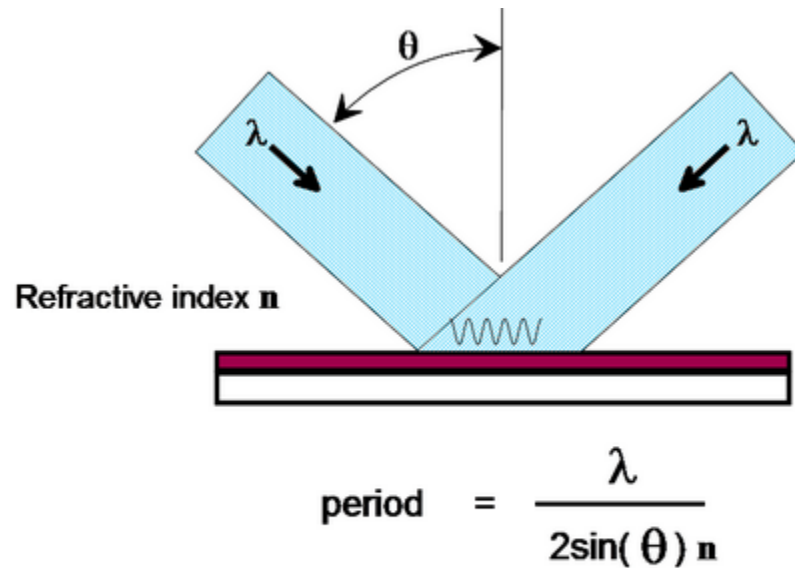
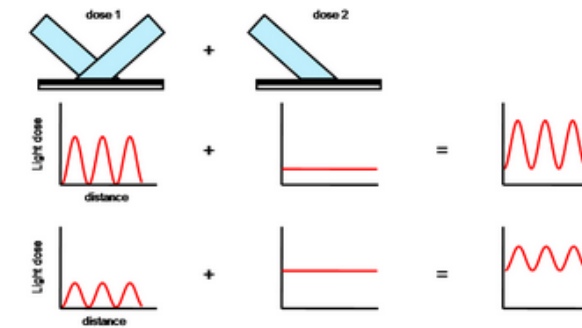


Figure 1. Schematic diagram of interferometric lithography



UVII-HS Resist, 230 nm lines on 500 nm pitch

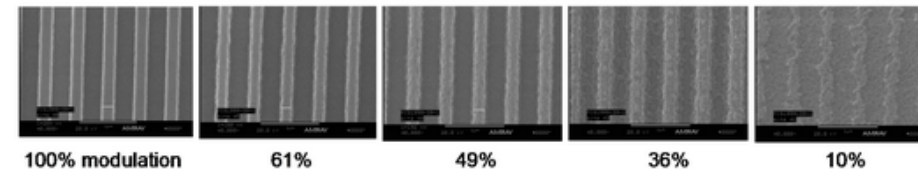
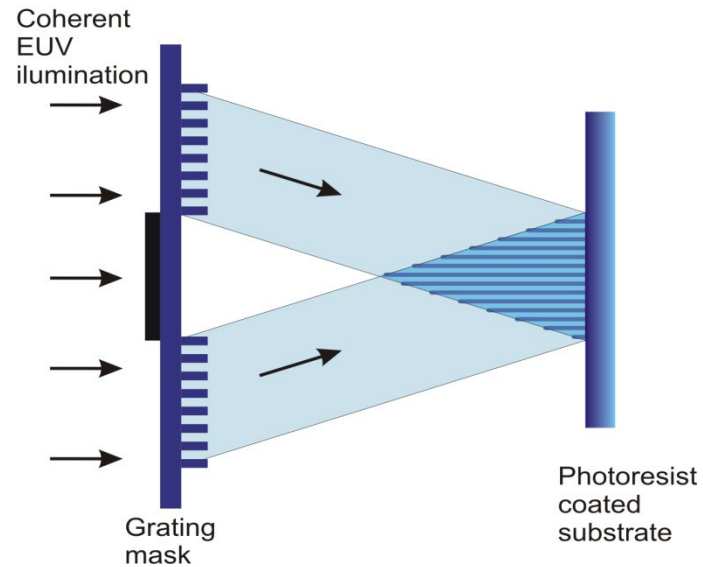


Figure 2. Control of aerial image contrast in interferometric lithography to test resist LER response

- A more general approach is based on holography and can be used to inscribe gratings inside a volume.

## Grating fabrication – Holographic grating (interference)

- The incident wavelength determines the minimal period that can be achieved
- EUV lithography from undulator ( $\lambda=13$  nm)



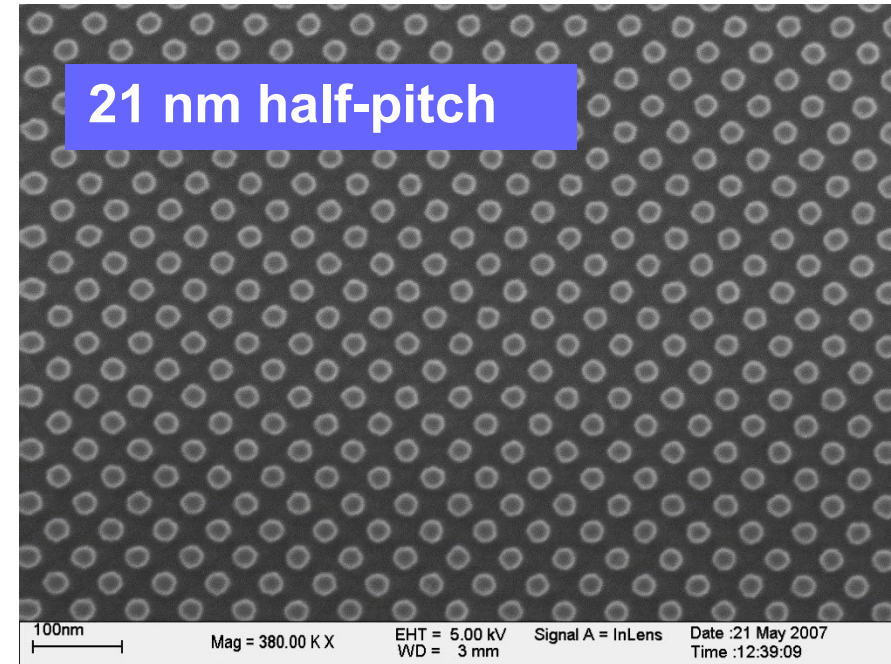
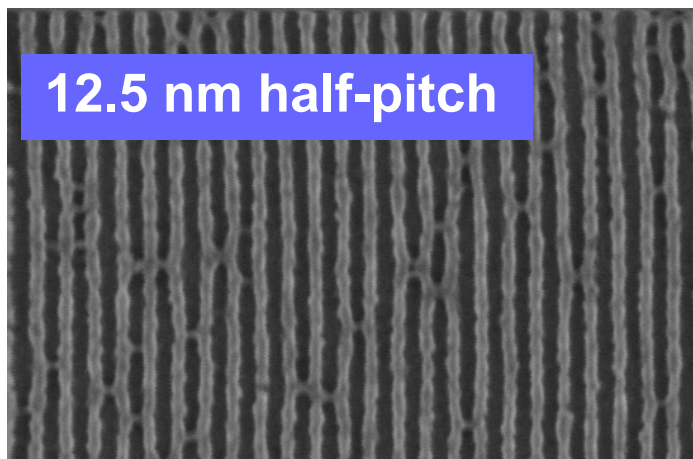
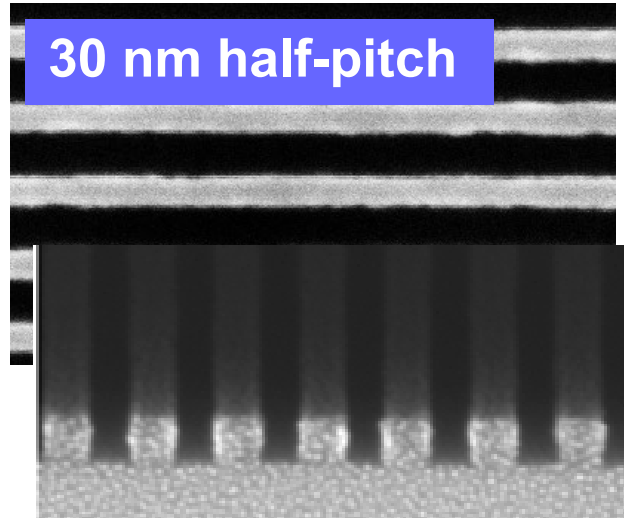
Performance:  
20-50nm period  
1-4 mm<sup>2</sup> area  
10-30 sec exposure



[lmn.web.psi.ch](http://lmn.web.psi.ch)

# Grating fabrication – Holographic grating (interference)

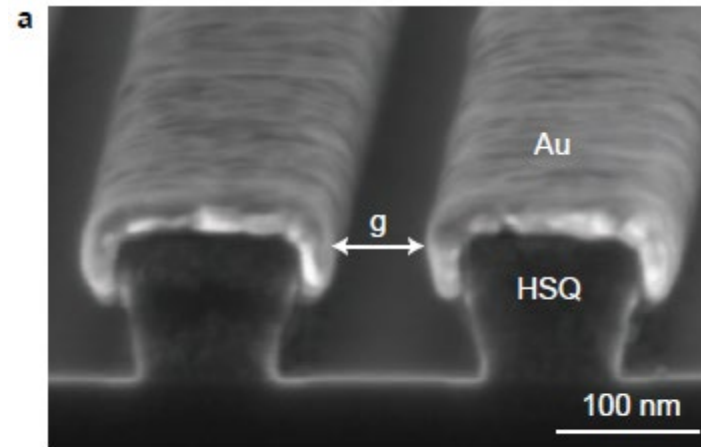
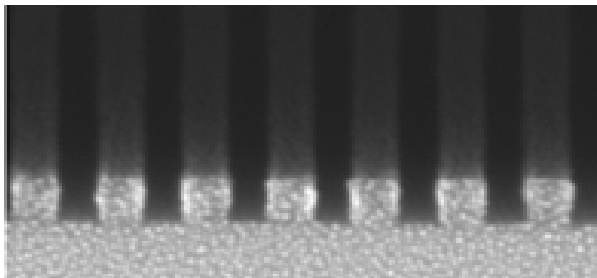
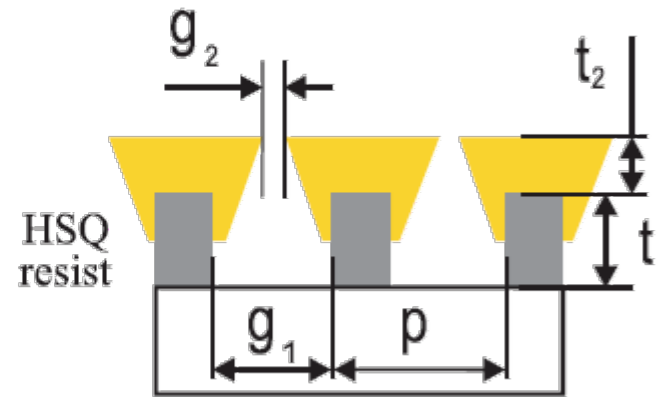
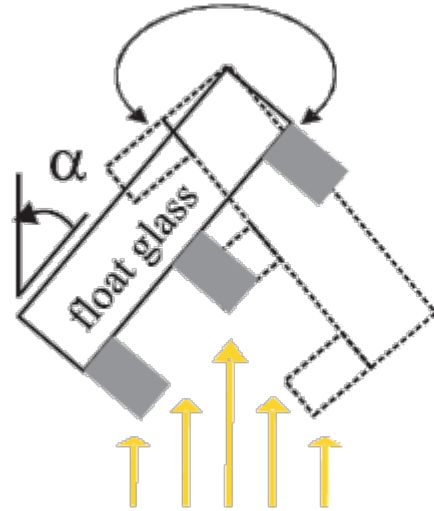
- Typical periodic structures that can be obtained by EUV interference lithography



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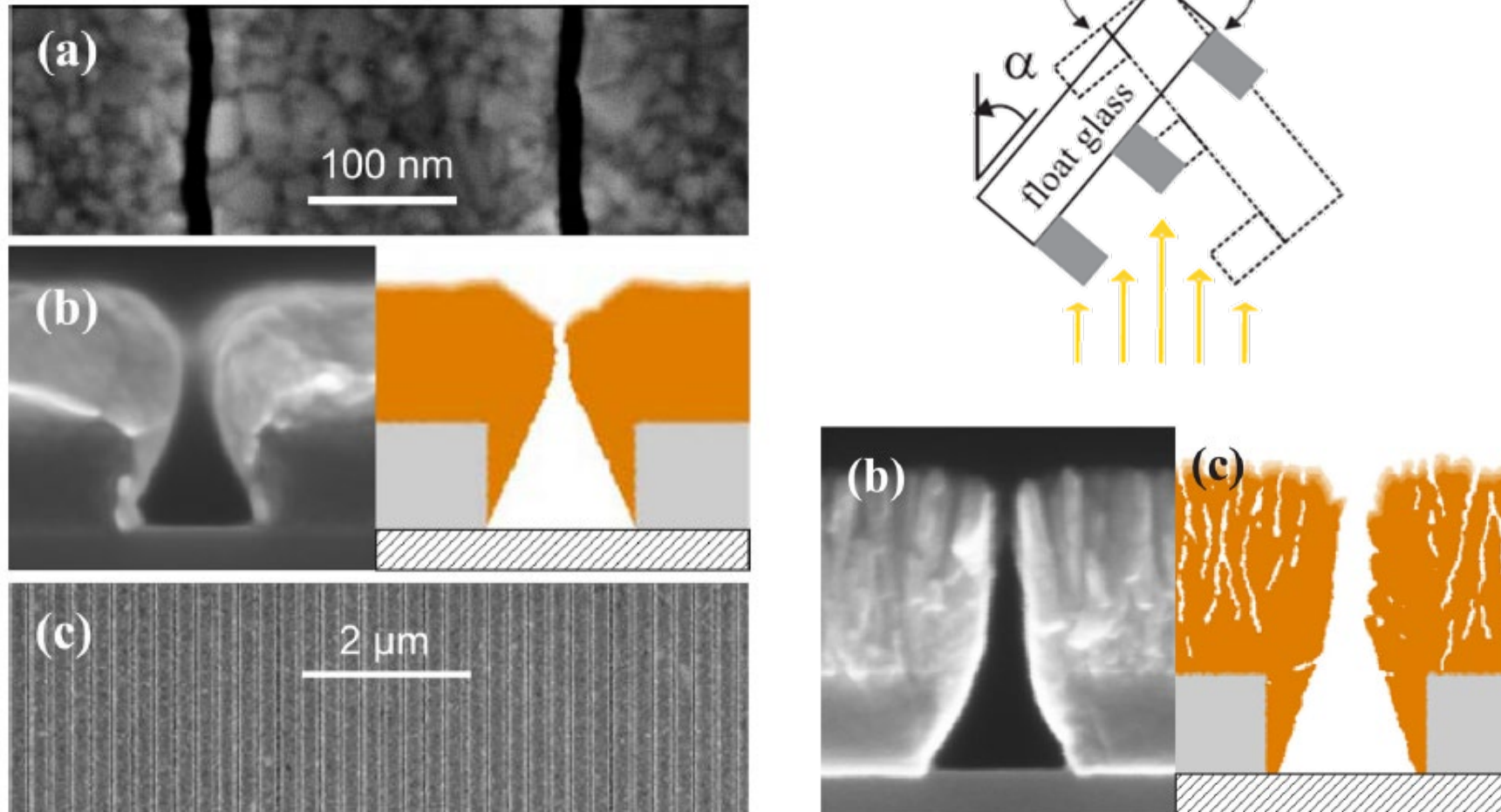
# Fabrication of sub-10nm gaps in gold

- Shadow evaporation of gold on the photoresist structure
- Successive, alternating direction, evaporation steps



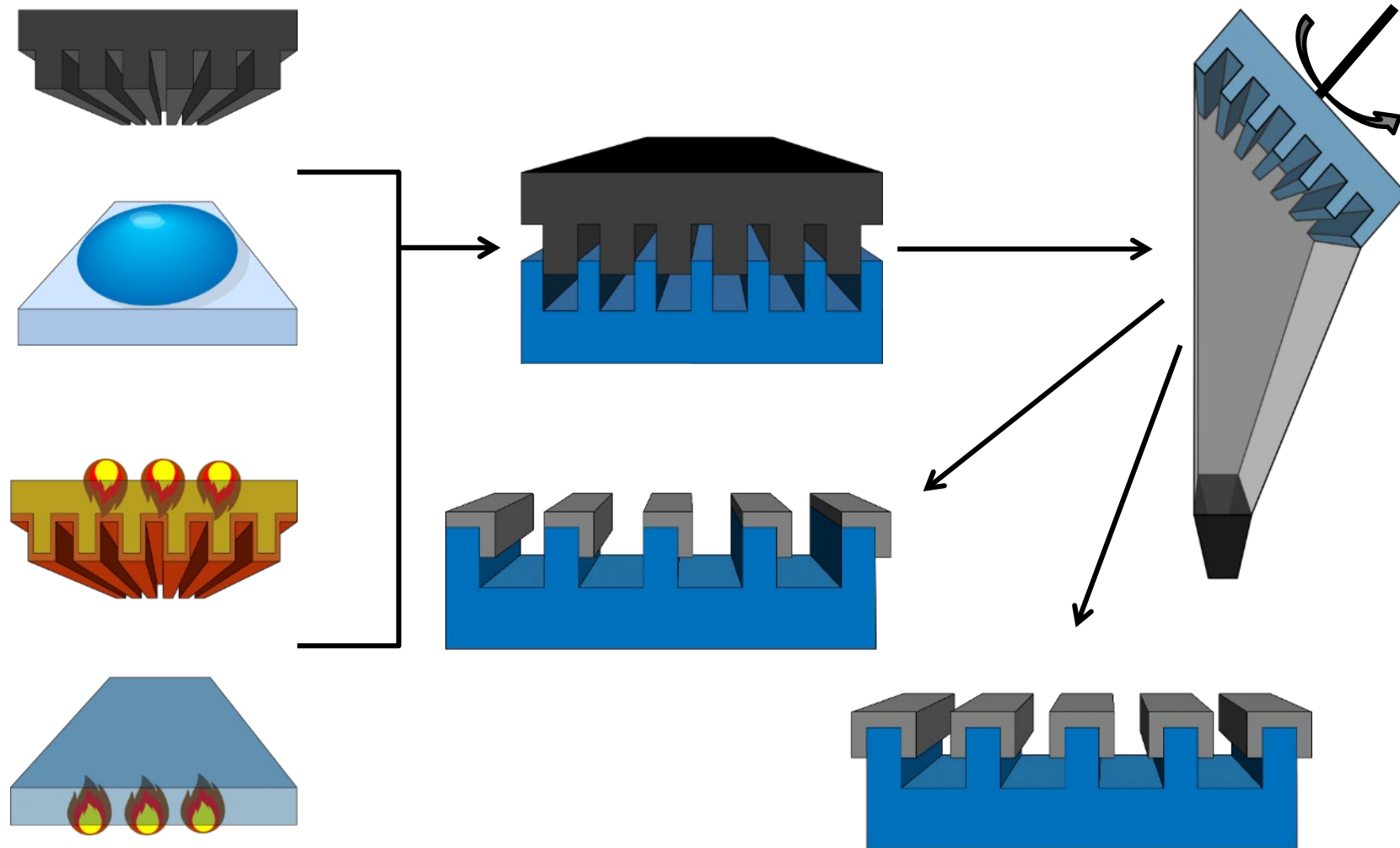
# Fabrication of sub-10nm gaps in gold

- Self-limiting process that can produce extremely narrow gaps over large areas



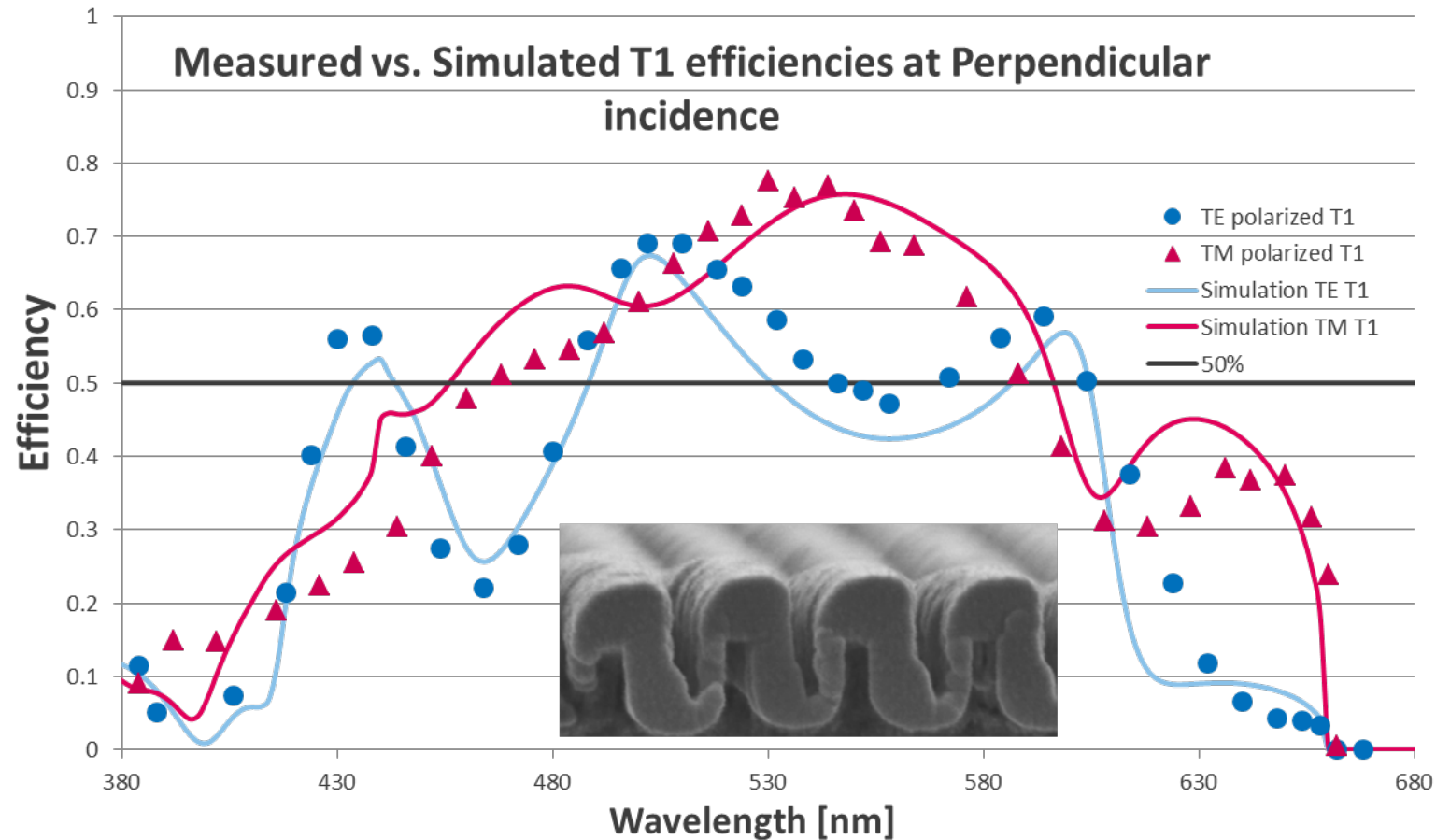
# Blazed Grating fabrication: Interference + angled evaporation

- Blazed gratings are complicated to fabricate
- Angled evaporation provides a useful technology



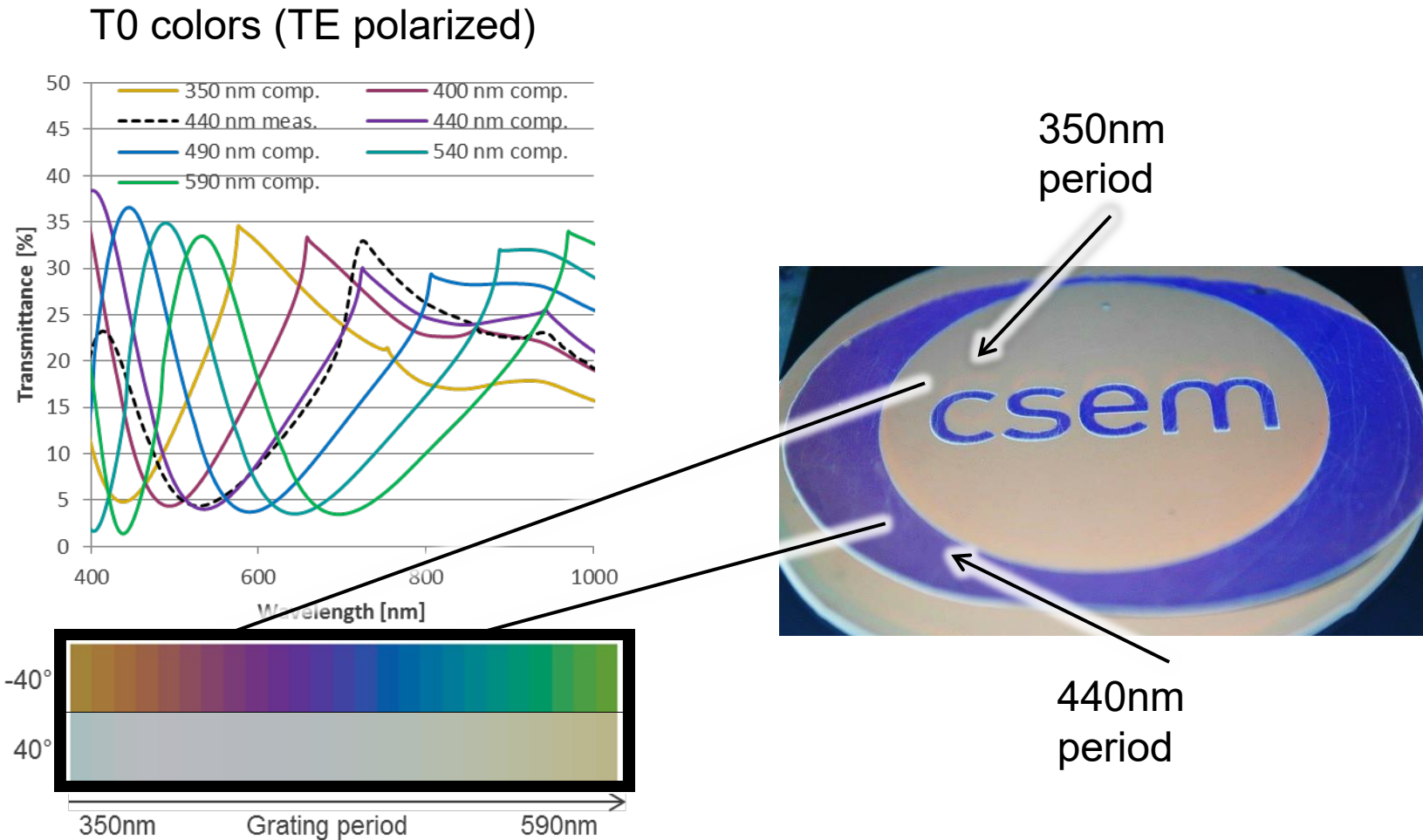
# Blazed Grating fabrication: Interference + angled evaporation

- A similar response to ruled blazed gratings



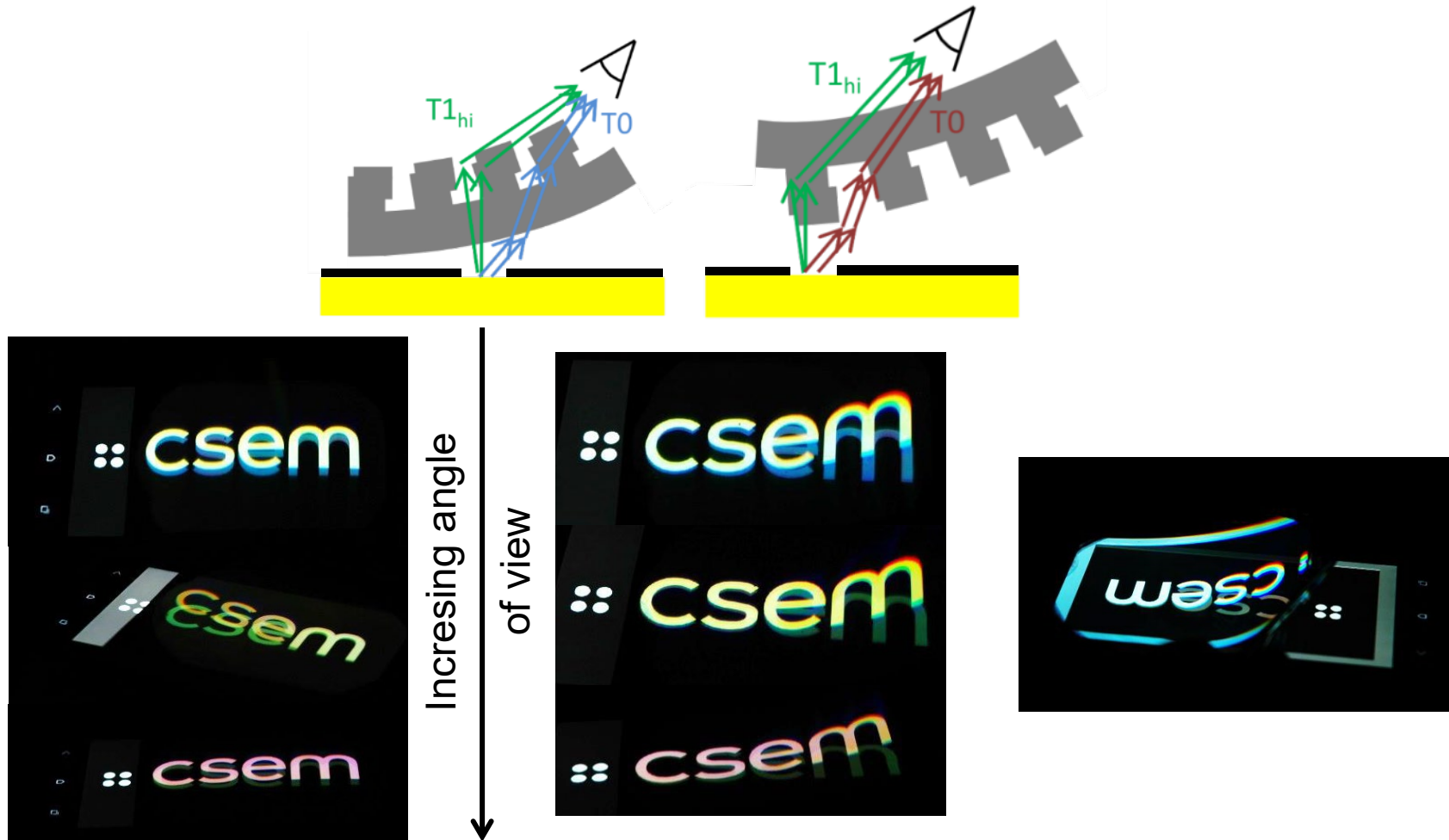
# Blazed Grating application: Colours through the grating period

- Varying the period produces different colours



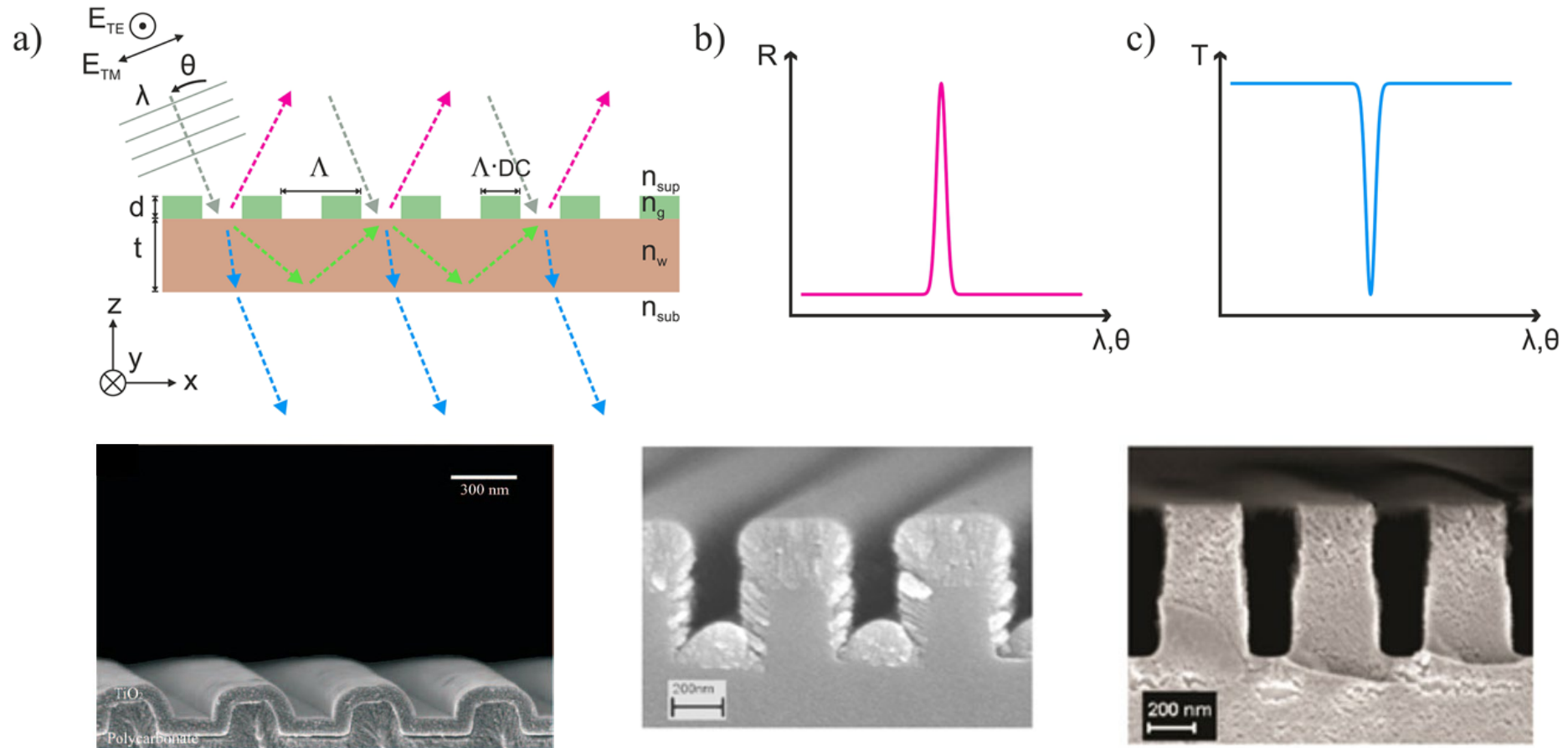
# Blazed Grating application: Fancy floating colour effects

- By superposing different grating orders, it is possible to give the impression that there are two superposed images



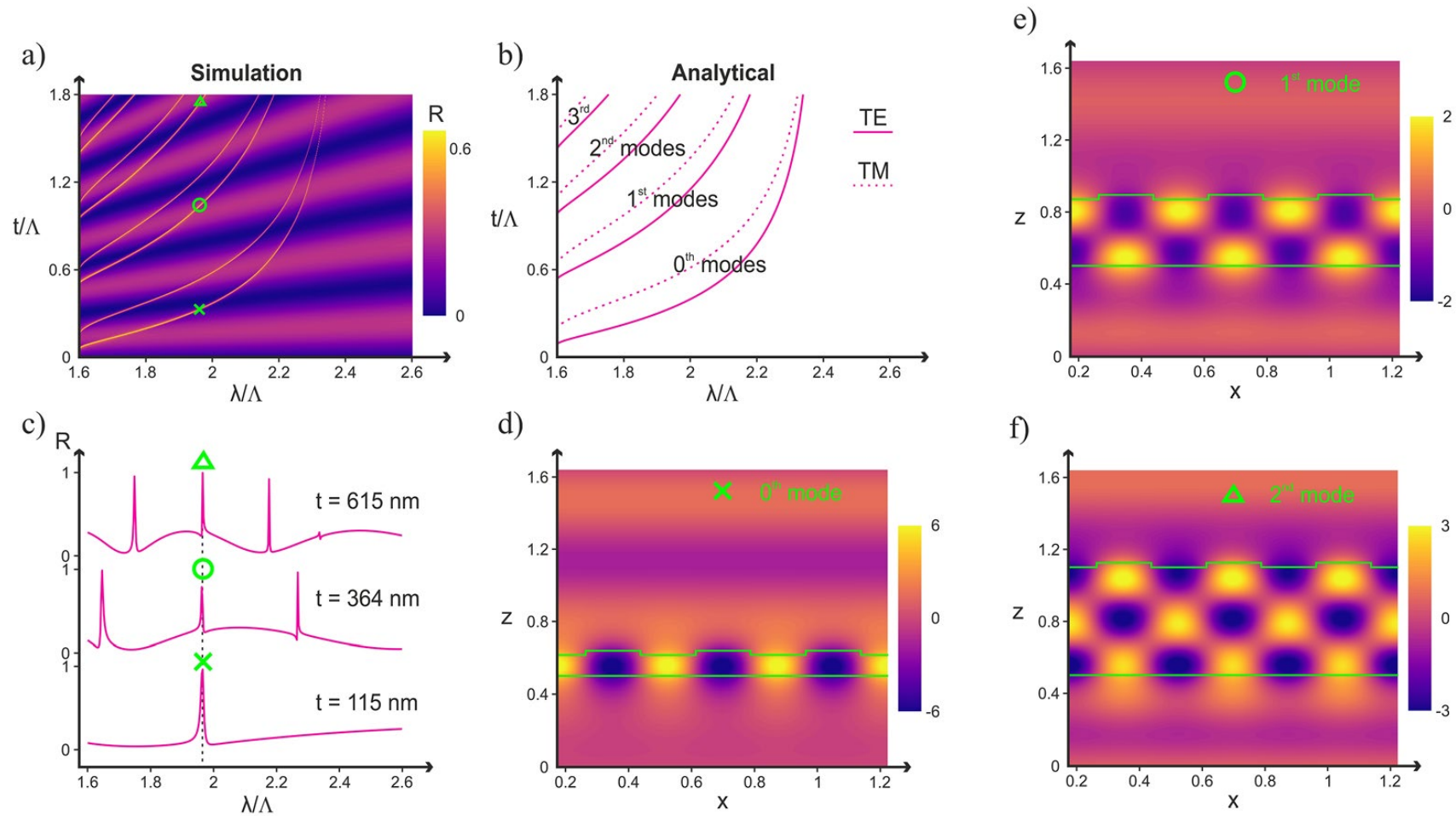
# Resonant waveguide gratings

- Microscopic optical components built from grating(s) and a waveguide



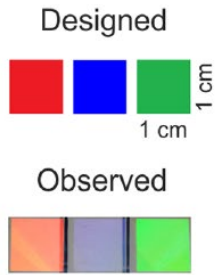
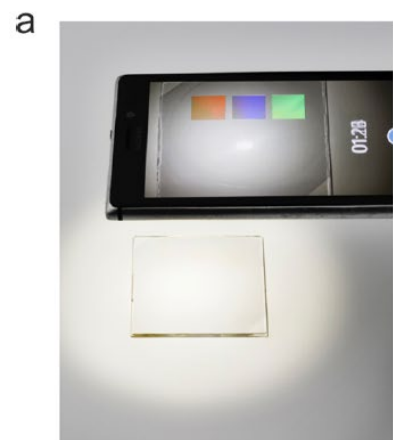
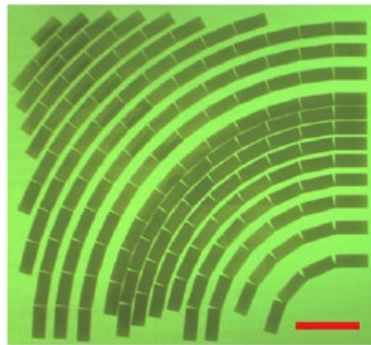
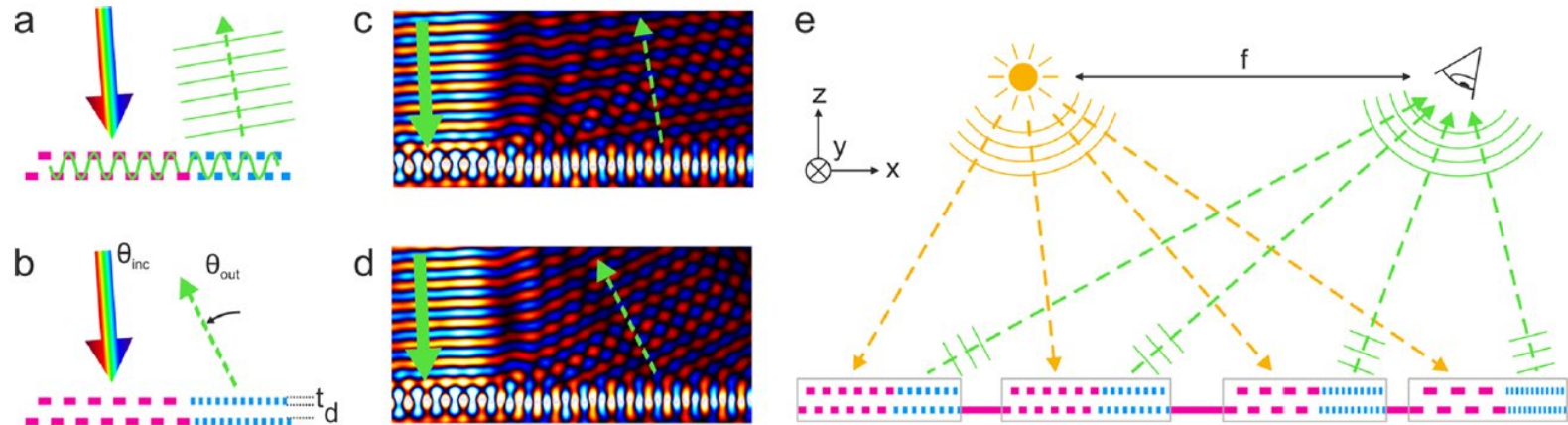
# Resonant waveguide gratings

- Different modes can be excited in the waveguide



# Resonant waveguide gratings

- Two gratings can be combined to select the wavelength and the out-coupling direction and produce colour elements



# Resonant waveguide gratings

- Since they are sensitive to their environment, such structures can be used for sensing

