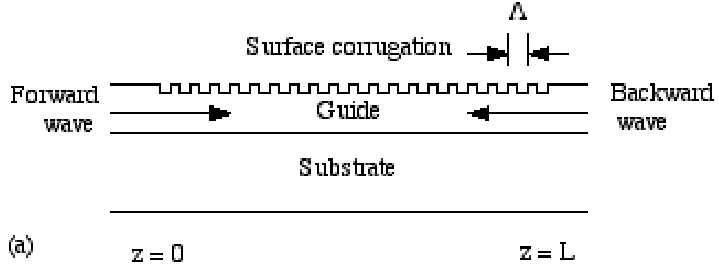
Optik under diffraktionsgrænsen

Martin Kristensen

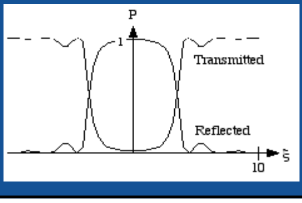
Institut for Fysik og Astronomi og iNANO, Aarhus Universitet,
Ny Munkegade Bygning 1520, DK-8000 Århus C, Danmark

NEDO

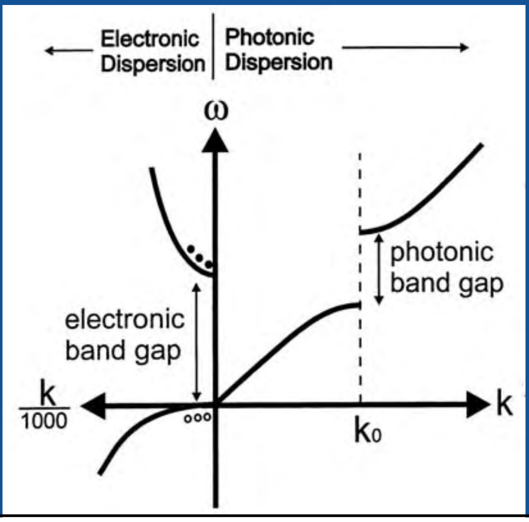
I klassisk optik er gitre de eneste elementer med typiske dimensioner under diffraktionsgrænsen



$$2n_{eff}\Lambda = m\lambda_0$$



Nano-optik: Fotoniske båndgab (PBG) i periodiske optiske strukturer under diffraktionsgrænsen

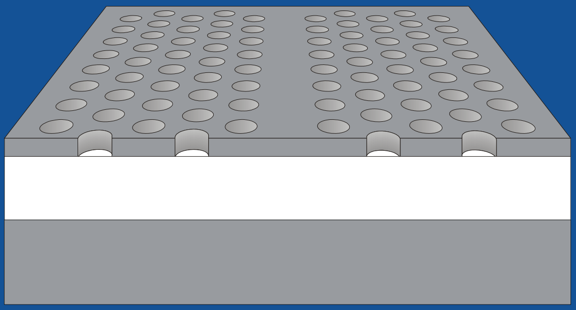


Naturen kom først…

Den optiske båndgabs effekt kan findes i naturen, hvor de flotte stærke farver som ses på sommerfuglevinger ofte er resultatet af naturligt forekommende periodiske strukturer.

Billedet til højre stammer fra et overflade elektronmikroskop (SEM), som er zoomet ind på de mindste strukturer i vingen på sommerfuglen.

Planar fotonisk krystal-struktur med et optisk båndgab i planen



← Si , ~330nm

← SiO_2 , 1-2µm

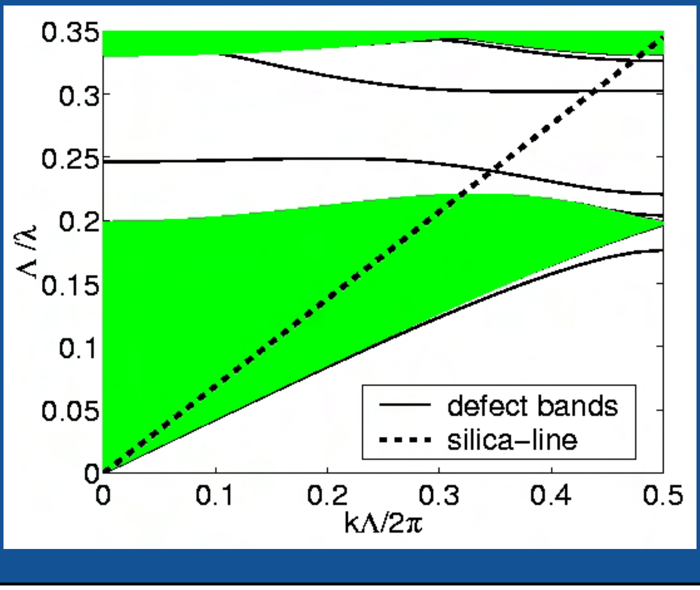
← Si-substrat

- Silicium på isolator
- Triangulært arrangement af huller
  - Gitterperiode Λ ≈ 400nm
  - Hul diameter D ≈ 275nm

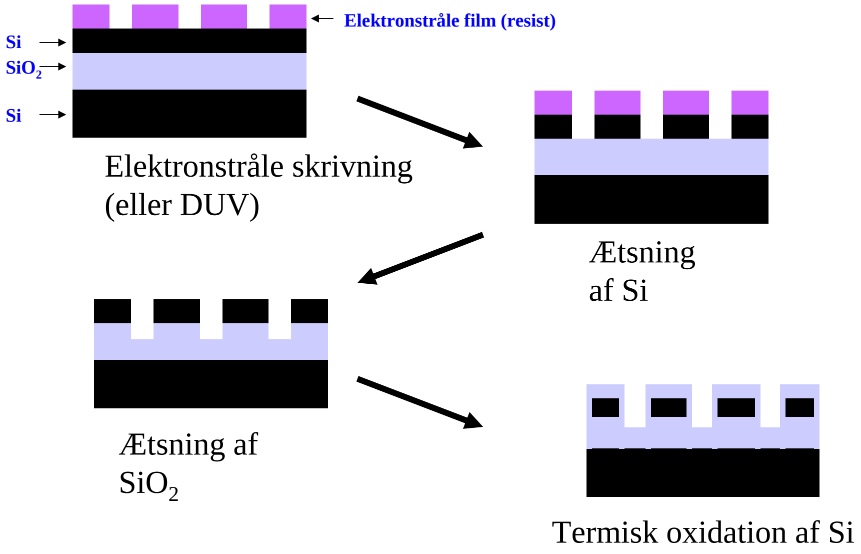
Båndgab i planen for TE polariseret lys

Total intern refleksion vinkelret på planen

Bånddiagrammer



Fremstilling



Elektronstråle film (resist)

Si

SiO_2

Si

Elektronstråle skrivning
(eller DUV)

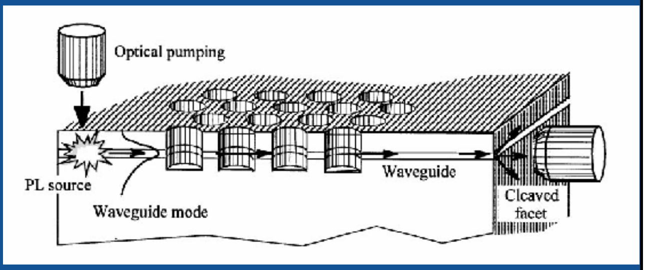
Ætsning
af Si

Ætsning af
SiO_2

Termisk oxidation af Si

Materialer der anvendes til PBG

III-V halvledere
- aktive medier (+)
(gain og ulinearitet)



Silicium-på-isolator (SOI)
- Naturlig høj indeks kontrast (+)
- Simpel integration med silicium mikroelektronik (+)
- Passivt medium? (-)

Måling på komponenter

Light Emitting Diode

Polarization Controller

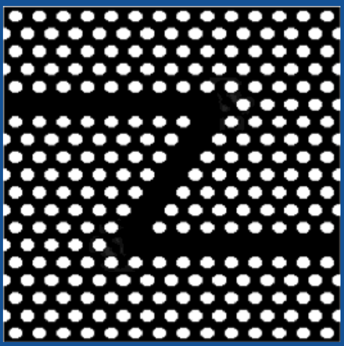
Polarizer Crystal

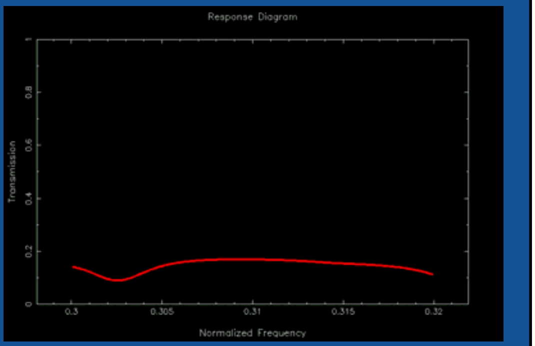
Polarization Controller

Device Under Test

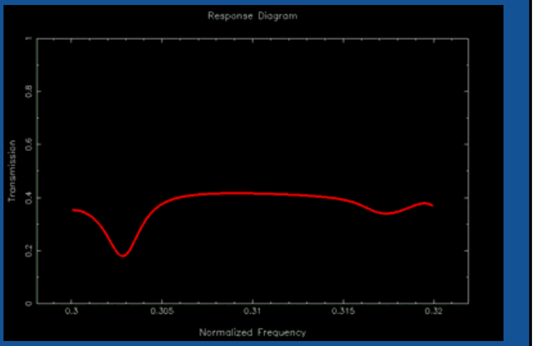
Optical Spectrum Analyzer

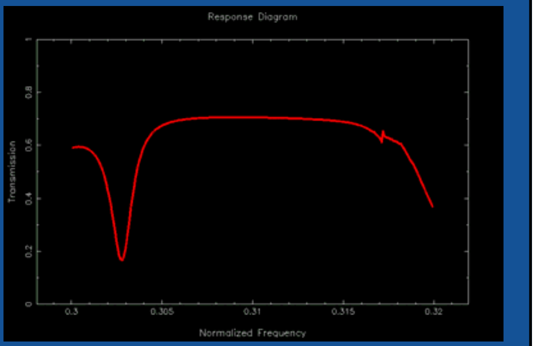
Topologi optimering:





Det er meget delikat at designe komponenter!


Response Diagram
Transmission
0
0.2
0.4
0.6
0.8
1
0.3
0.305
0.31
0.315
0.32
Normalized Frequency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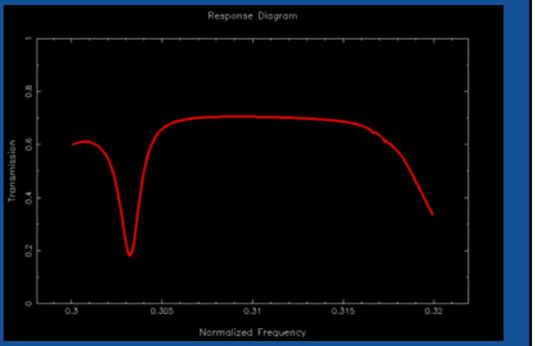
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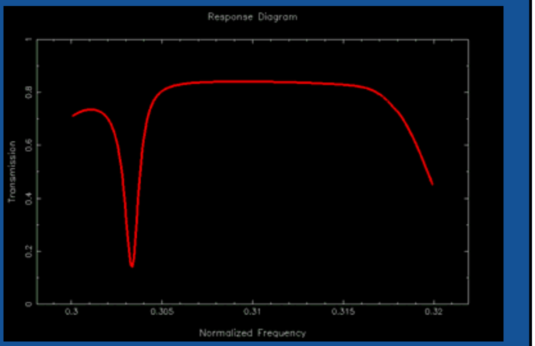
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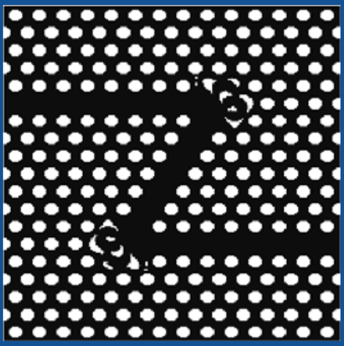

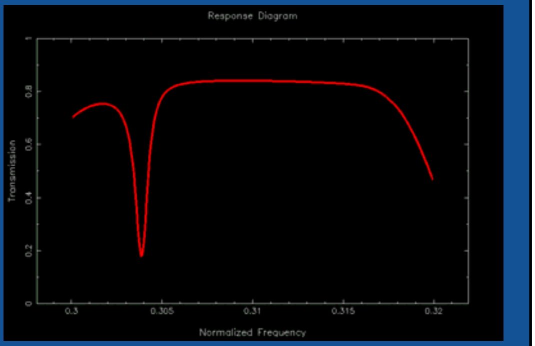
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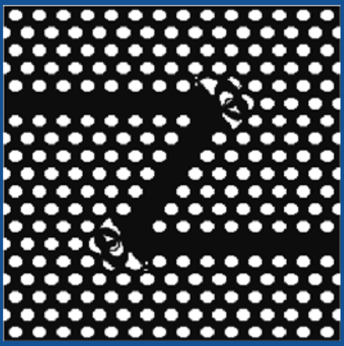

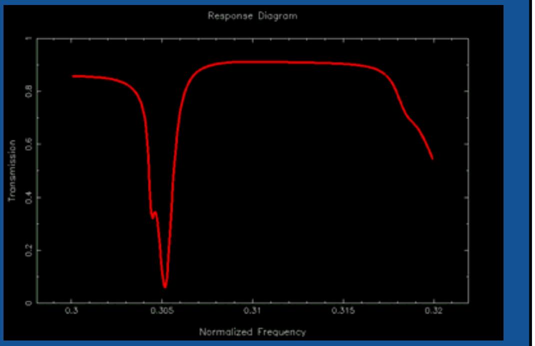
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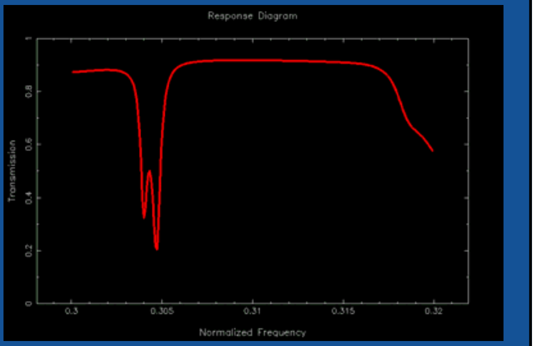
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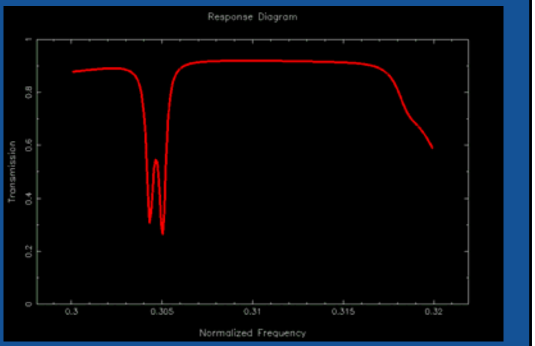
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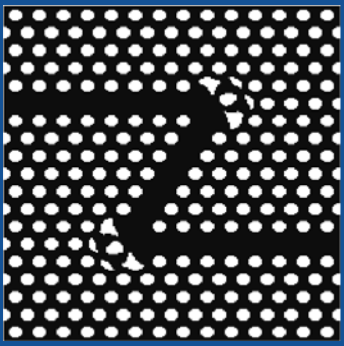

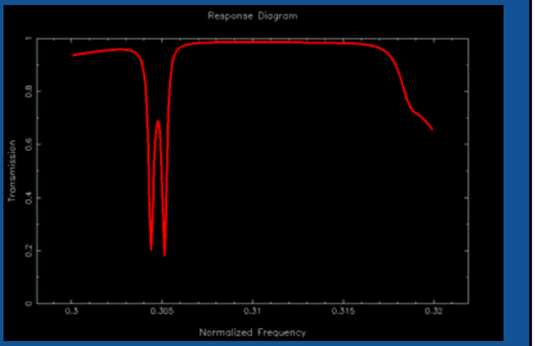
Response Diagram
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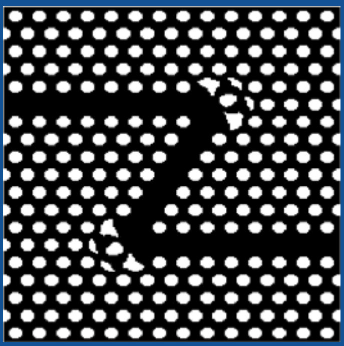

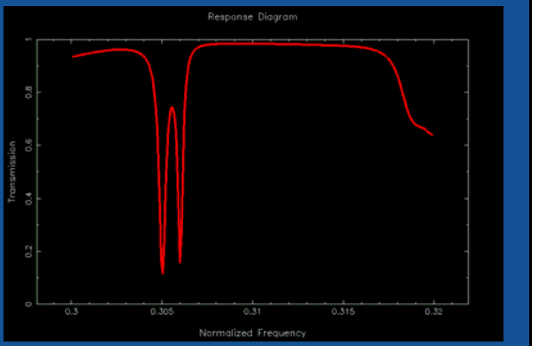
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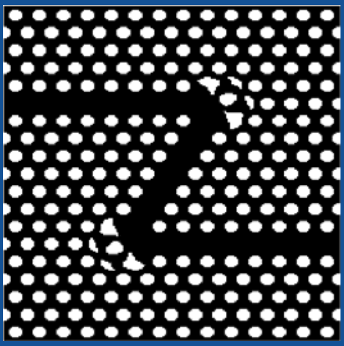
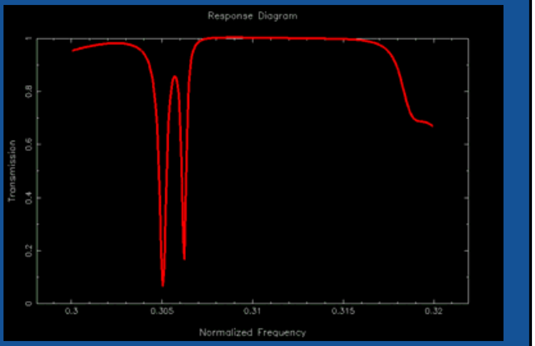
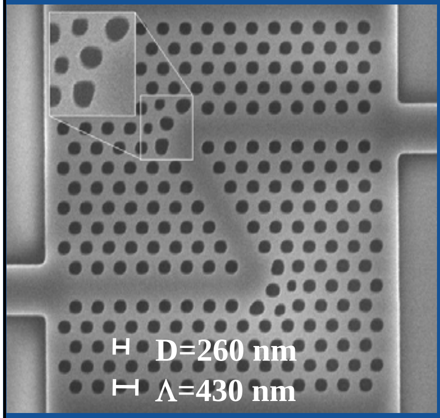
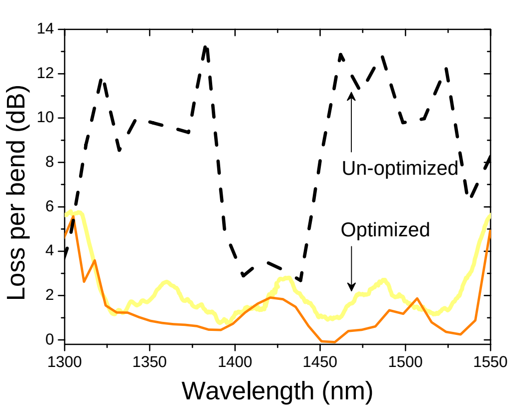




Topologi optimering, 120º-bøj

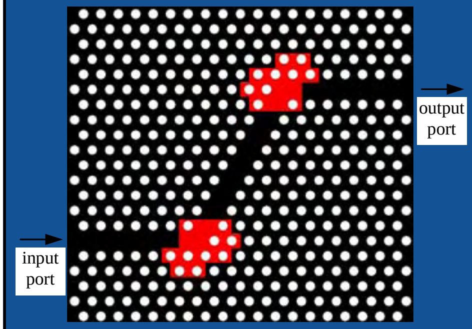




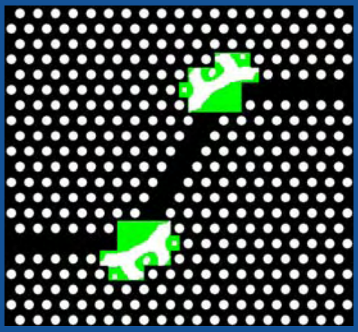
Topologi optimering er baseret på 2D finite-element beregninger

For en detaljeret beskrivelse se:
PECS V, Kyoto, Japan (2004)
Optics Express <u>12</u>, 1996 (2004)

Topologi optimering, 60°-bøj

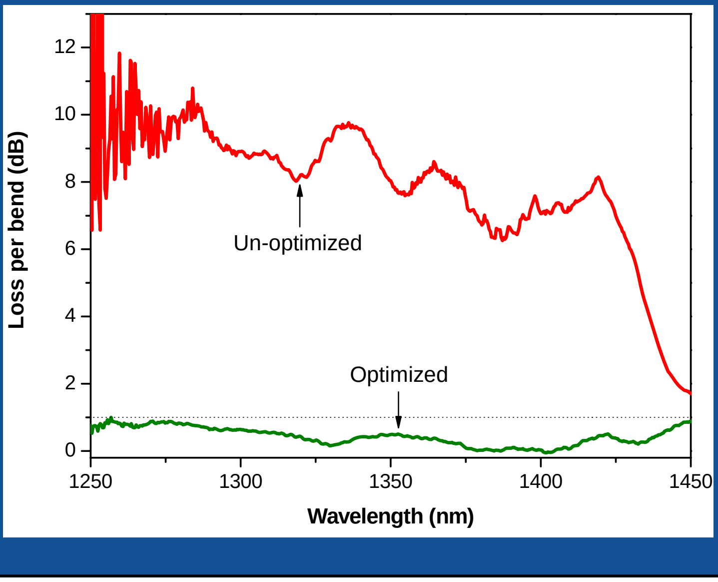


Simple skarpe bøj med angivelse af områder der skal optimeres

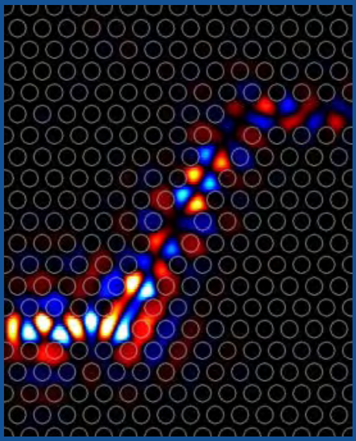


Topologi optimerede bøj med bløde strukturer

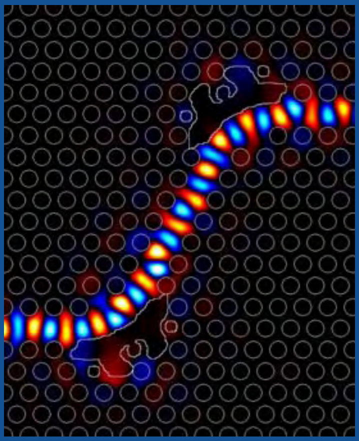
Målte egenskaber



Simulering af lysudbredelsen

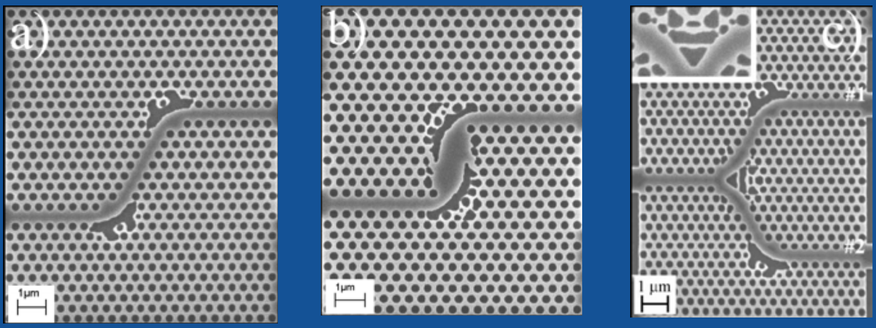


Skarpe bøj

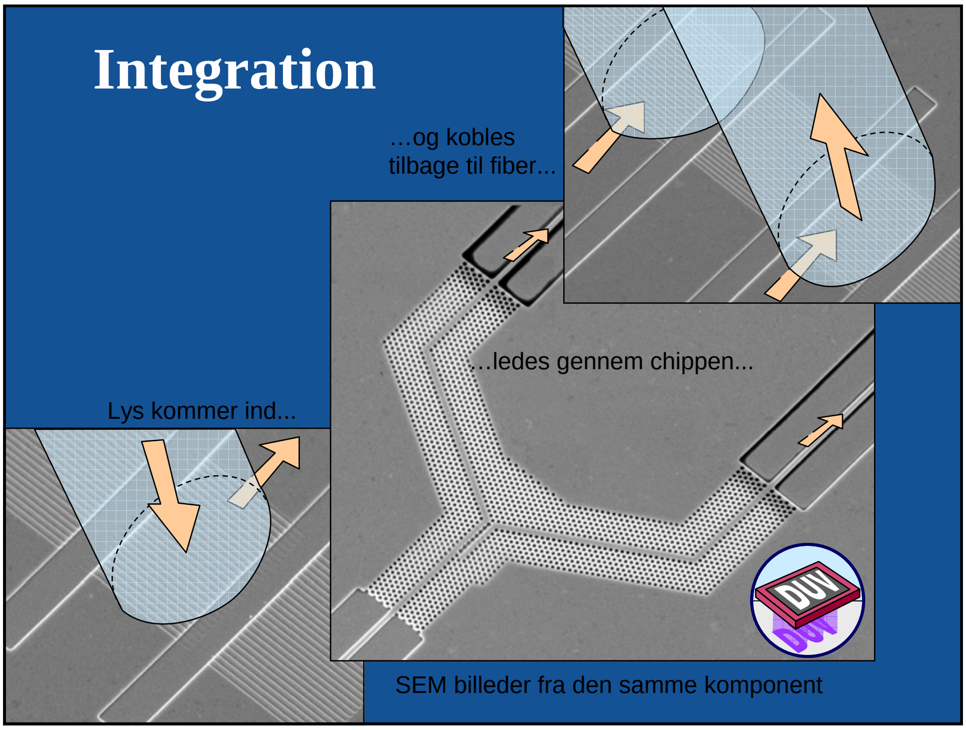


Optimerede bøj

Eksempler på topologi optimerede strukturer:



Integration



...og kobles tilbage til fiber...

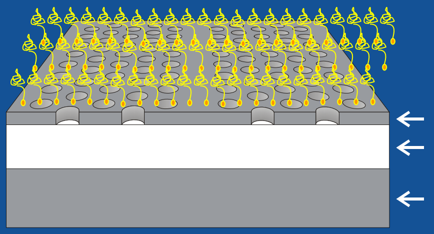
...ledes gennem chippen...

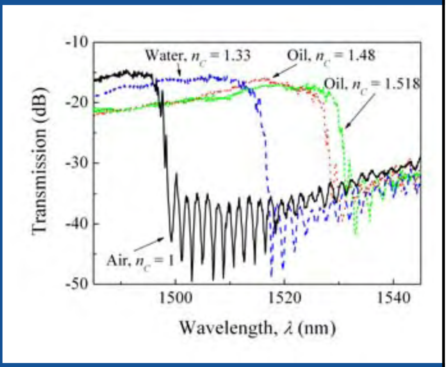
Lys kommer ind...

SEM billeder fra den samme komponent

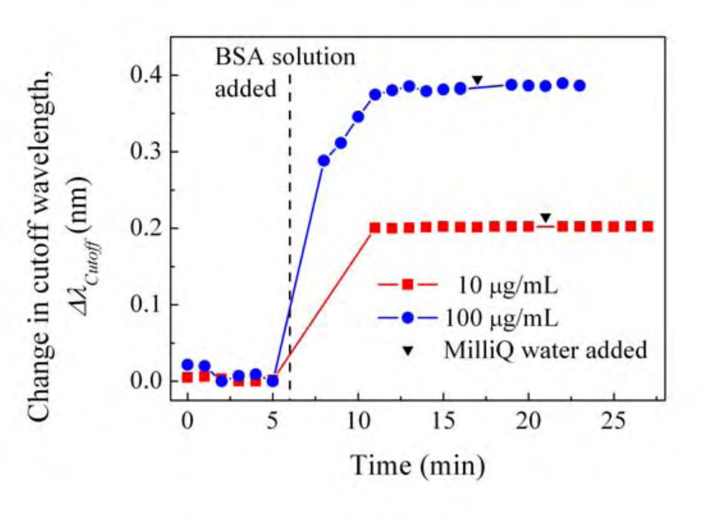
Bio-sensorer

Sensor anvendelse af fotoniske krystaller



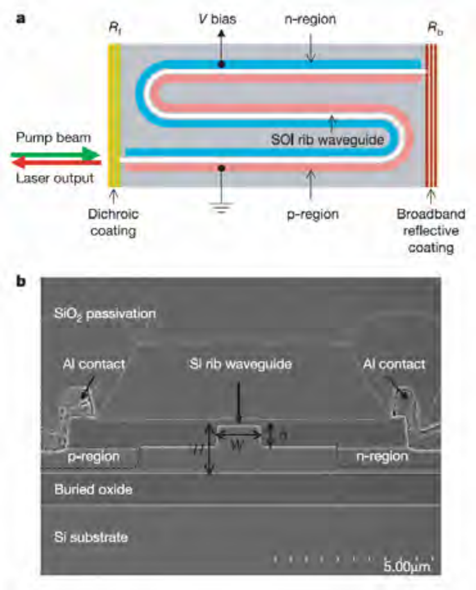


Bio-sensorer

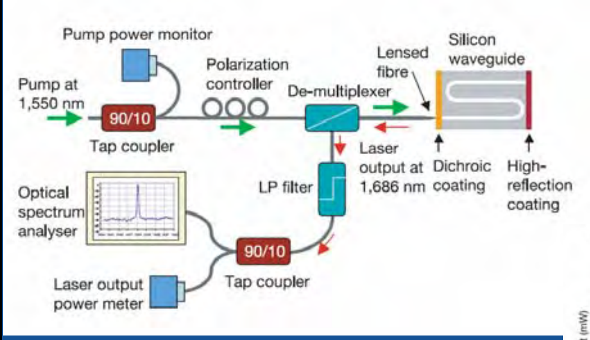


Forstærkning og ulineære processer i silicium bølgeledere

CW Raman Si laser (Intel)



CW Raman Si laser (Intel)



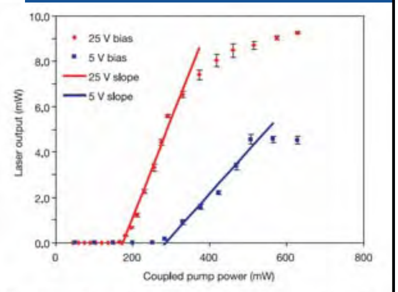


Figure 3 Silicon Raman laser output power as a function of the input pump power at a reverse bias of 25 and 5 V. The pump wavelength is 1,550 nm and the laser wavelength is 1,686 nm. The slope efficiency (single side output) is 4.3% for 25-V bias and 2% for 5-V bias. Error bars represent standard deviations.

CW Raman Si laser (Intel)

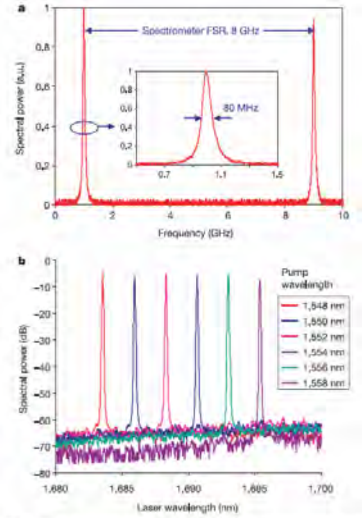
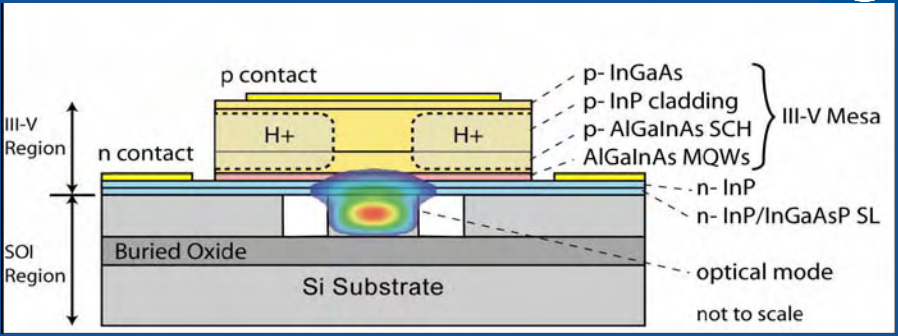


Figure 4 Silicon Raman laser spectra. **a**, Measured with a confocal scanning Fabry–Pérot spectrum analyser. Displayed is a scan over one free spectral range of 8 GHz showing single-mode operation of the laser. The measured linewidth of 80 MHz is limited by the resolution of the spectrum analyser. **b**, Measured with a grating-based optical spectrum analyser at different pump wavelengths from 1,548 nm to 1,558 nm in 2-nm steps, showing a side mode suppression of >55 dB.

III-V og Si laser (Intel)



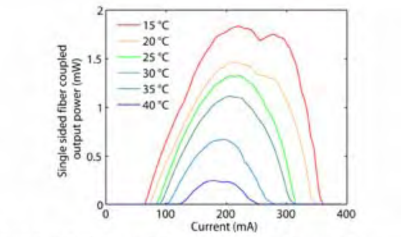


Fig. 3. The single sided fiber coupled laser output as a function of drive current for various operating temperatures.

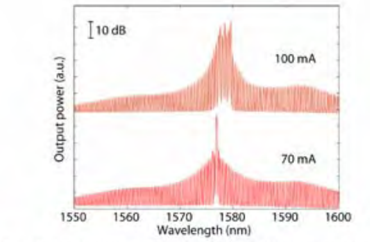


Fig. 4. The hybrid laser spectrum taken slightly above threshold (70 mA) and well above threshold (100 mA). The y-axis is on a logarithmic scale.

Ladningsbærer Si modulator

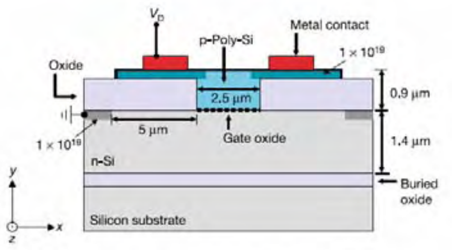


Figure 1 Schematic diagram showing the cross-sectional view of a MOS capacitor waveguide phase shifter using 'silicon-on-insulator' technology. The n-type doped crystalline silicon layer thickness is ~1.4 µm, and the p-type doped polysilicon thickness at the centre of the waveguide is ~0.9 µm. The gate oxide thickness is 120 Å. The polysilicon rib and the gate oxide widths are both ~2.5 µm. The n-type silicon has an active doping concentration of $\sim 1.7 \times 10^{16}\,\mathrm{cm}^{-3}$ and the p-type poly-silicon has an active doping concentration of $\sim 3 \times 10^{16}\,\mathrm{cm}^{-3}$. These doping concentrations were chosen to produce a modulation speed of the phase shifter of above 1 GHz, as the speed of the device depends on silicon and polysilicon resistances. A surface doping density of $1 \times 10^{19}\,\mathrm{cm}^{-3}$ was designed to minimize the metal–semiconductor contact resistance.

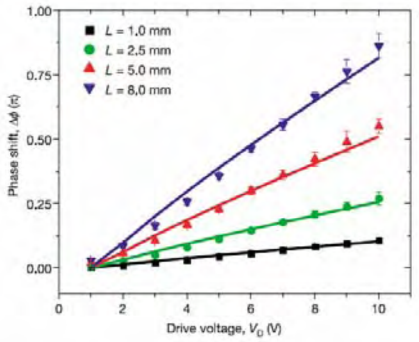


Figure 2 Phase shift $\Delta\phi$ versus drive voltage V_D of the MOS capacitor phase shifter in Fig. 1 at a wavelength of $\lambda = 1.55\,\mu\mathrm{m}$ for different phase shifter lengths. The symbols represent the measured phase shifts, and the solid lines are the simulated phase shifts.

INTEL, Nature 427 (2004)

Ladningsbærer Si modulator

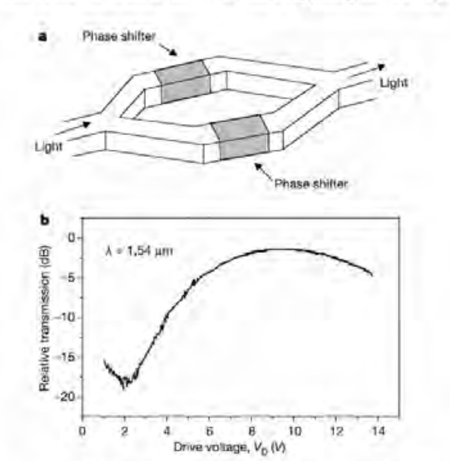


Figure 3 Integrated silicon optical modulator and measured drive-voltage-dependent output optical intensity. **a**, Schematic diagram showing an asymmetric Mach–Zehnder interferometer (MZI) containing two identical MOS capacitor phase shifters in the two arms. **b**, Measured relative transmission of a MZI as a function of applied voltage at a wavelength of 1.54 µm.

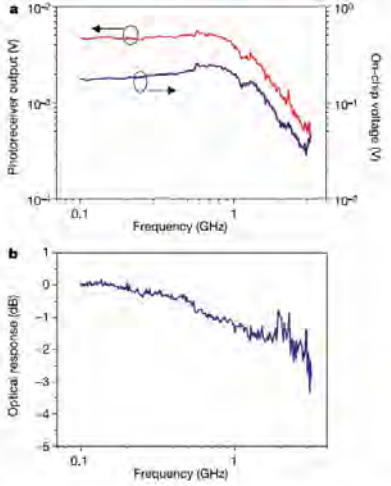
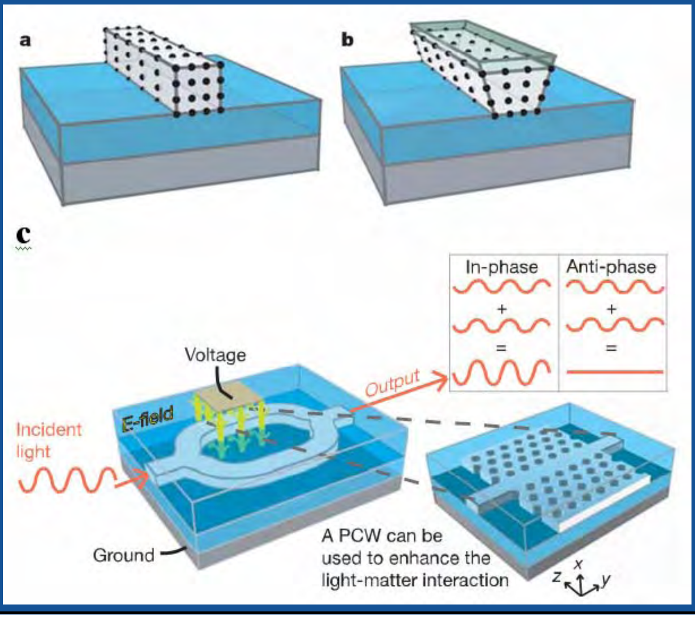
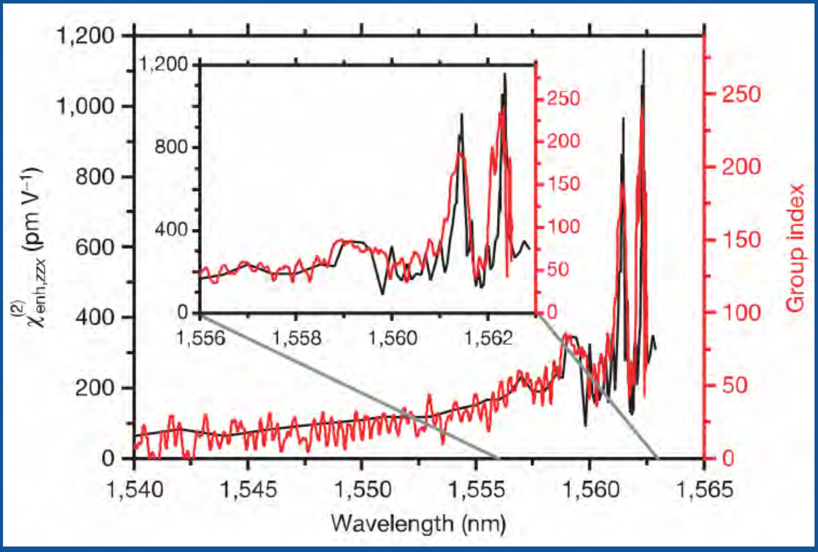


Figure 4 Frequency dependence of the optical response of a silicon MZI modulator. **a**, Measured photoreceiver output and on-chip r.m.s. voltage as a function of frequency for a MZI modulator containing a single 2.5-mm-long MOS capacitor phase shifter in one arm. **b**, Optical response of the MZI modulator as a function of frequency.

Elektro-optisk modulation i Si



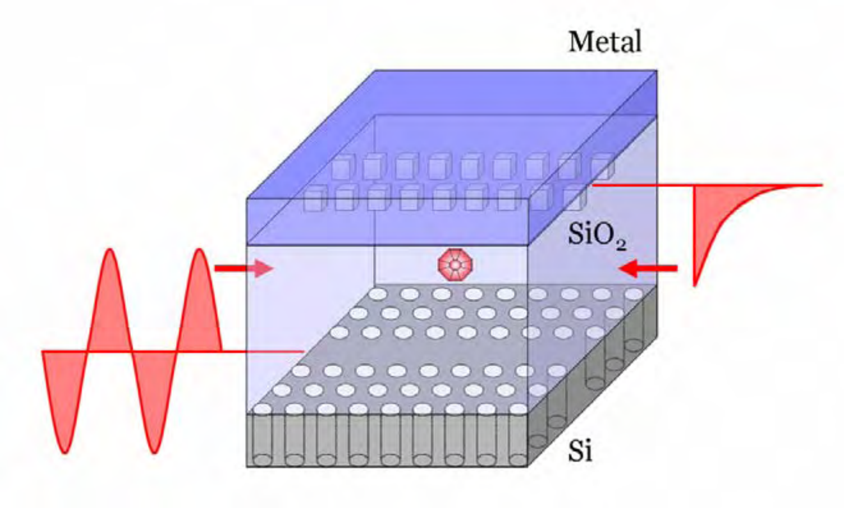
Stress-baserede modulations resultater



Anvendelsesmuligheder

- Alle integrerede passive funktioner der kendes i dag
- Bio-fotonik (erstatning for elektromekaniske sensorer)
- Elektrooptisk modulation og lasere i silicium
- Integration med elektronik (kompatibel med CMOS)
- I den yderste konsekvens muliggøres optiske computere!

Outlook



Relevans for solceller

- Fotoniske krystaller kan lede lys hen til de fotofølsomme områder.
- Man kan adskille forskellige bølgelængdeområder og derved omsætte lyset mere effektivt (publiceret i sidste uge i III-V!).
- Virkningen af nano-clusters kan forbedres.

Negativt brydningsindeks

- Fotoniske krystaller med negativt μ kan få et negativt brydningsindeks!
- Sådanne krystaller kaldes metamaterialer.
- Muliggør fokusering (lidt) under diffraktionsgrænsen i luft.
- Kan bruges til at optisk isolere områder af rummet – muliggør usynlighed (næsten)!

Konklusioner

- Vi har optimeret og fremstillet adskillige typer af passive komponenter i planare fotoniske bånd-gabs bølgeledere.
- Komponenterne har gode egenskaber over ~200nm.
- Silicium lasere er demonstreret af INTEL.
- Electro-optisk modulation demonstreret [1].
- Vi studerer andre typer af aktiv funktionalitet.

[1] R.S. Jacobsen, K.N. Andersen, P.I. Borel, J. Fage-Pedersen, L.H. Frandsen, O. Hansen, M. Kristensen, A.V. Lavrinenko, G. Moulin, H. Ou, C. Peucheret, B. Zsigri and A. Bjarklev, 'Strained silicon as a new electro-optic material', Nature 441, 199-202 (2006)