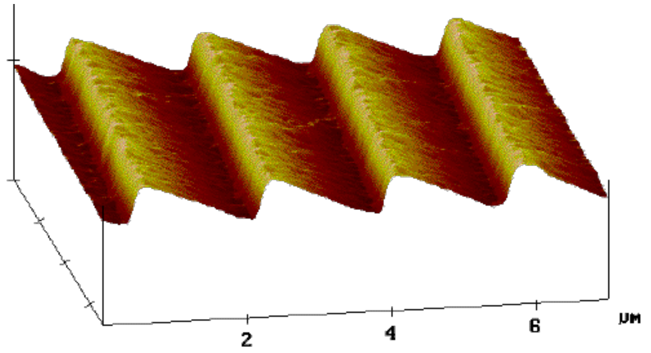
Selected Topics in Advanced Optics

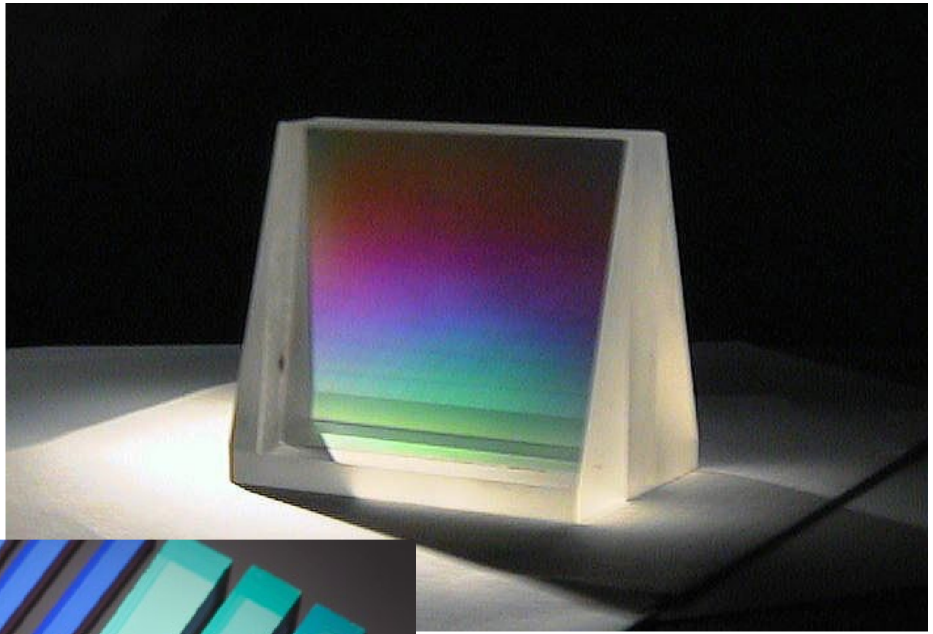
Week 8 – part 1

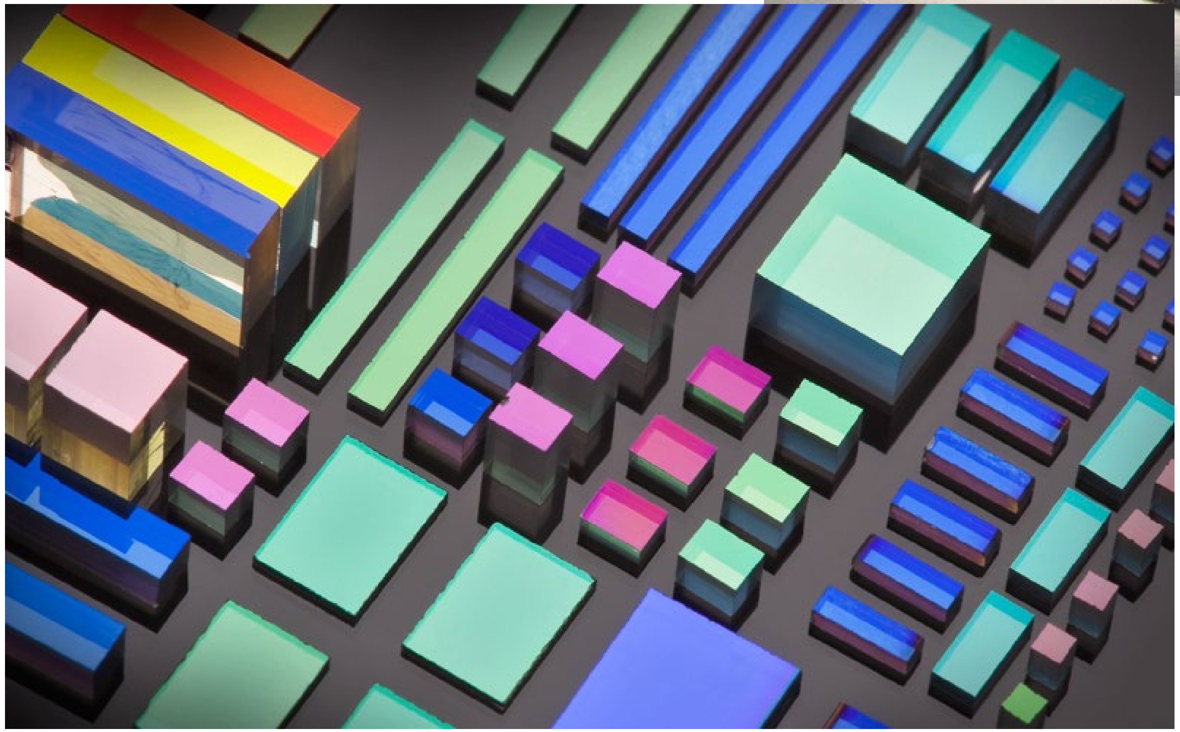
Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

EPFL

Gratings, stratified media and photonic crystals
Part I – Gratings







Olivier J.F. Martin

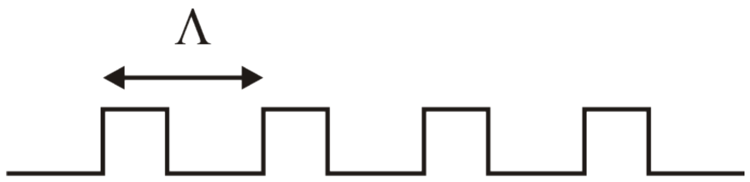
Some references

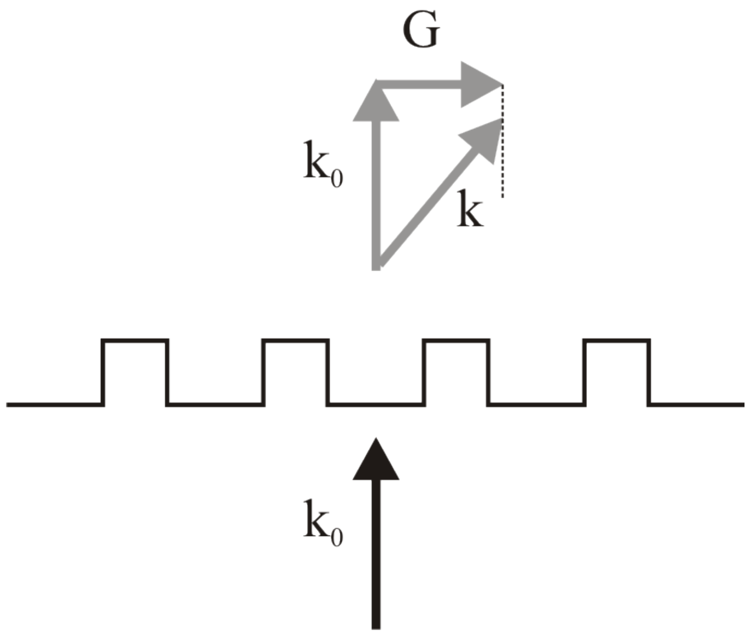
- B.E.A. Saleh & M.C. Teich, Fundamental of photonics 2nd Ed. (Wiley, Hoboken, 2007), Chapter 7.
- C. Palmer and E. Loewen, Diffraction grating handbook 6th Ed. (Newport Corporation, Rochester), available at gratings.newport.com and on Moodle.

Bragg grating on a surface – Transmission

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

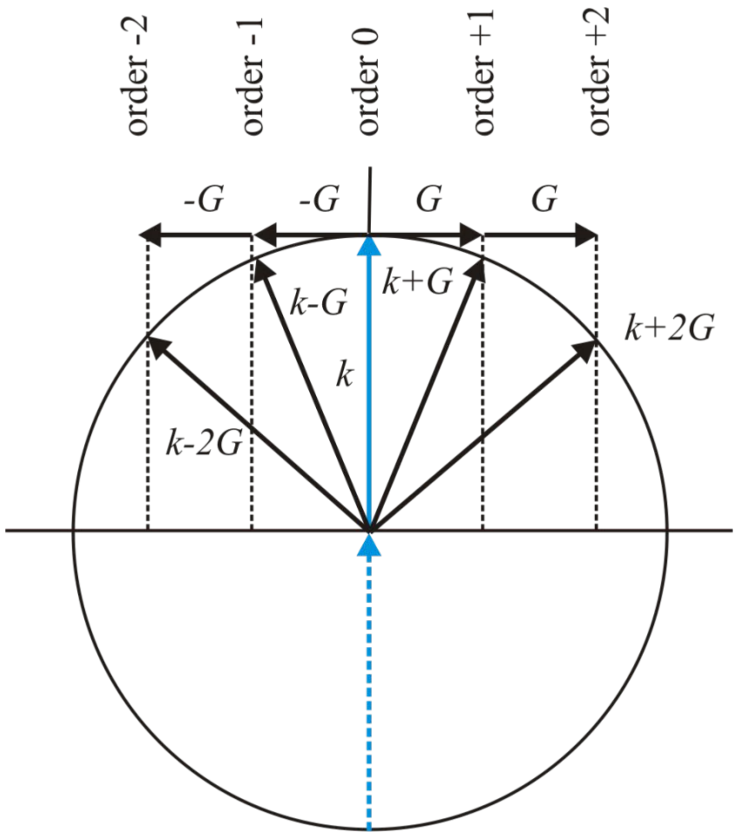
$$G = g = 2\pi / \Lambda$$

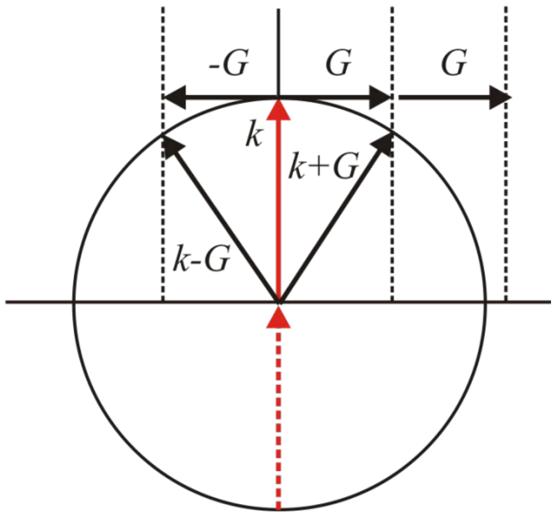




Bragg grating on a surface – Transmission

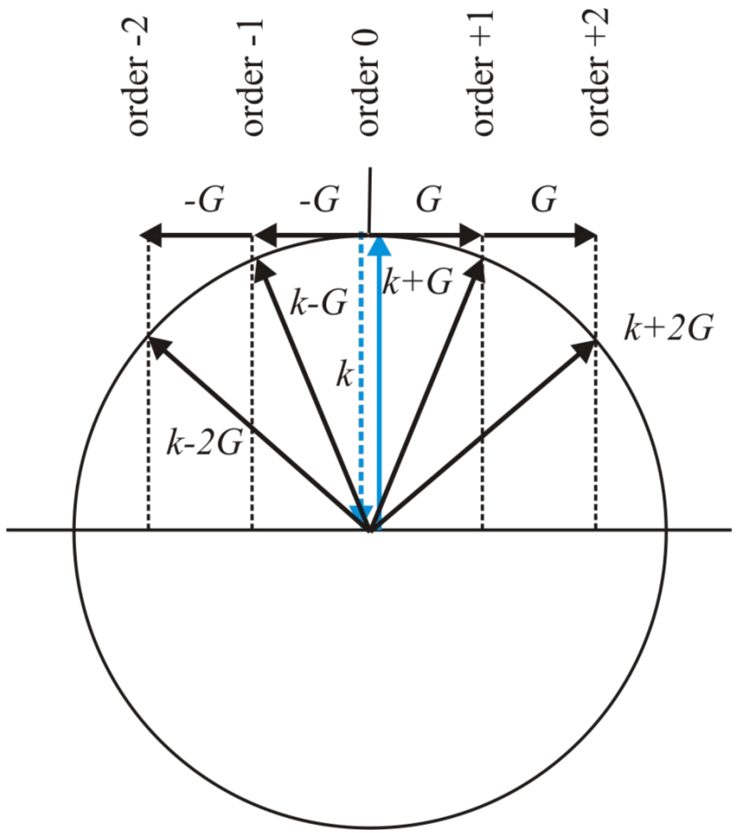
- The direction of the wave scattered by the grating depends on the periodicity and on the frequency
- Not all the orders exist for all frequencies; there are cases where no orders exist

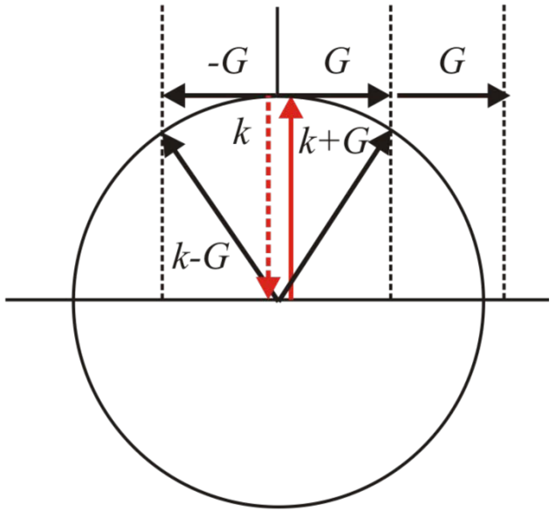




Bragg grating on a surface – Reflection

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

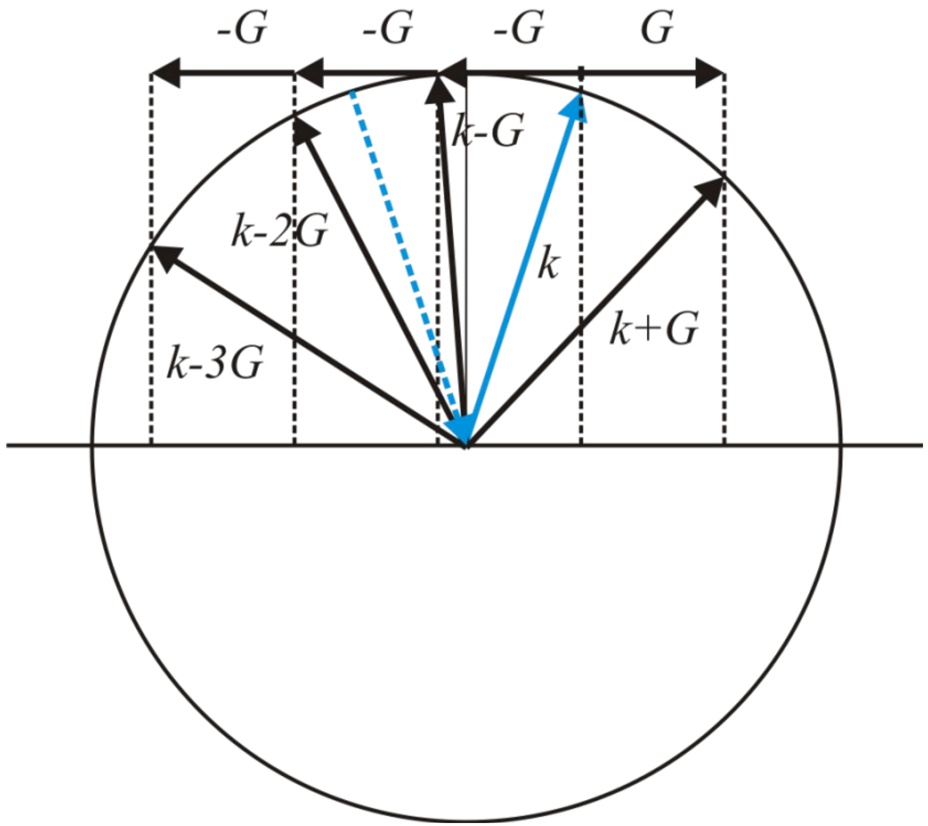




Olivier J.F. Martin

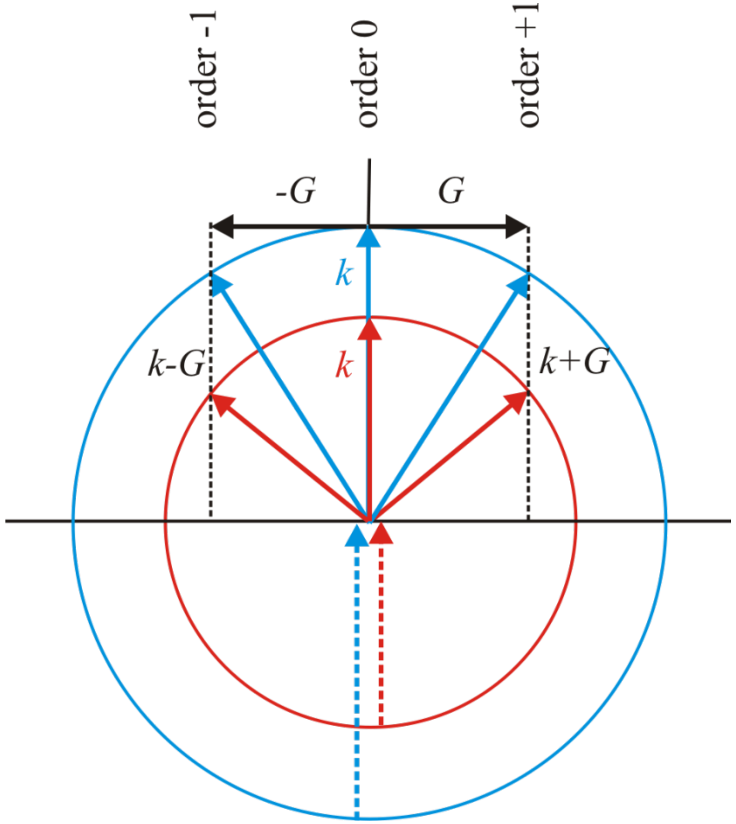
Bragg grating on a surface – Non-normal incidence

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



Bragg grating on a surface – Spectral spread

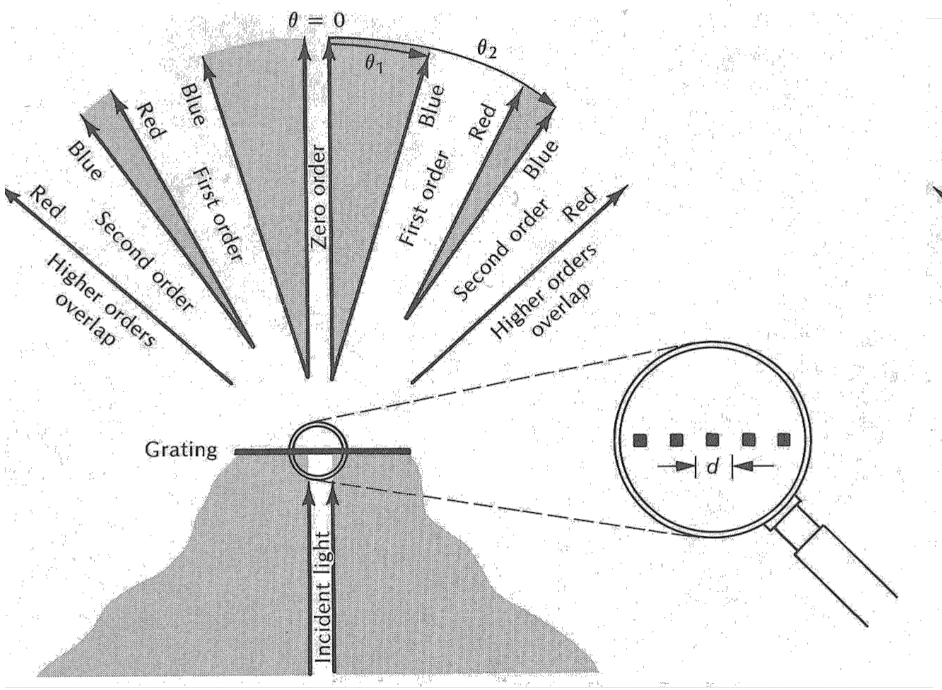
- Since the direction of the diffraction orders depends on the wavelength, a grating can be used to spread the different colours (like a prism)

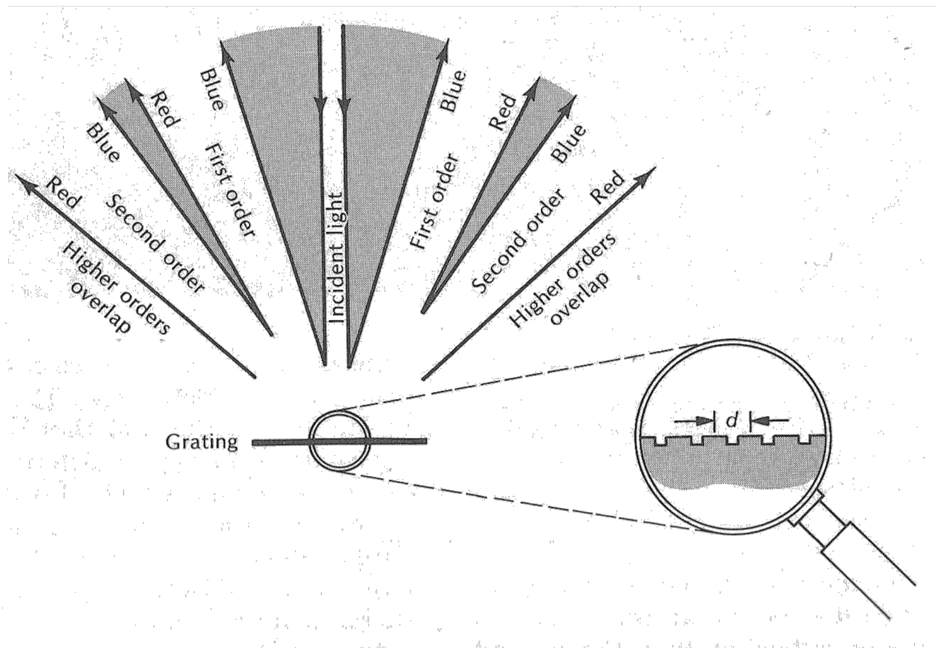


- The colour order is the same within each order

Bragg grating on a surface – Spectral spread

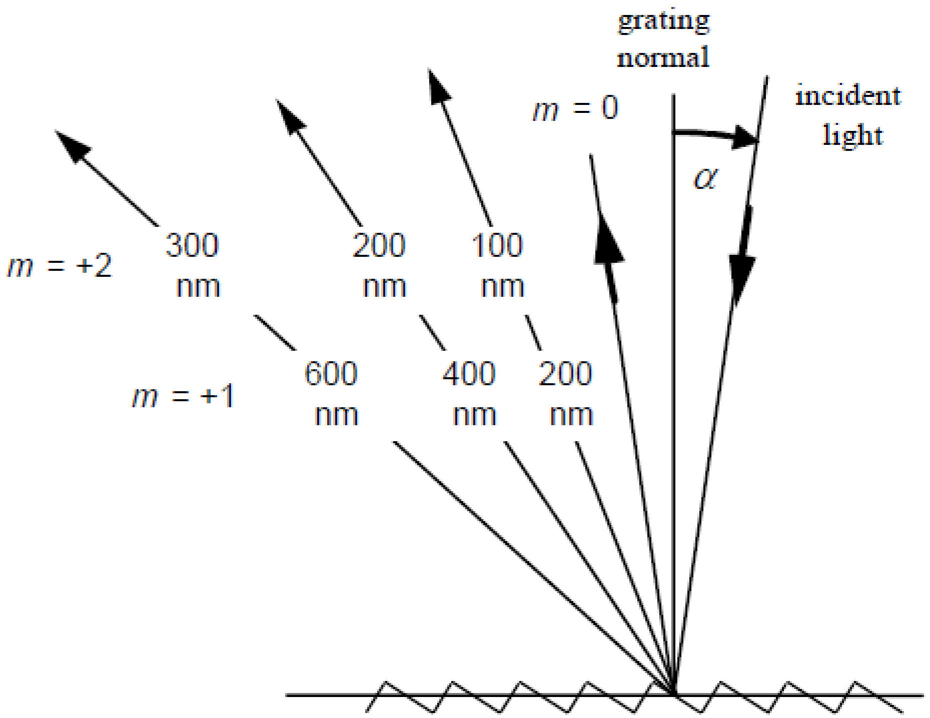
- A grating can work in reflection or transmission; the orders are the same
- The spatial spread increases with the order (i.e. red and blue are more separated in a high order, and can even overlap between orders)





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:

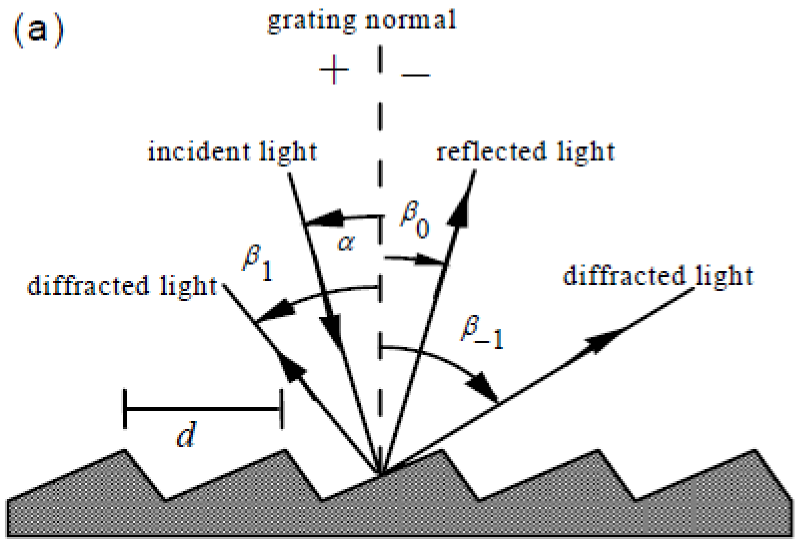


- The resolving power R of a grating is a measure of its ability to separate adjacent spectral lines of average wavelength λ : $R = \lambda / \Delta\lambda$
- For example Sodium D-line doublet: λ=589.00 nm and 589.59 $\rightarrow$ R=1000

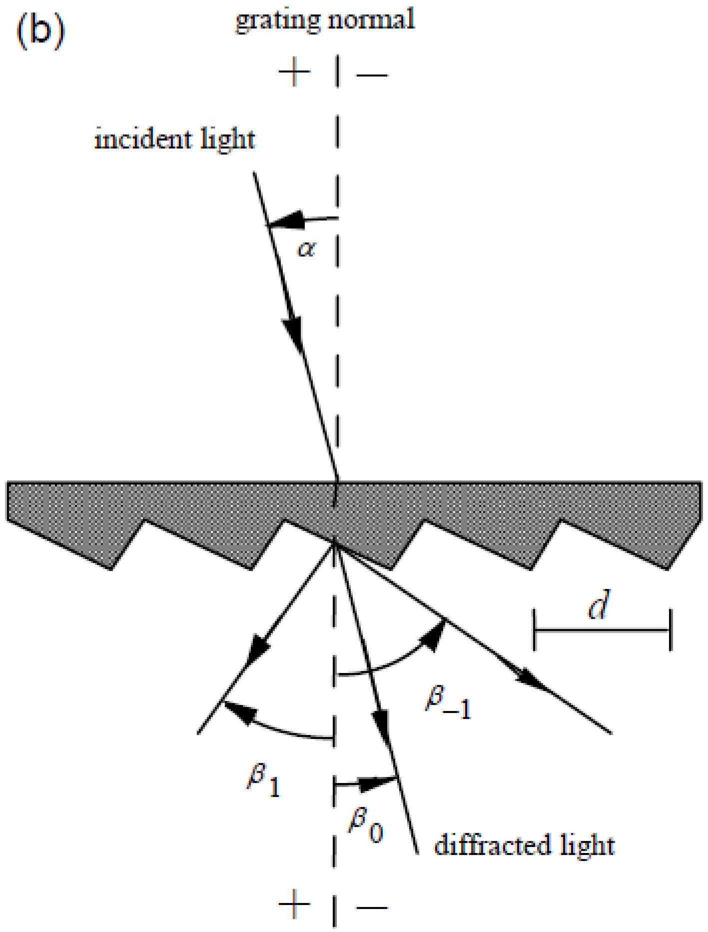
Grating equation – Sign convention

- The angles are measured from the normal to the grating to the beam (→ different signs for the different β below)

Reflection grating:

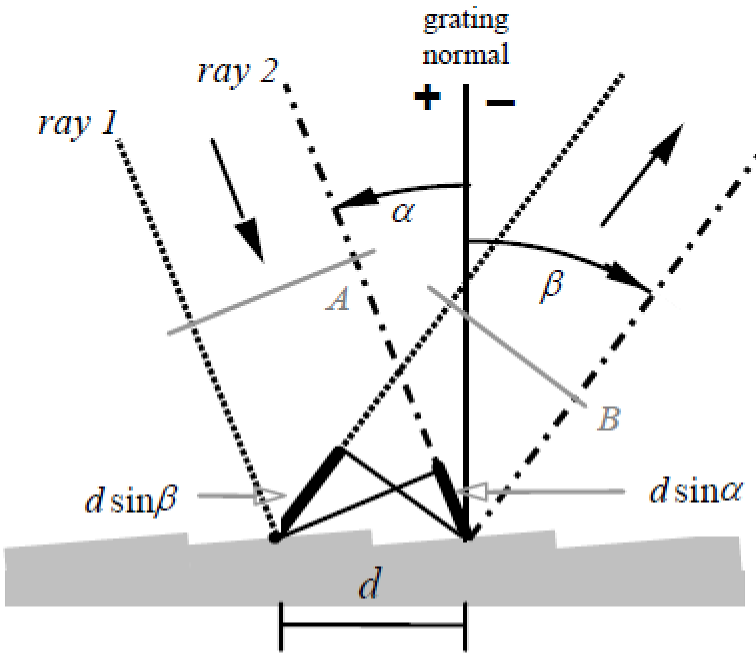


Transmission grating:



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 λ:

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

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

Existence of the different diffraction orders

- Assuming normal incidence (α=0): $\sin\beta = m\dfrac{\lambda}{d}$
- The first diffracted orders appear for $m = \pm 1$
- The cutoff for the first order modes appears when $\beta = 90^\circ$

$$\sin\beta = m\frac{\lambda}{d} \quad \rightarrow \quad \mathrm{d} = \lambda$$

- No diffraction order if $\mathrm{d} < \lambda$ (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,±1, ±2,…): $\mathrm{M} = \dfrac{2d}{\lambda} + 1$

Selected Topics in Advanced Optics

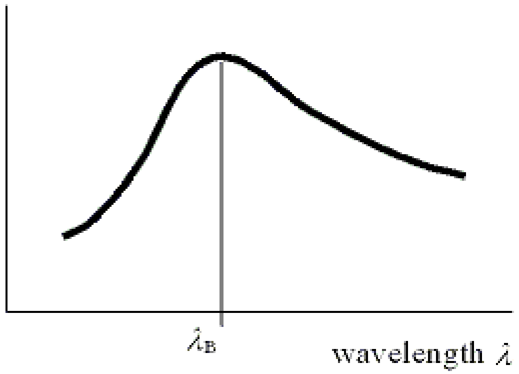
Week 8 – part 2

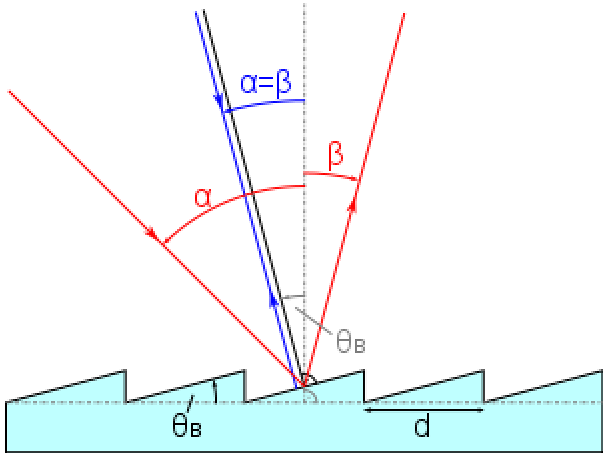
Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

EPFL

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 λ:

$$R = \frac{\lambda}{\Delta\lambda}$$

$\Delta\lambda$: minimal spectral range that can still be detected

- Theoretical resolving power for a planar grating:

$$R = mN$$

N: total number of illuminated grooves

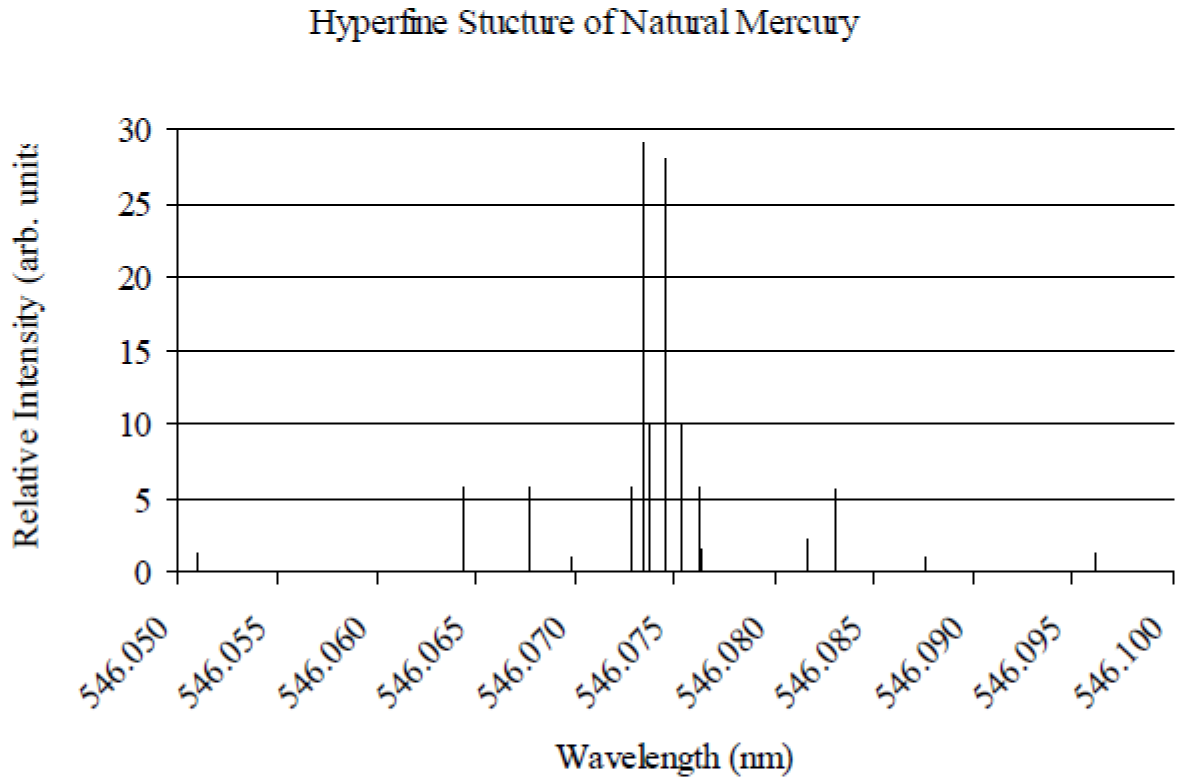
$$\boxed{R = \frac{Nd(\sin\alpha + \sin\beta)}{\lambda} = \frac{W(\sin\alpha + \sin\beta)}{\lambda}}$$

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:



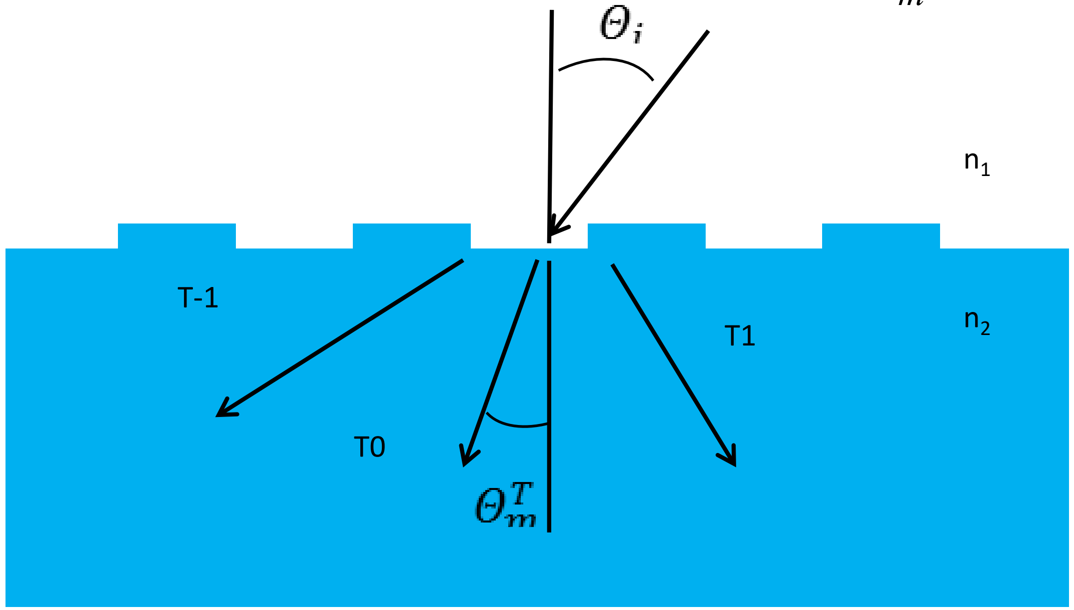
Grating equation across two different media

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

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

- Equation for the different diffraction orders:

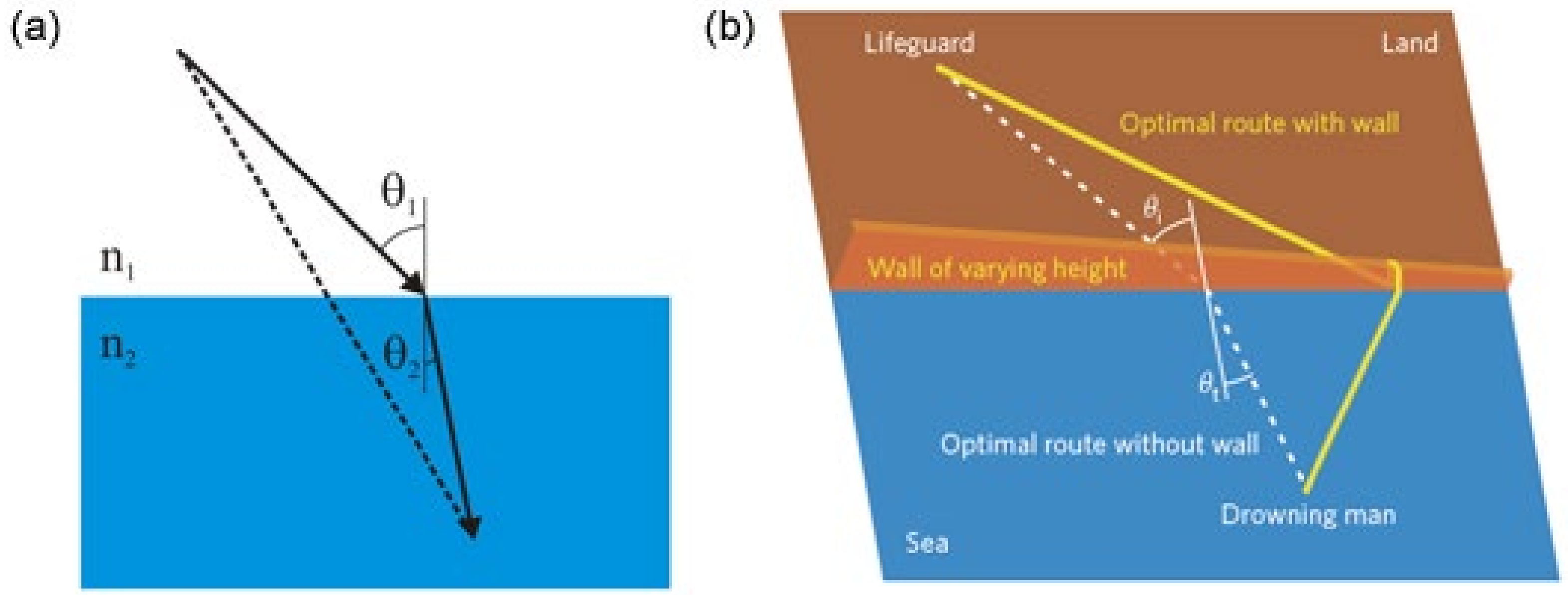
$$\theta_m^T = \sin^{-1}\left(\frac{n_1 \sin \theta_i + m \frac{\lambda}{\Lambda}}{n_2} \right)$$



Grating equation: Generalized Snell's law

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

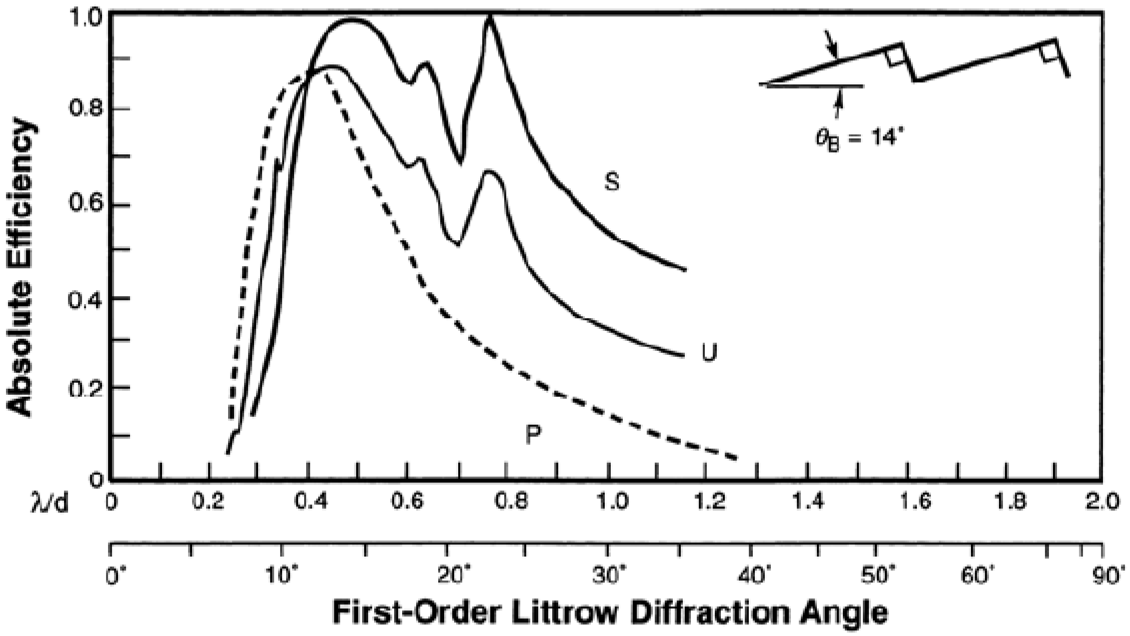
$$n_1 \sin\theta_1 - n_2 \sin\theta_2 = 0 \qquad\qquad n_1 \sin\theta_1 - n_2 \sin\theta_2 = \frac{\lambda}{2\pi}\frac{d\varphi}{dx}$$



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

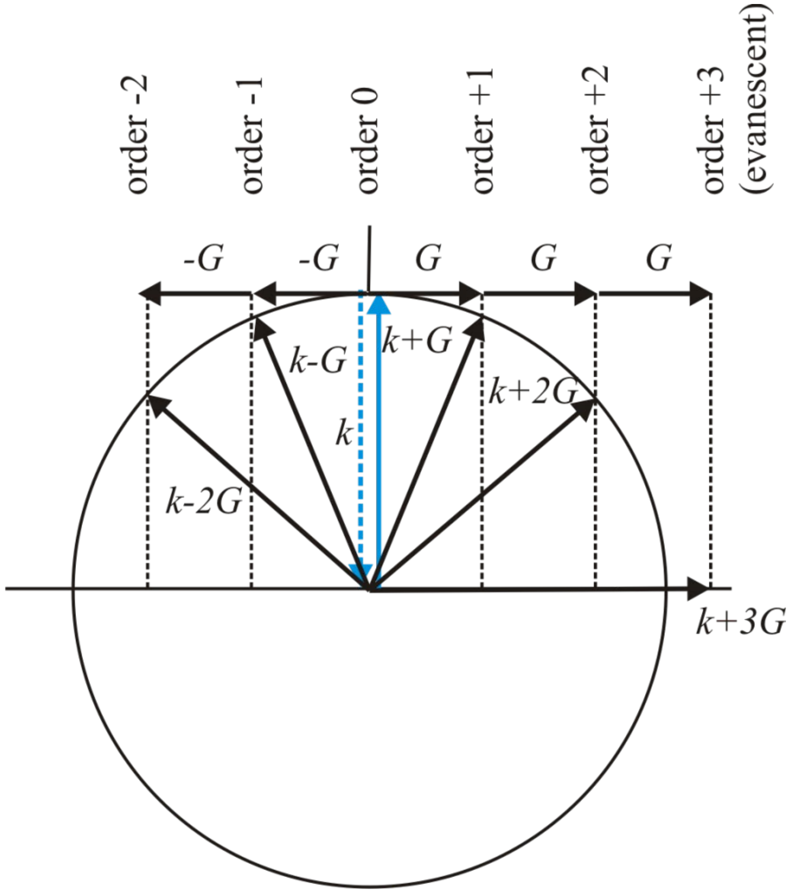
Polarization effects

- 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°), 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

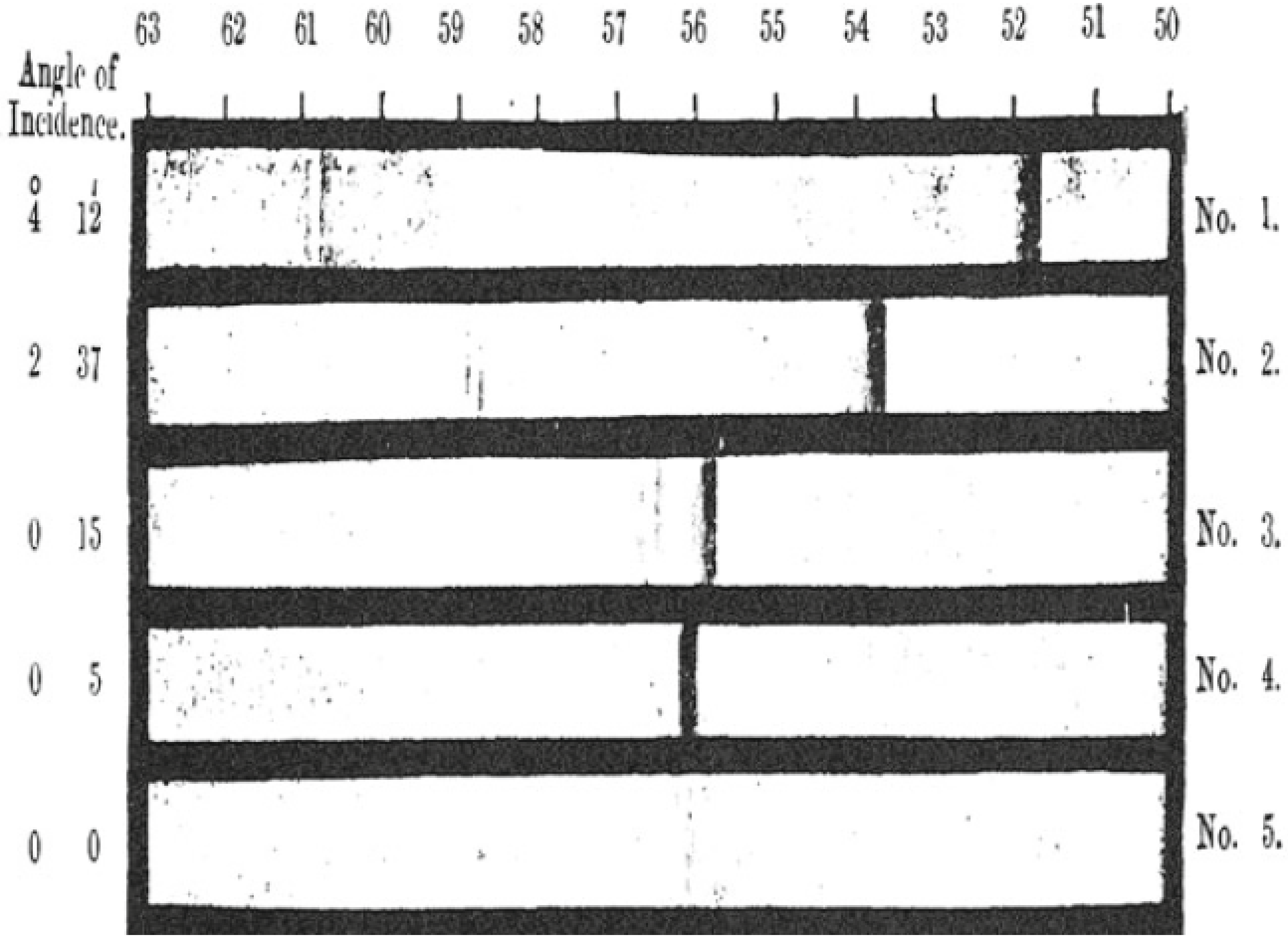


Wood's anomalies

- These anomalies are observed in the spectral response of gratings, they usually correspond to the condition when:
  - Light of a given wavelength λ' and spectral order m' is diffracted at an angle $\left|\beta\right| = 90°$, 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

Wood's anomalies

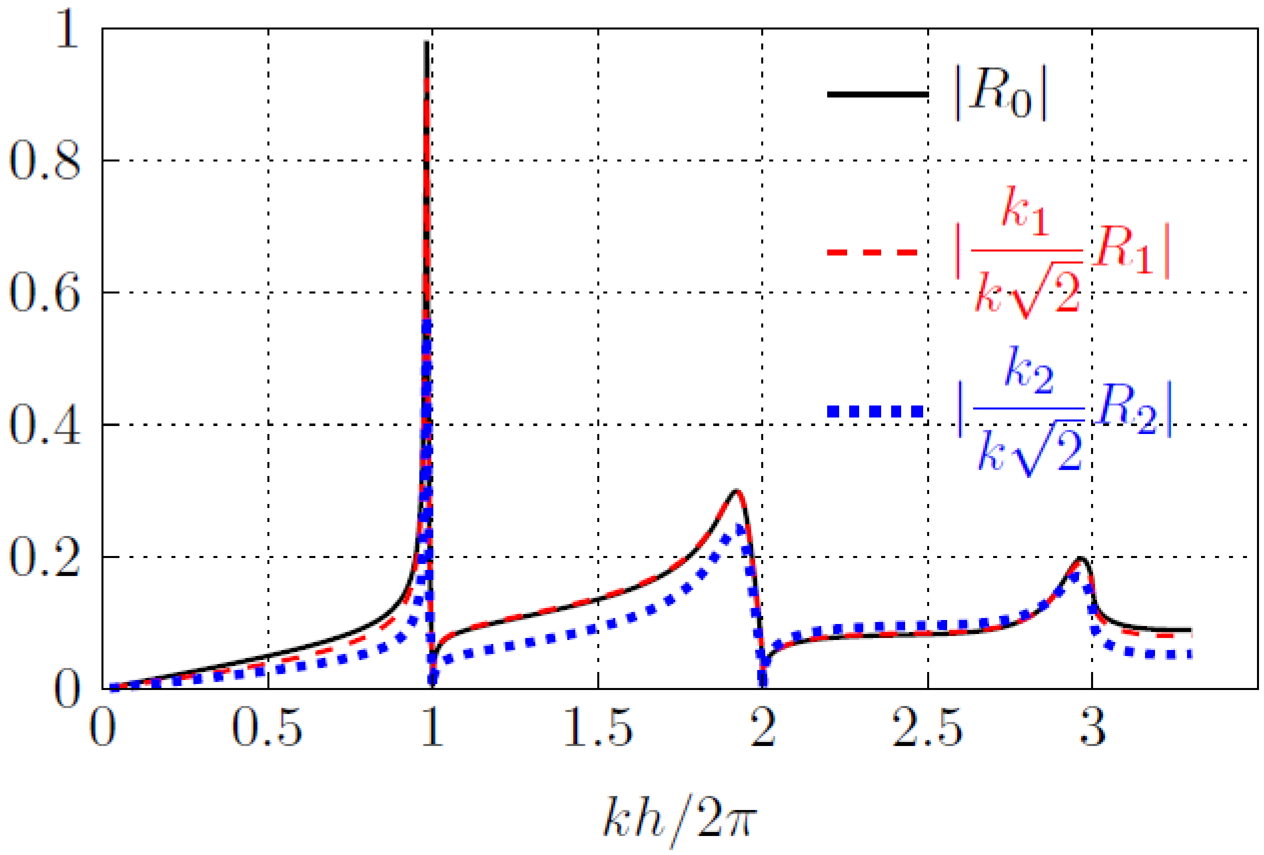
- Spectra of a continuous source



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

Wood's anomalies

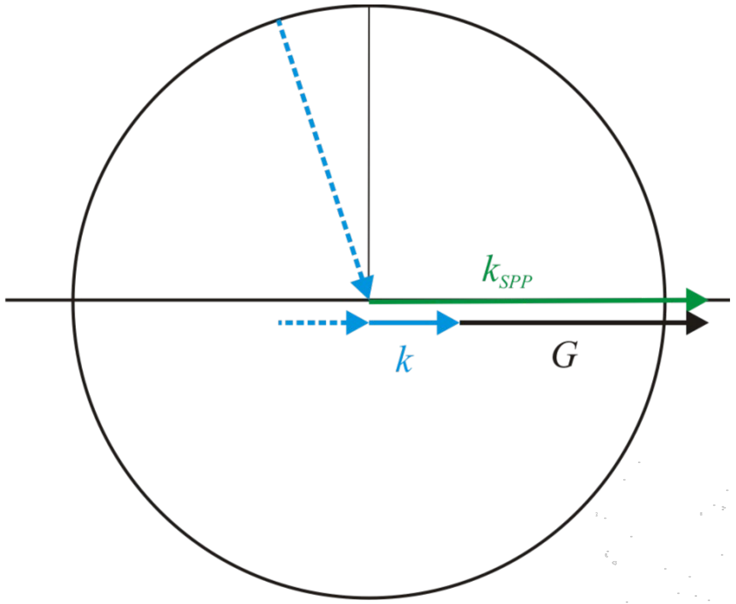
- At specific points, the reflection goes to zero, but just before there are strong scattering peaks

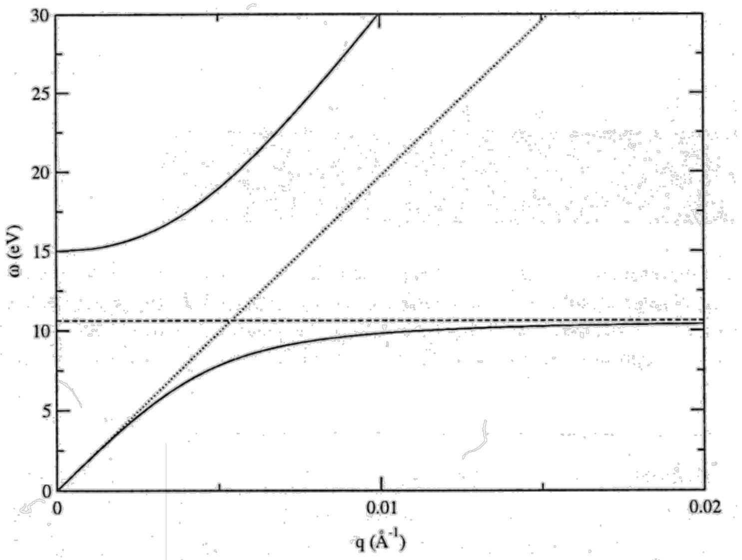


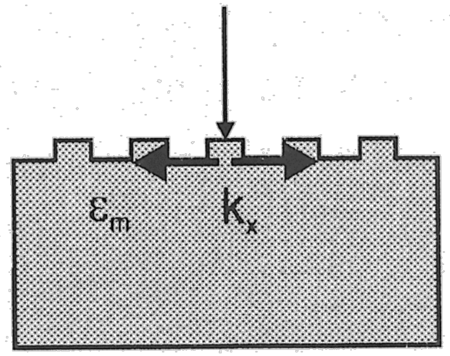
A. Maurel, J. Europ. Opt. Soc. Rap. Public. 9, 14001 (2014)

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







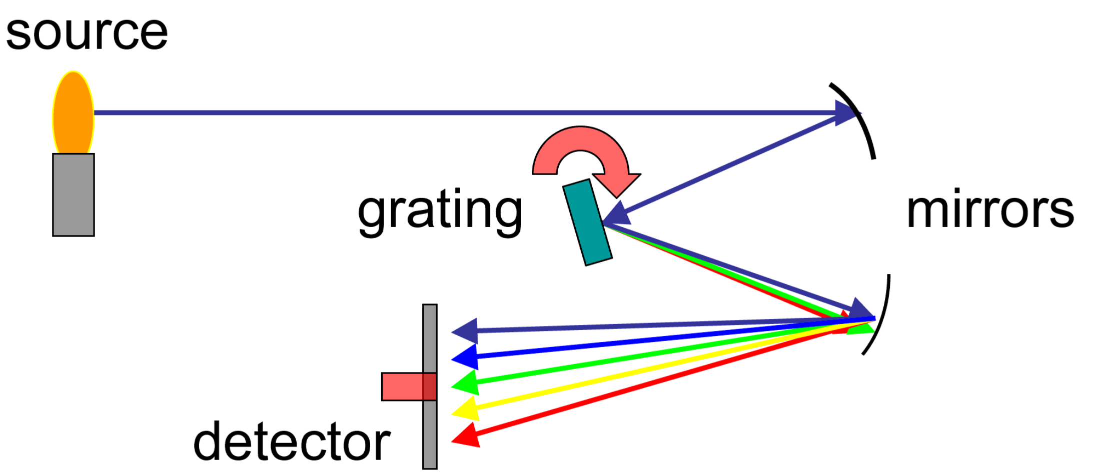
Selected Topics in Advanced Optics

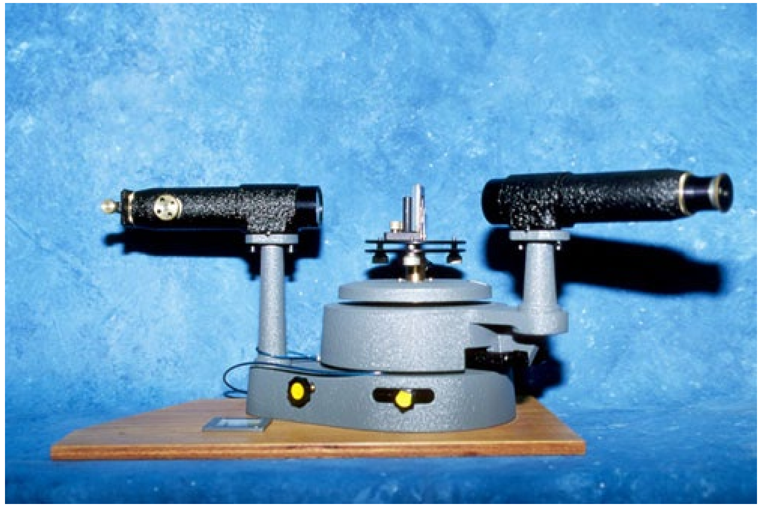
Week 8 – part 3

Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

EPFL

Spectrometer - monochromator

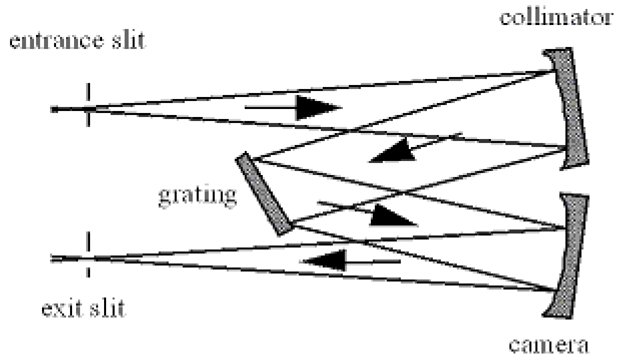


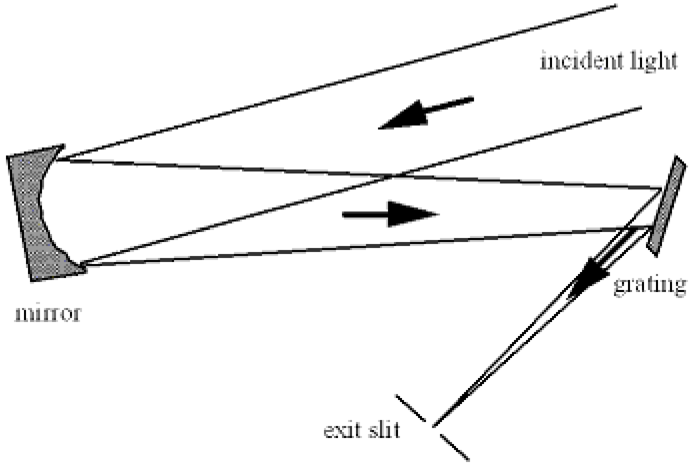


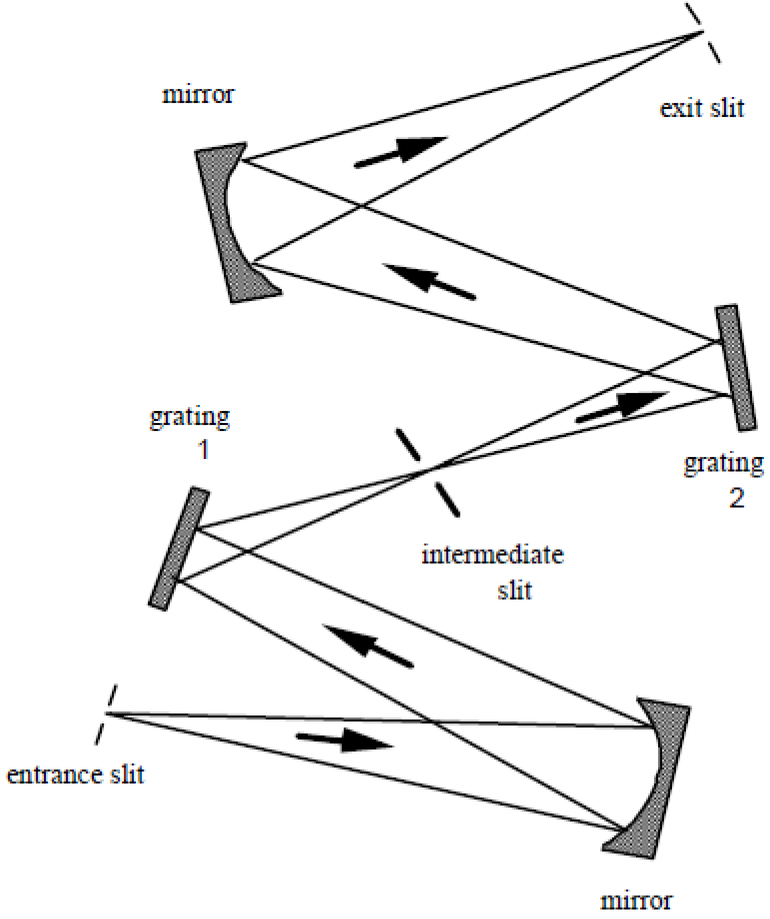
Olivier J.F. Martin

Spectrometer – monochormator

- 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 – monochormator

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

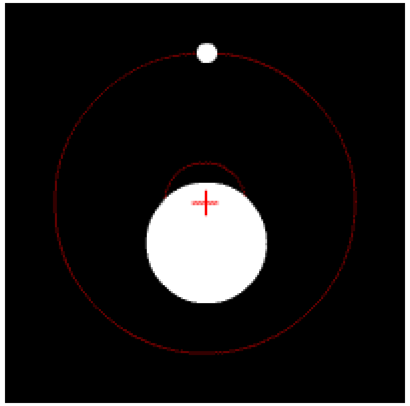
OCTOBER II **1996**, PAGE 373

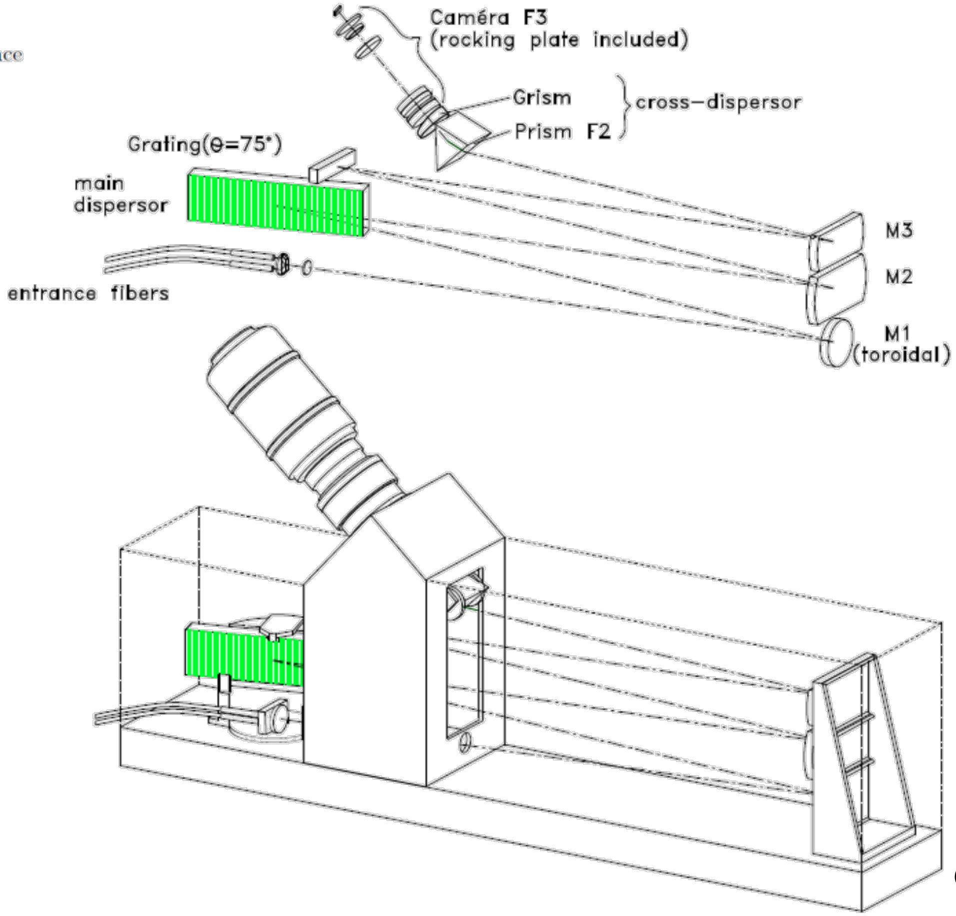
Astron. Astrophys. Suppl. Ser. **119,** 373-390 (1996)

ELODIE: A spectrograph for accurate radial velocity measurements

A. Baranne[1], D. Queloz[2], M. Mayor[2], G. Adrianzyk[3], G. Knispel[3], D. Kohler[3], D. Lacroix[3], J.-P. Meunier[3], G. Rimbaud[3] and A. Vin[3]

[1] Observatoire de Marseille, 2 Place Le Verrier, F–13248 Marseille, France
[2] Observatoire de Genève, CH–1290 Sauverny, Switzerland
[3] Observatoire de Haute–Provence, F–04870 Saint Michel l'Observatoire, France

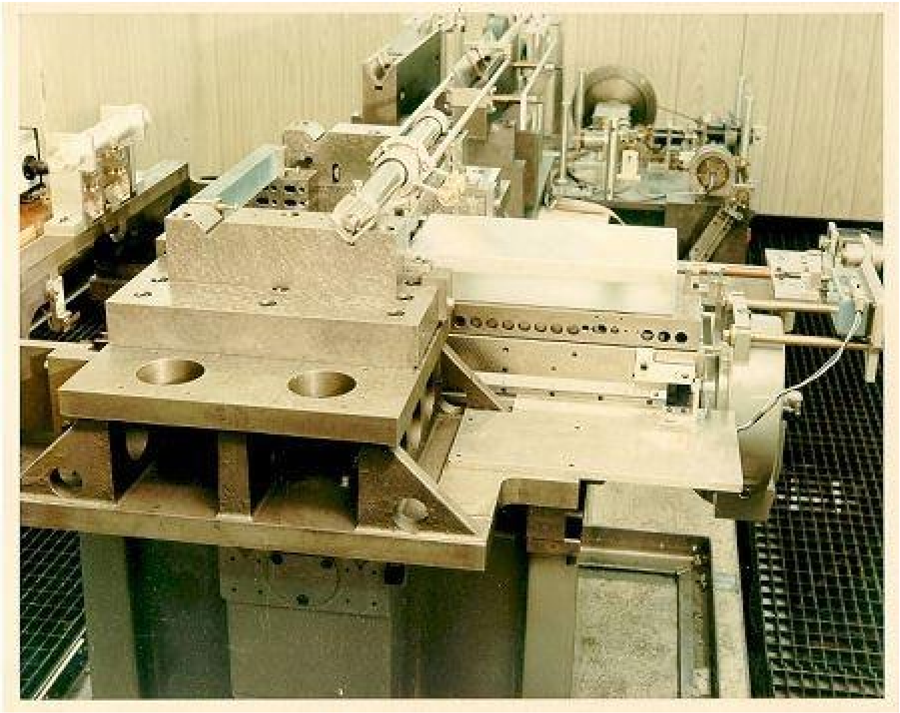


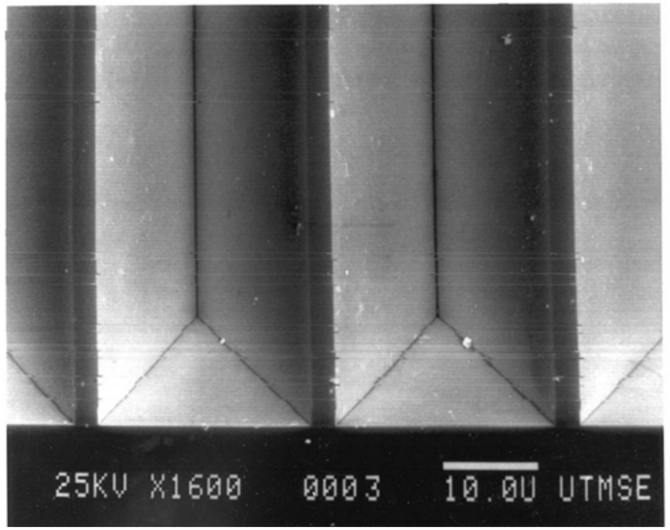


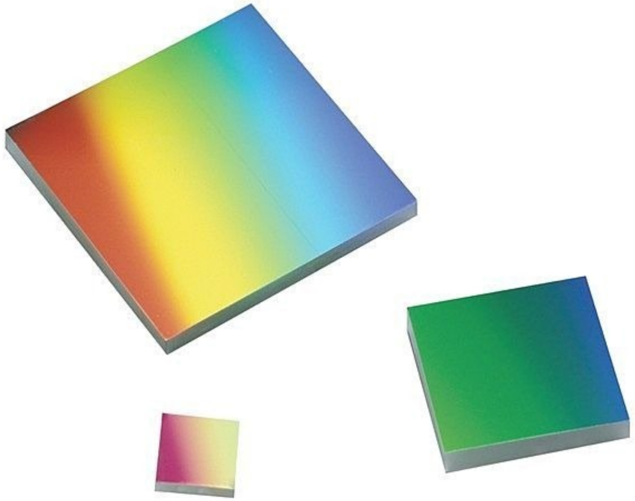
Olivier J.F. Martin

Grating fabrication – Ruled grating

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

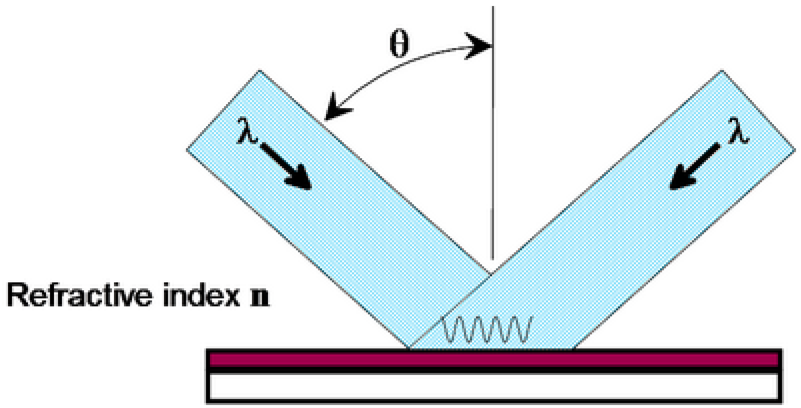






Newport

Grating fabrication – Holographic grating (interference)



$$\text{period} = \frac{\lambda}{2\sin(\theta)\,n}$$

Figure 1. Schematic diagram of interferometric lithography

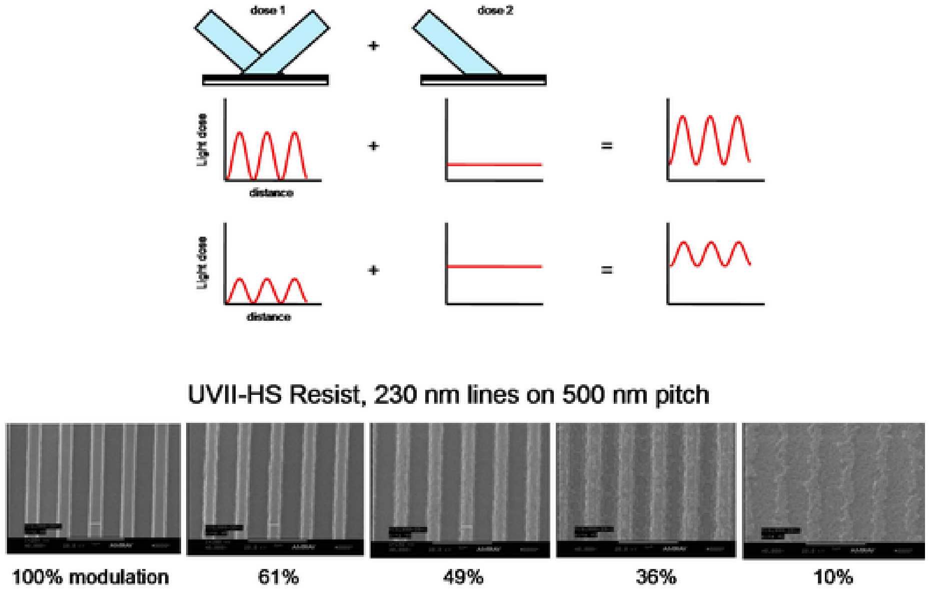


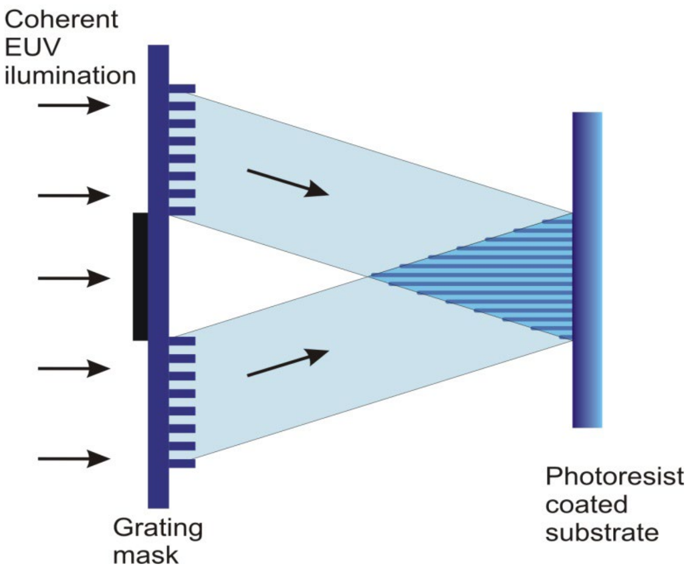
Figure 2. Control of aerial image contrast in interferometric lithography to test resist LER response

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

IBM Research Almaden

Grating fabrication – Holographic grating (interference)

- The incident wavelength determines the minimal period that can be achieved
- EUV lithography from ondulater (λ=13 nm)

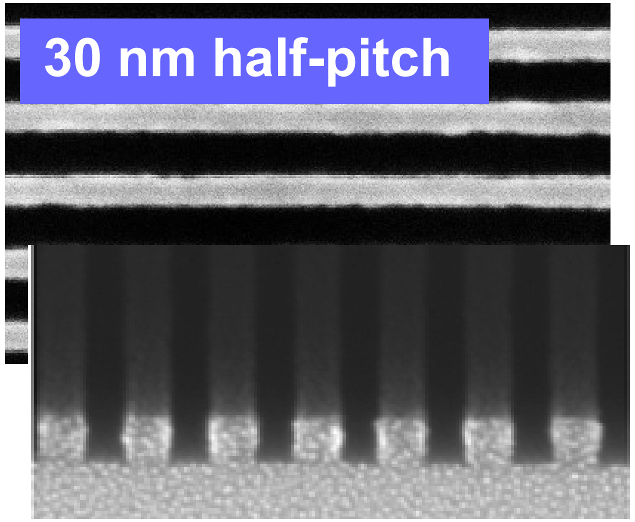


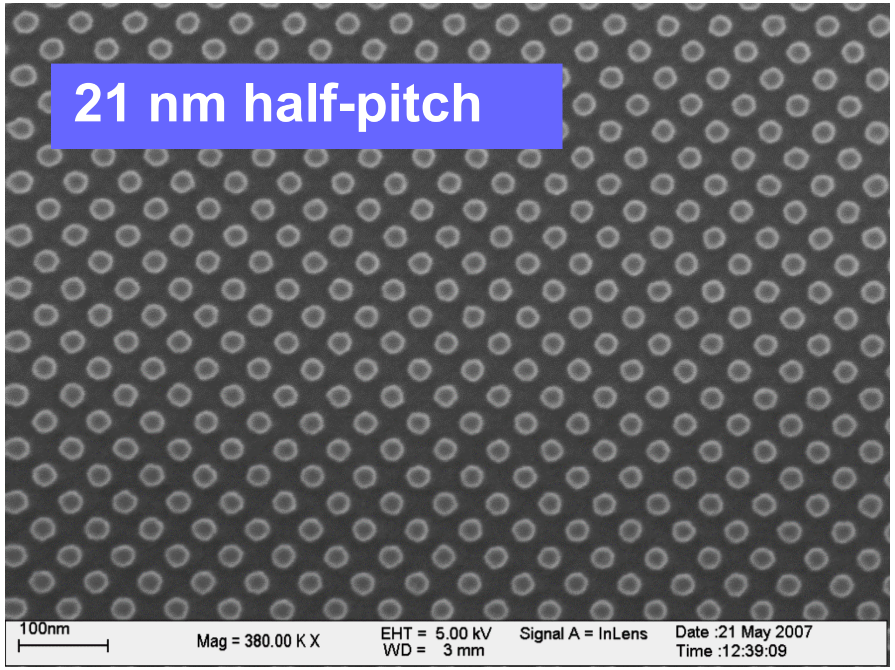
Performance:
20-50nm period
1-4 mm^2 area
10-30 sec exposure

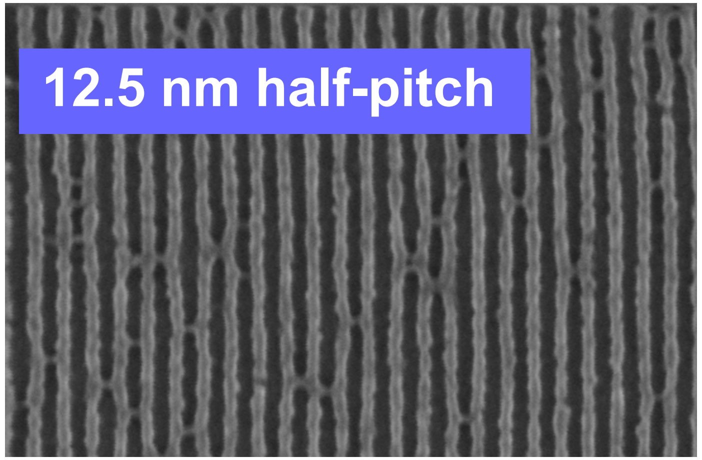
lmn.web.psi.ch

Grating fabrication – Holographic grating (interference)

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



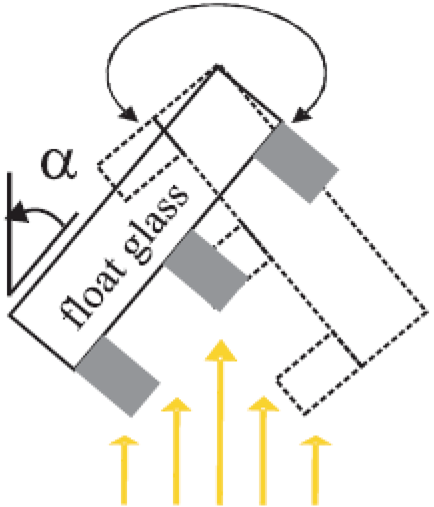


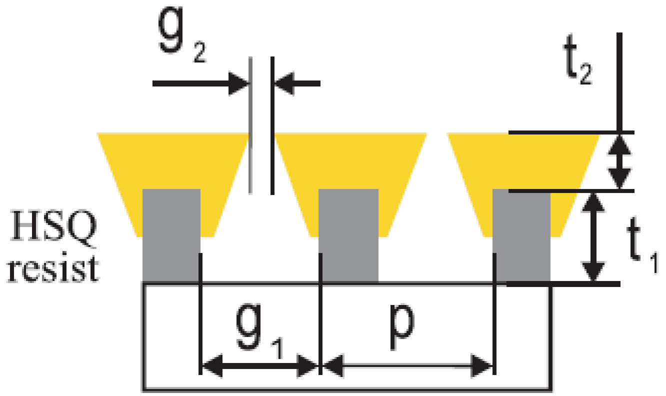


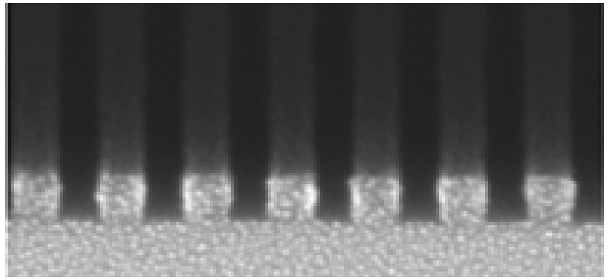
lmn.web.psi.ch

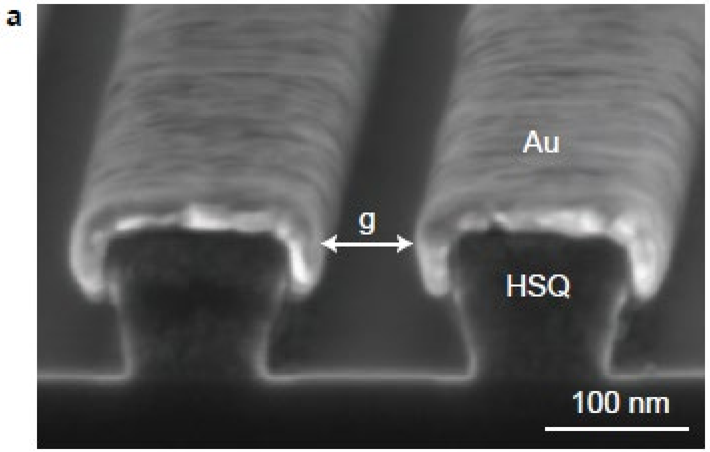
Fabrication of sub-10nm gaps in gold

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





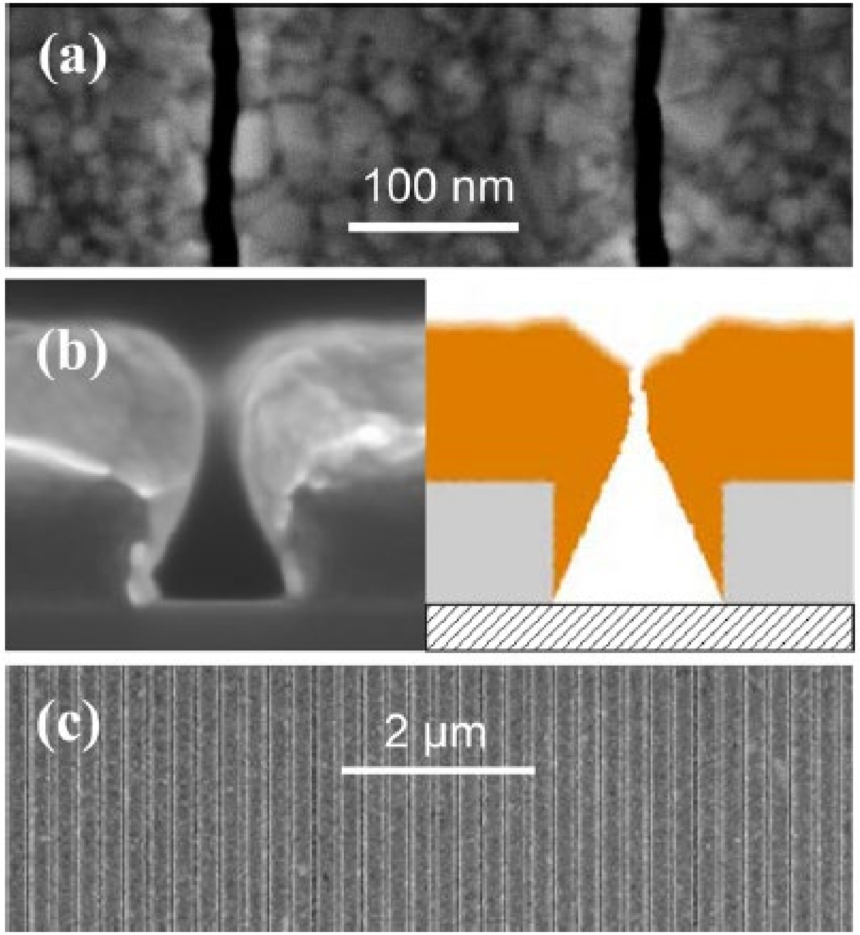


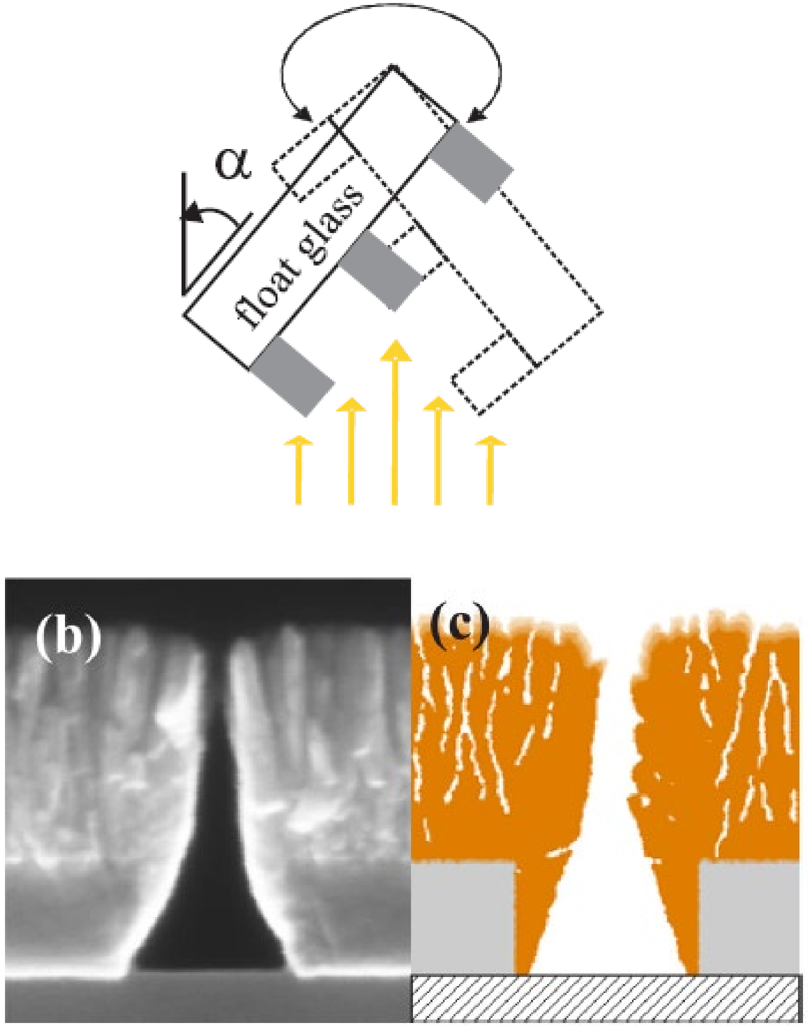


T. Siegfried, Applied Physics Letters vol. 99, p. 263302 (2011)

Fabrication of sub-10nm gaps in gold

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

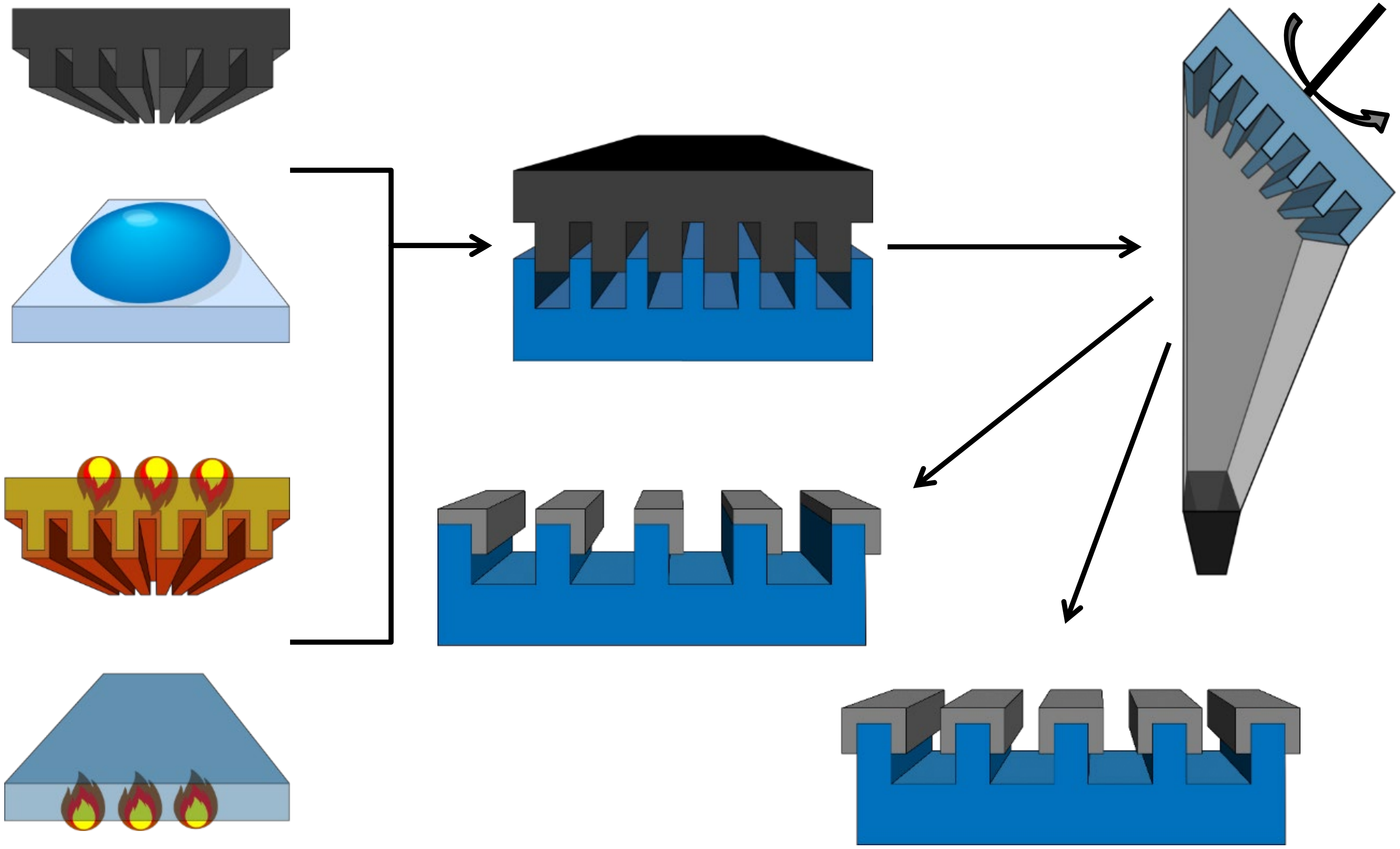




T. Siegfried, Applied Physics Letters vol. 99, p. 263302 (2011)

Blazed Grating fabrication: Interference + angled evaporation

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

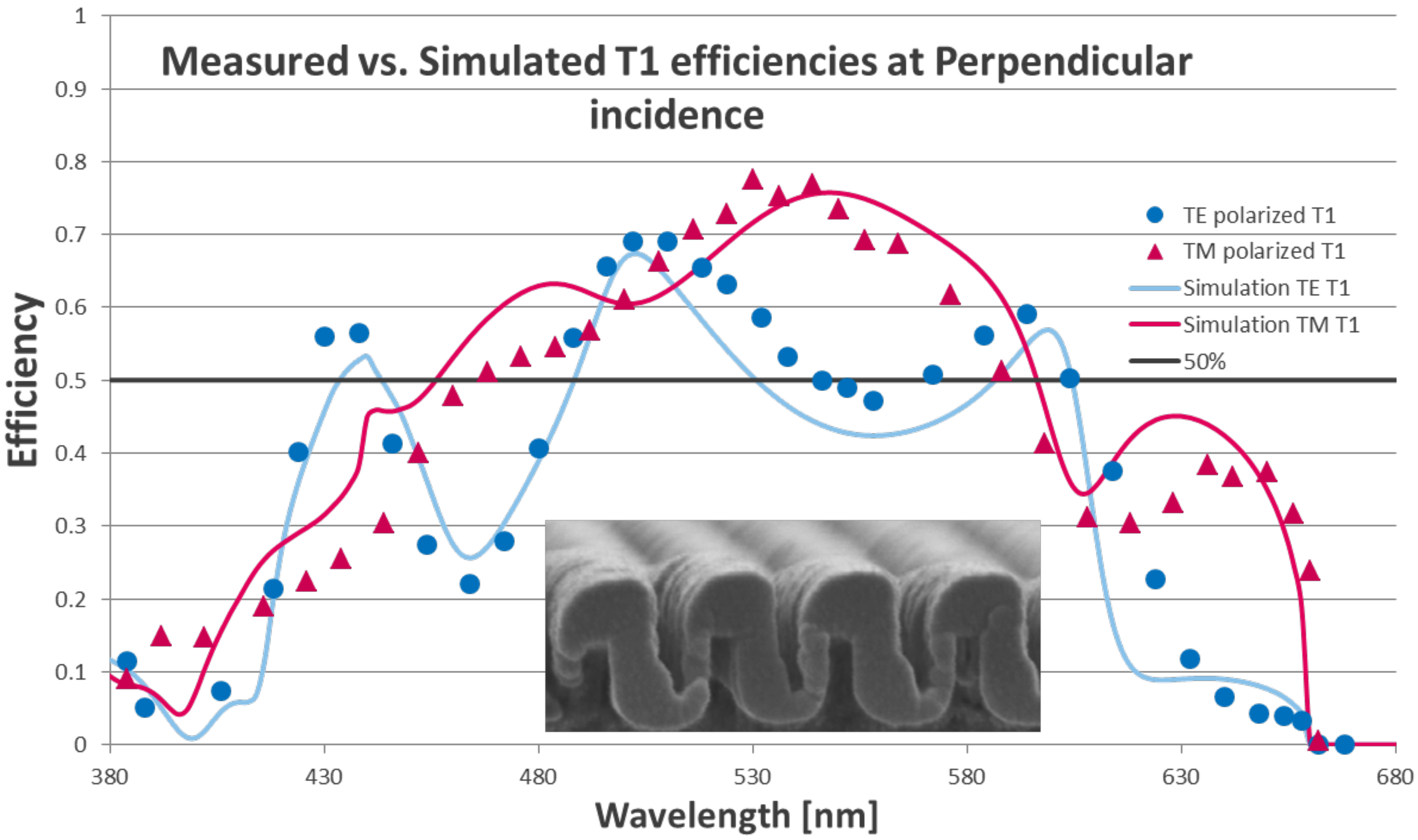


Collaboration with CSEM

Olivier J.F. Martin

Blazed Grating fabrication: Interference + angled evaporation

- A similar response to ruled blazed gratings

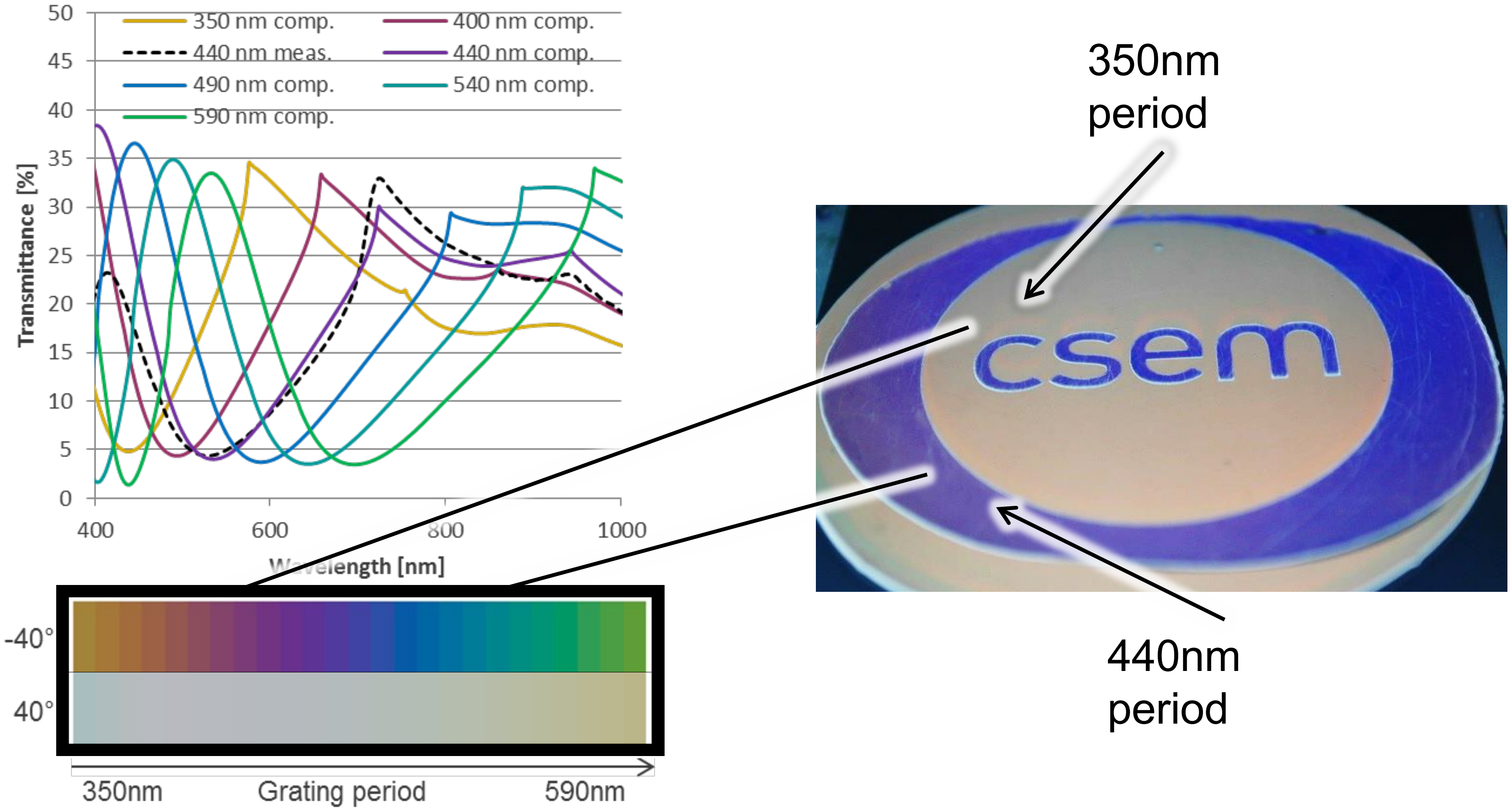


Collaboration with CSEM

Blazed Grating application: Colours through the grating period

- Varying the period produces different colours

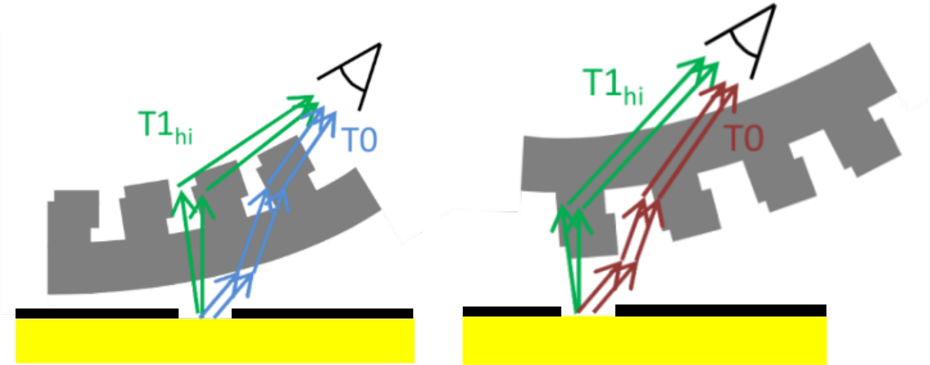
T0 colors (TE polarized)



Collaboration with CSEM

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

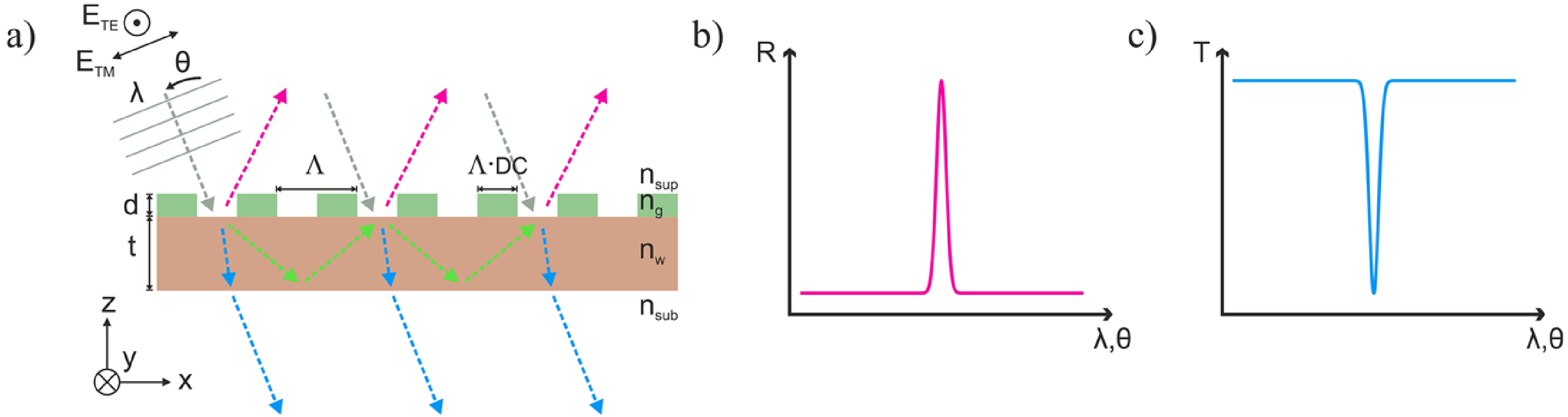


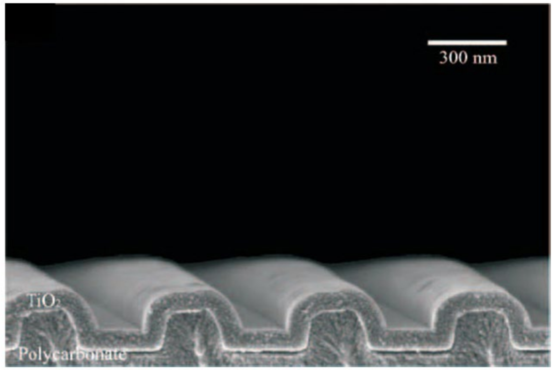
Incresing angle of view

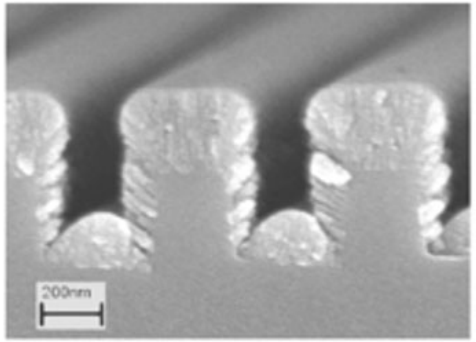
Collaboration with CSEM

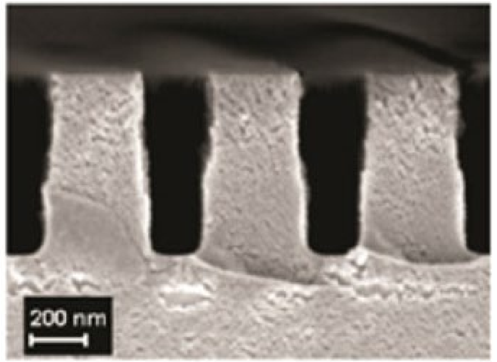
Resonant waveguide gratings

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





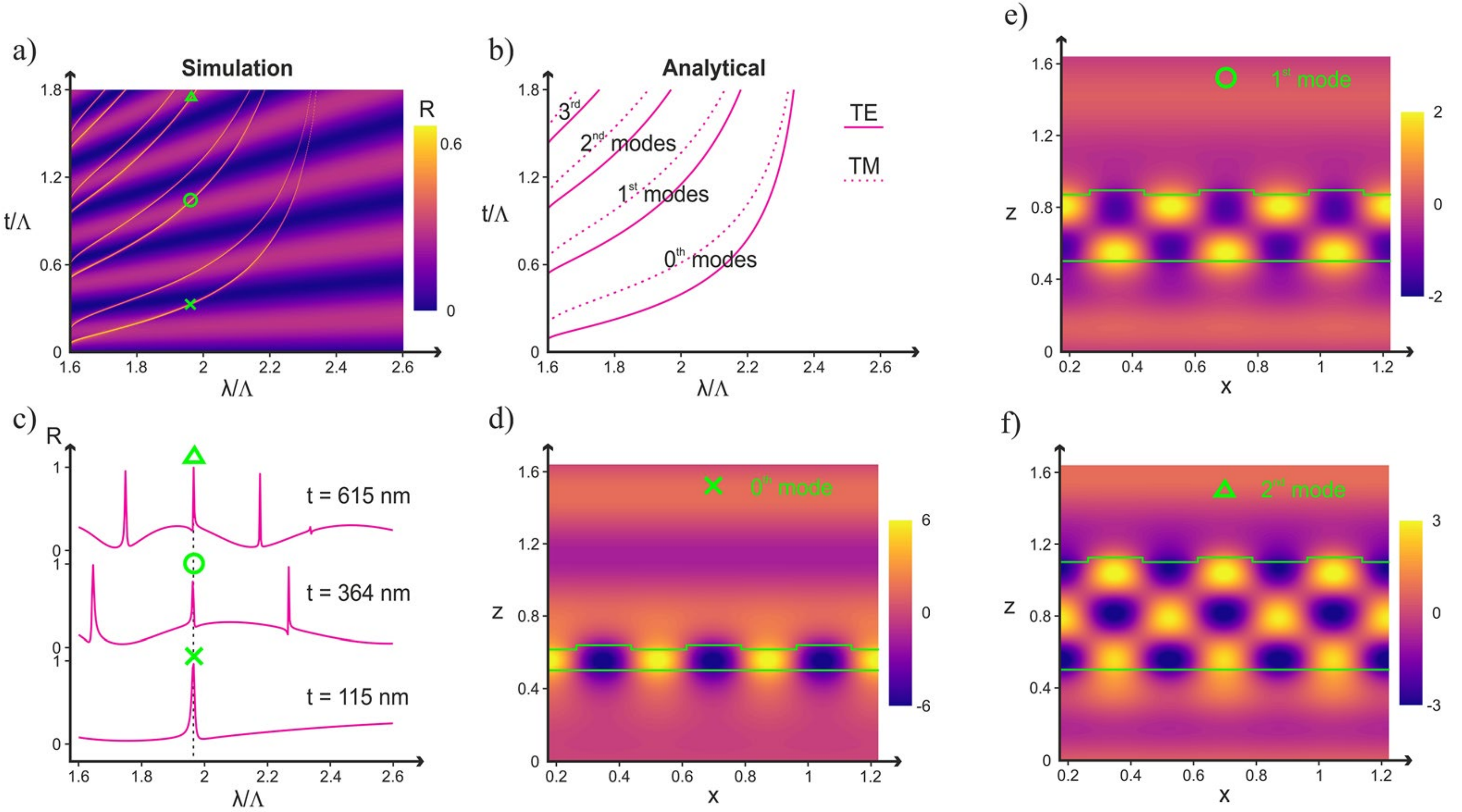




G. Quaranta, Laser and Photonics Reviews 2018, p. 1800017

Resonant waveguide gratings

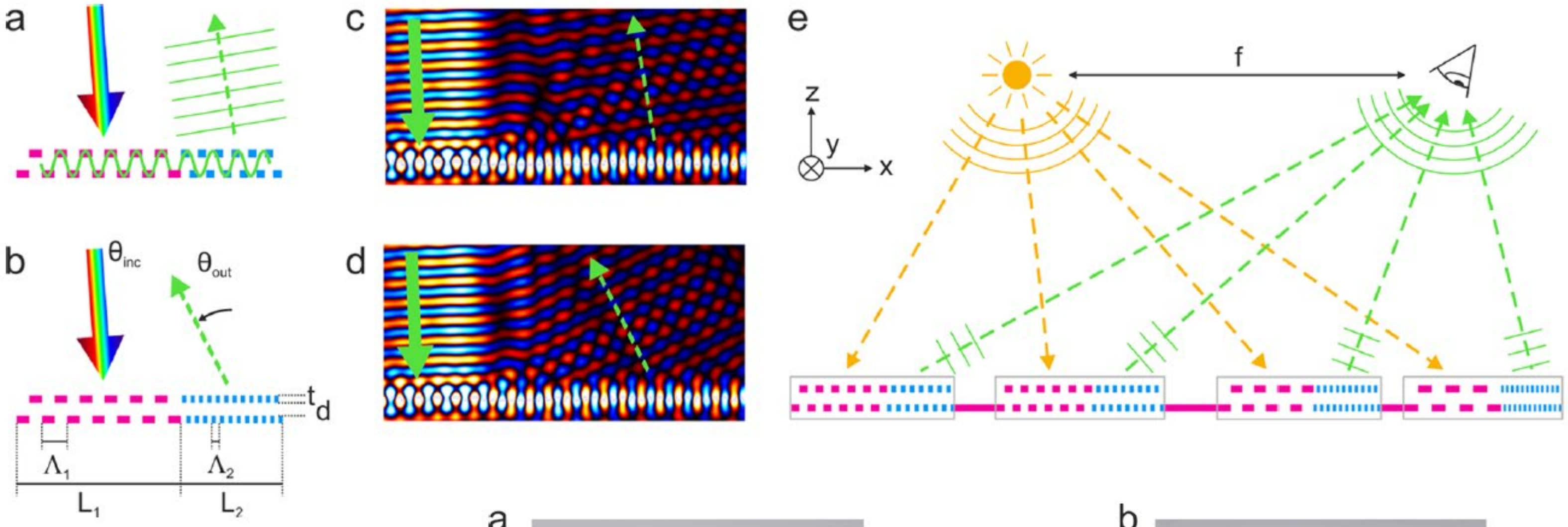
- Different modes can be excited in the waveguide

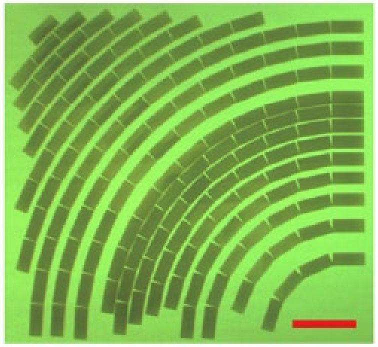


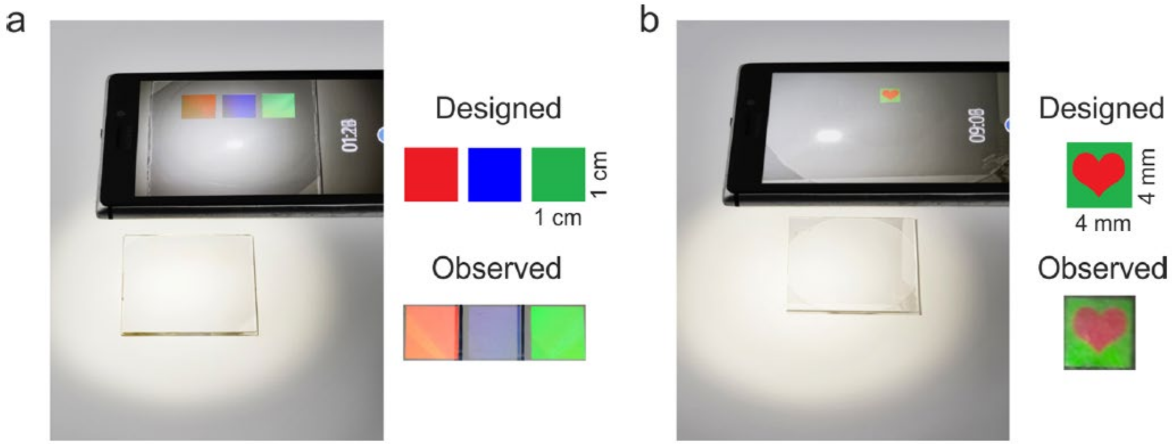
G. Quaranta, Laser and Photonics Reviews 2018, p. 1800017

Resonant waveguide gratings

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



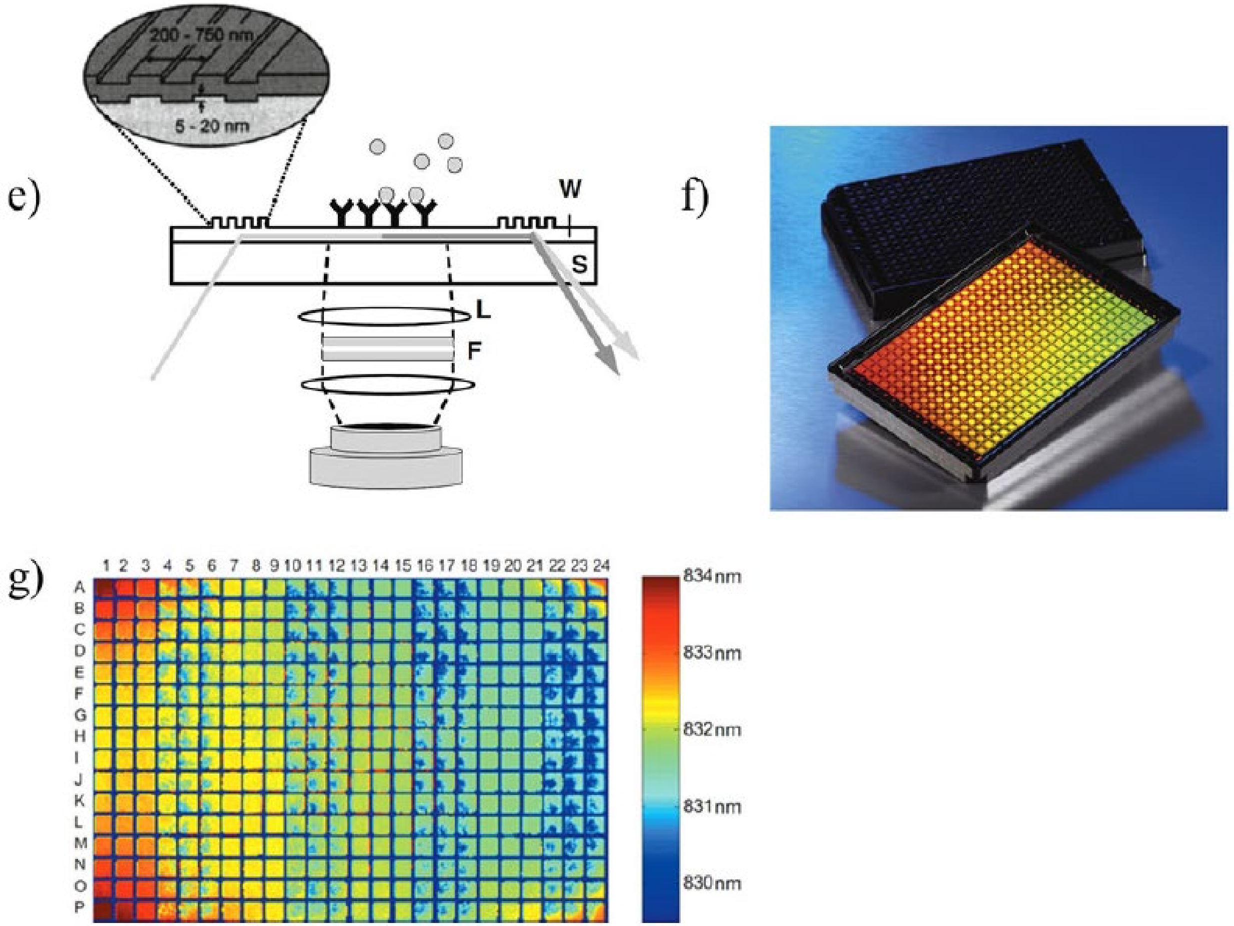




G. Quaranta, ACS Nano vol. 4, p. 1060 (2017)

Resonant waveguide gratings

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



G. Quaranta, ACS Nano vol. 4, p. 1060 (2017)