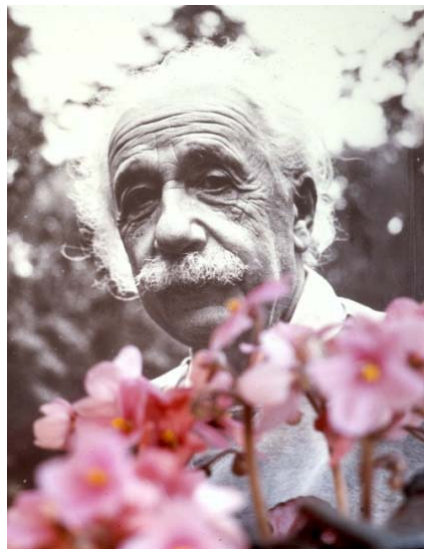


Tribute to the Career of Larry Coldren: An Old World's Perspective

K.J. Ebeling, Ulm University, Ulm, Germany

- Cathedral with highest spire in the world
- Birthplace of most famous scientist of last century
- Region of worldwide eldest human artwork



Albert Einstein
(1879 – 1955)



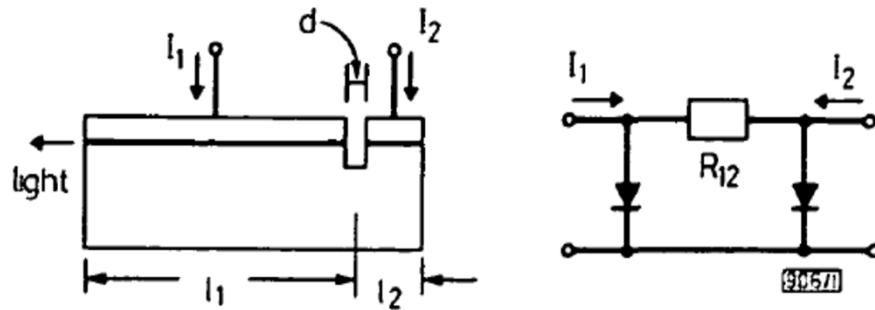
Muenster Cathedral
(1377, 161.4 m)



Ivory Lion Man
(40000 y, 31 cm)

Monolithic Two-Section Semiconductor Lasers

Two-section laser and equivalent circuit

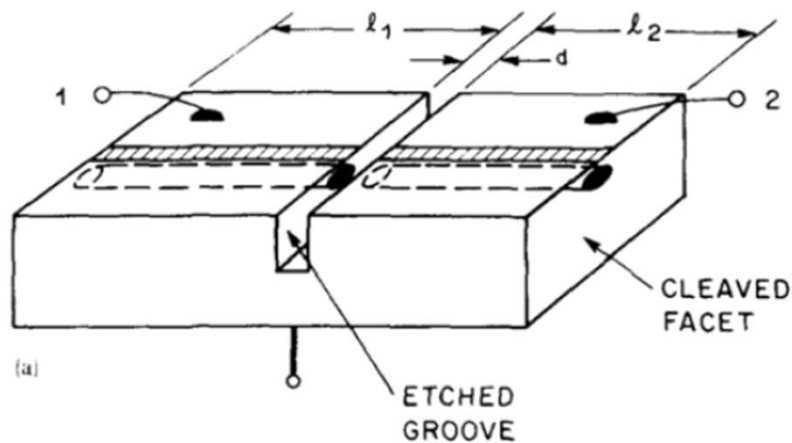


Features:

- Gain-guided coupled-cavity laser with ion-etched groove
- First dynamic single longitudinal mode emission in a two-section laser
- Mode-jump wavelength tuning by setting driving currents I_1 and I_2 appropriately

K.J. Ebeling, L.A. Coldren, B.I. Miller, J.A. Rentschler, Electronic Letters 18(1982)901 and Appl. Phys. Lett. 42(1983)6.

Monolithic buried-crescent coupled-cavity laser



Features:

- First continuous wave index-guided two-section lasers fabricated
- Tunable single-mode emission under high-speed current modulation
- Dynamic side-mode suppression larger than 20 dB

L.A. Coldren, K.J. Ebeling, J.A. Rentschler, C.A. Burrus, D.P. Wilt, Appl. Phys. Lett. 44(1984)368.

Sampled-Grating DBR Tunable Semiconductor Laser

United States Patent [19]

[11] **Patent Number:** **4,896,325**

Coldren

[45] **Date of Patent:** **Jan. 23, 1990**

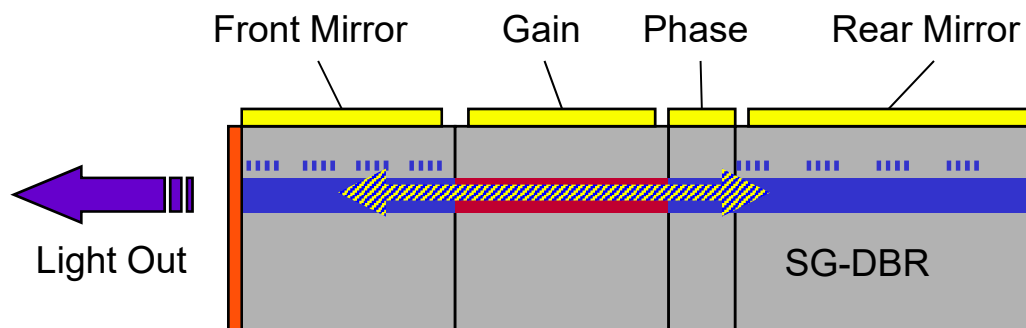
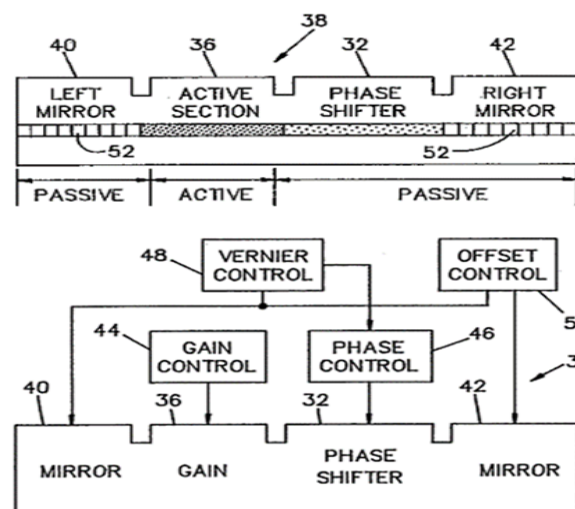
[54] **MULTI-SECTION TUNABLE LASER WITH DIFFERING MULTI-ELEMENT MIRRORS**

[75] **Inventor:** Larry A. Coldren, Santa Barbara, Calif.

[73] **Assignee:** The Regents of the University of California, Berkeley, Calif.

[21] **Appl. No.:** 235,307

[22] **Filed:** Aug. 23, 1988

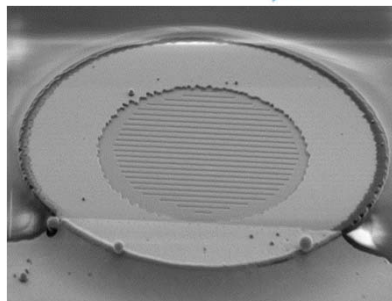
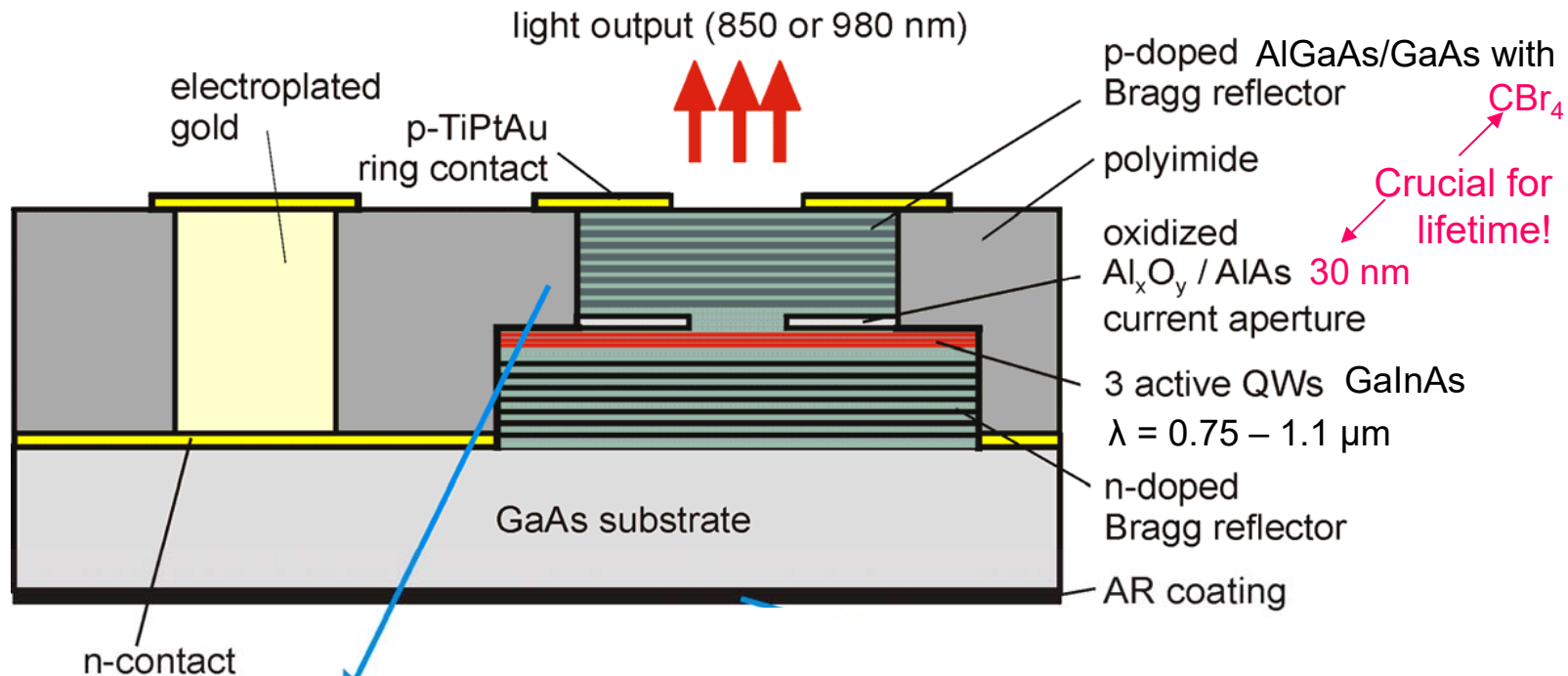


Features:

- Combines discrete mode-jump tuning with continuous $\Delta n/n$ tuning
- 5-10 X tuning range of DBR
- Can cover C band, L band, or C and L bands



VCSEL with 30 nm Oxide Aperture and Carbon Modulation Doping



inverted surface grating

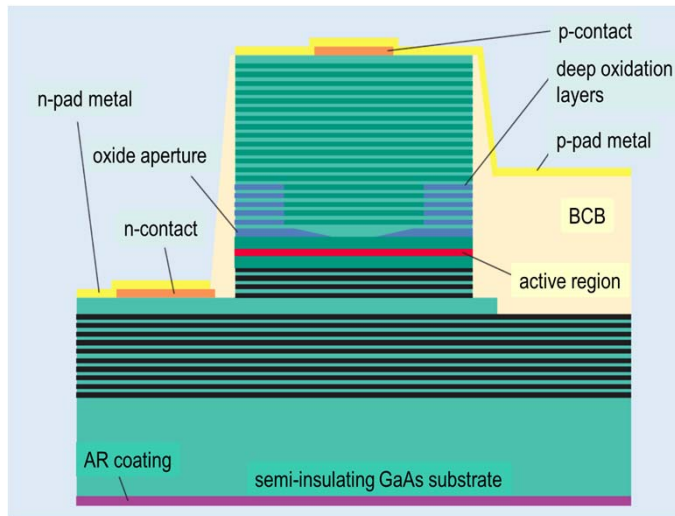
Features:

- Carbon modulation-doped p-type Bragg reflector
- 20-30 nm thin oxide aperture for minimal stress and strain
- Control of optical wave guiding by axial aperture position
- ~ 50 % wallplug efficiency, high reliability
- Linear polarization, orthogonal mode suppression > 25 dB

Our start-up company U-L-M photonics (founded in 2000), subsequently Philips Photonics (since 2006) have fabricated millions of 10 Gb/s VCSELs as well as tens of millions of stable linearly polarized devices!



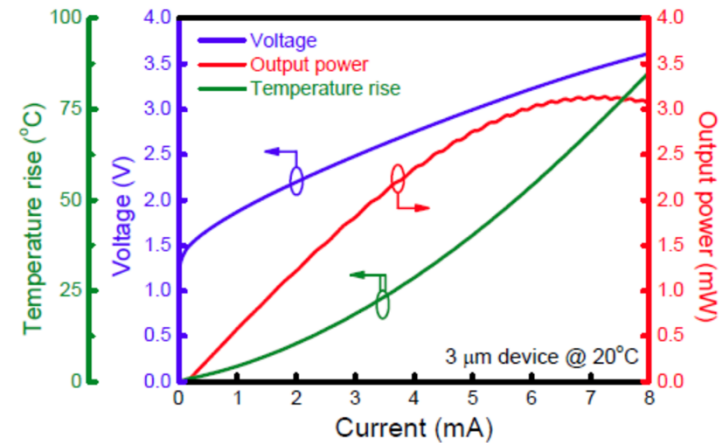
Larry's Record High-Speed VCSEL with Tapered Oxide Aperture



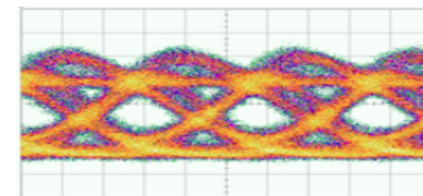
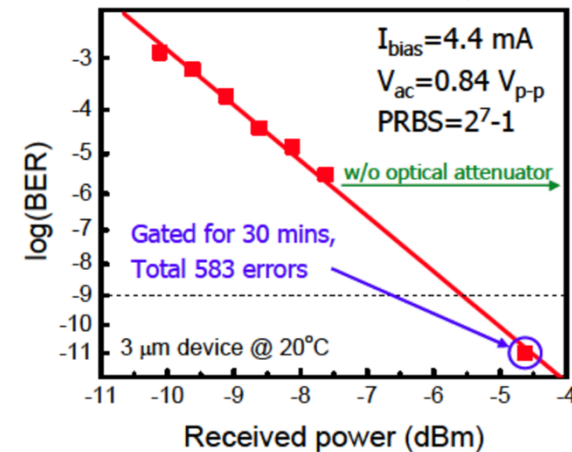
Features:

- Record error-free 35 Gb/s data transmission without electronic pre-emphasis or feed-forward equalization
- Record-high modulation current efficiency factor of $16.8 \text{ GHz/mA}^{1/2}$ and highest data-rate/power-dissipation ratio of 3.5 Gb/s/(mW)
- Tapered aperture to reduce scattering losses, blunter taper to optimize mode volume
- Deep lateral oxidation layers to minimize electrical parasitics

Y.C. Chang, L.A. Coldren, Efficient High-Data-Rate Tapered Oxide-Aperture VCSELs, IEEE J. Sel. Topics Quant. Electron. 15(2009)704

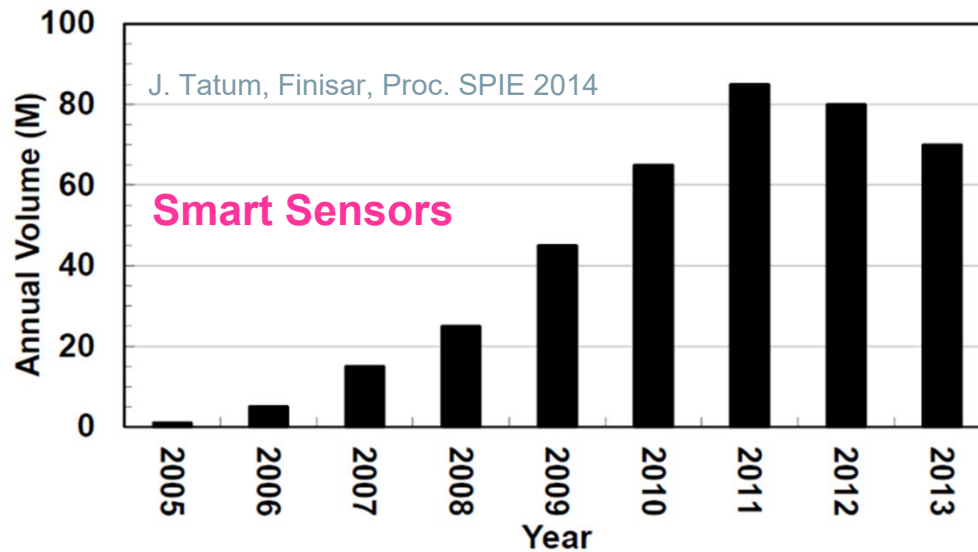
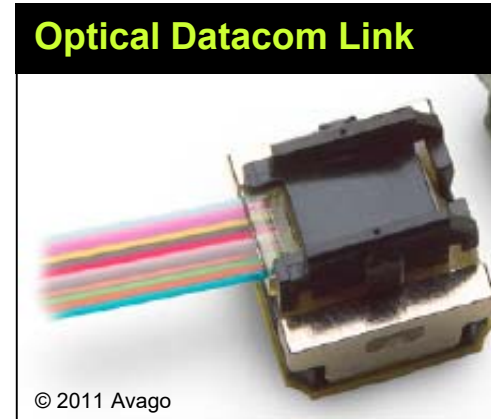
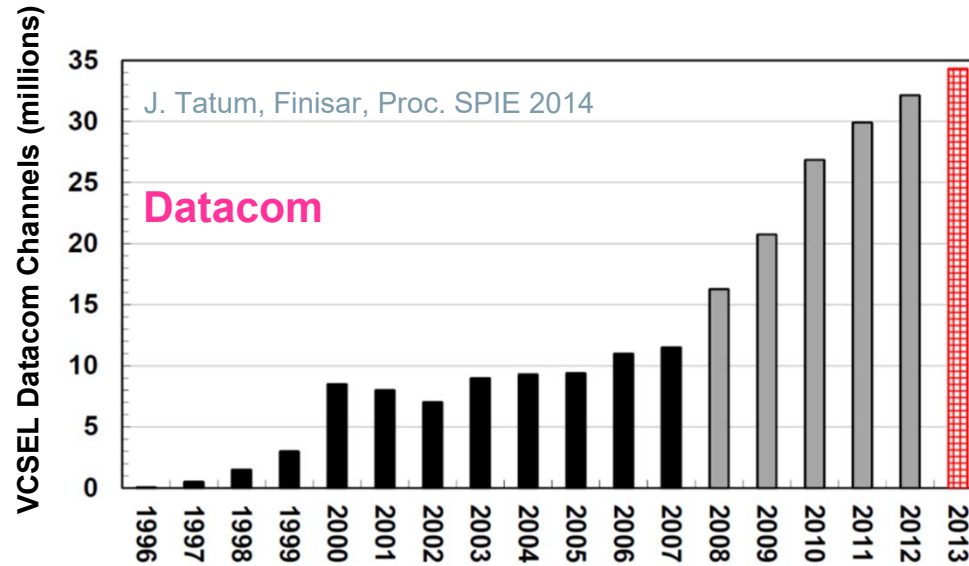


BER curve @ 35 Gb/s



35 Gb/s optical eye, extinction ratio 5.4 dB

Datacom and Smart Sensor VCSELs Shipped and Prominent Applications

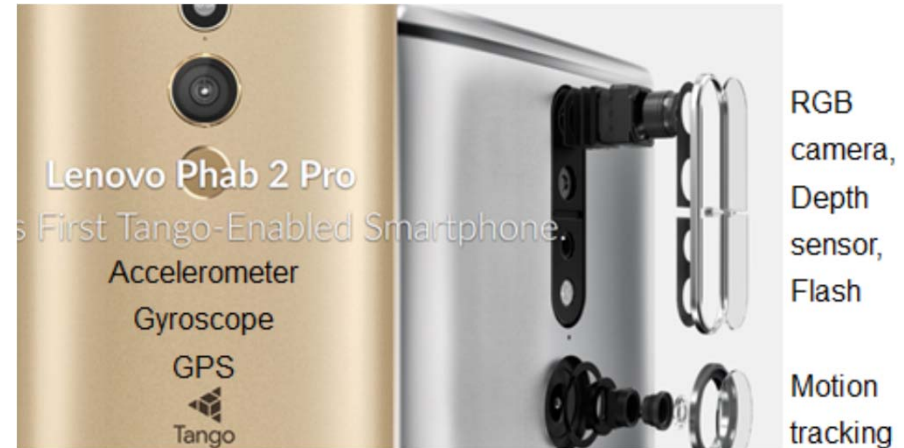


Arising Mass Market Applications of VCSELs in Smartphones

iphone X



Lenovo Phab 2 Pro



Recent new features of VCSELs:

- Proximity detection using gain switched VCSELs
- Autofocus systems also using gain switched VCSELs
- Mobile 3-D sensing with structured light uses individually addressable power VCSEL arrays (iphone X)
- Mobile 3-D sensing applying time-of-flight technology uses high-frequency modulated power VCSEL arrays (Lenovo Phab 2 Pro)
- 3-D sensing is often combined with artificial reality (AR)

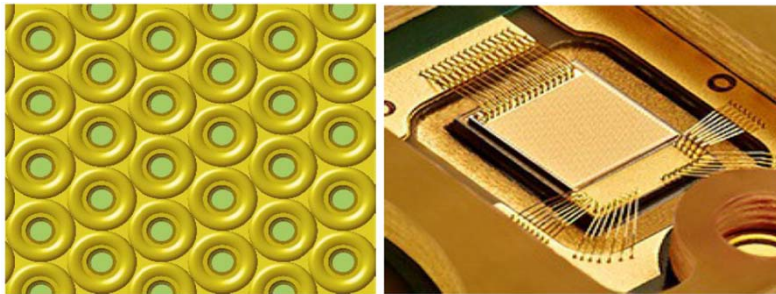
In 2016 Philips Photonics produced ~ 250 million VCSELs in a total annual market certainly far beyond 1 billion pieces!

Power VCSELs and VCSEL Arrays

Some history:

- F.H. Peters, M.G. Peters, D.B. Young, J.W. Scott, B.J. Thibeault, S.W. Corzine, L.A. Coldren, Electronics Letters 29(1993)200: 70 μm size VCSEL with 113 mW cw output power, first VCSEL above 100 mW
- M. Miller, M. Grabherr, R. Jäger, K.J. Ebeling, IEEE Phot. Techn. Lett. 13(2001)173: VCSEL array with > 1 W cw output at 18 % wallplug efficiency, 1 kW/cm² average power density, > 10000 h lifetime
- M. Grabherr, Proc. SPIE 9381, 938102 (2015): 2-D VCSEL array module with 4.8 kW cw output power
- H. Moench, R. Conrads, S. Gronenborn, X. Gu, M. Miller, P. Pekarski, J. Pollman-Retsch, A. Pruijboom, U. Weichmann, Proc. SPIE 9733, 97330V (2016): Integrated high power VCSEL systems

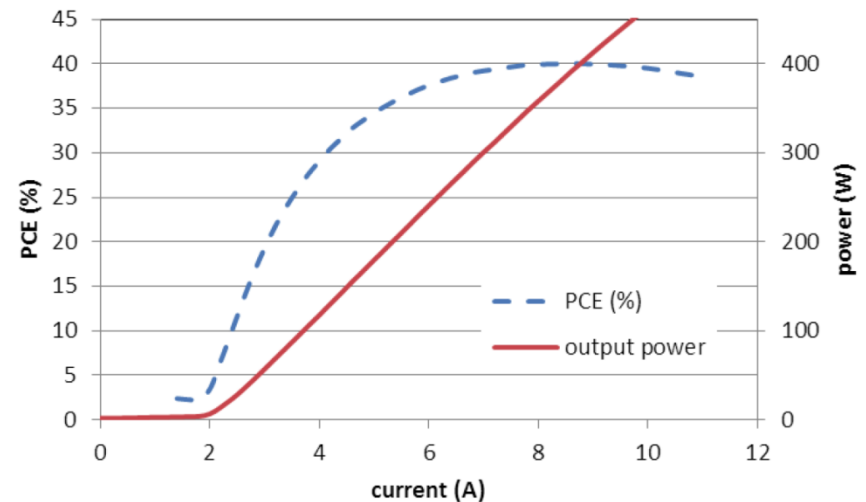
Array of 8 μm VCSELs arranged at 40 μm pitch and assembled 2 mm x 2 mm chip with 2205 lasers



Emitter bar of 4 x 14 = 56 chips of 2 mm x 2 mm size



CW output power and efficiency of bar with 56 chips

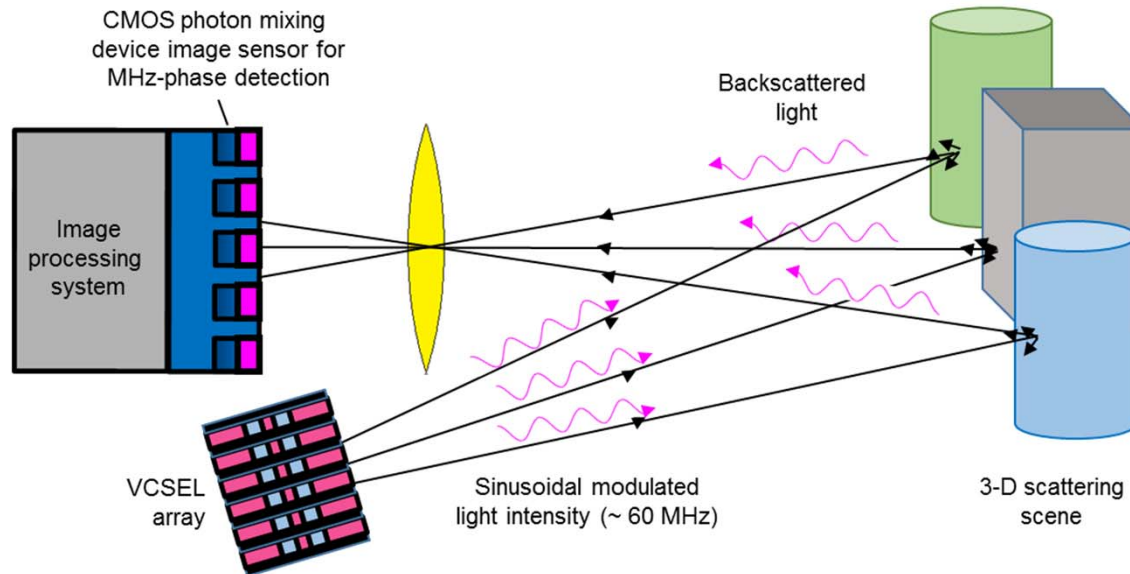


Maximum cw output power of 2 mm x 2 mm chip is ~ 8 W at 40 % power conversion efficiency!

M. Grabherr, Proc. SPIE 2015; H. Moench et al., Proc. SPIE 2016

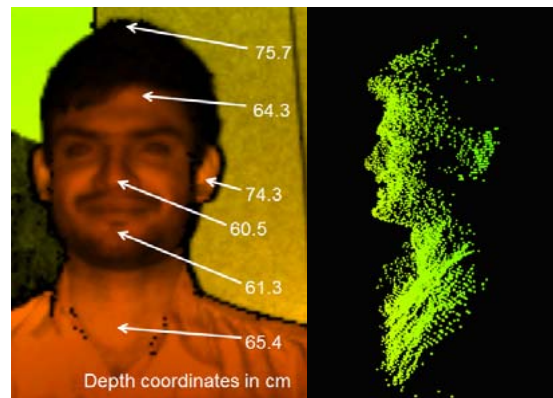
3-D Photography Using Modulated Power VCSEL Array Light Source and Photon Mixer Device (PMD) Image Sensor

Picoflexx 3-D time-of-flight camera system using proprietary Infineon REAL3 image sensor with ~ 40000 pixels, ~ 300 mW total power consumption

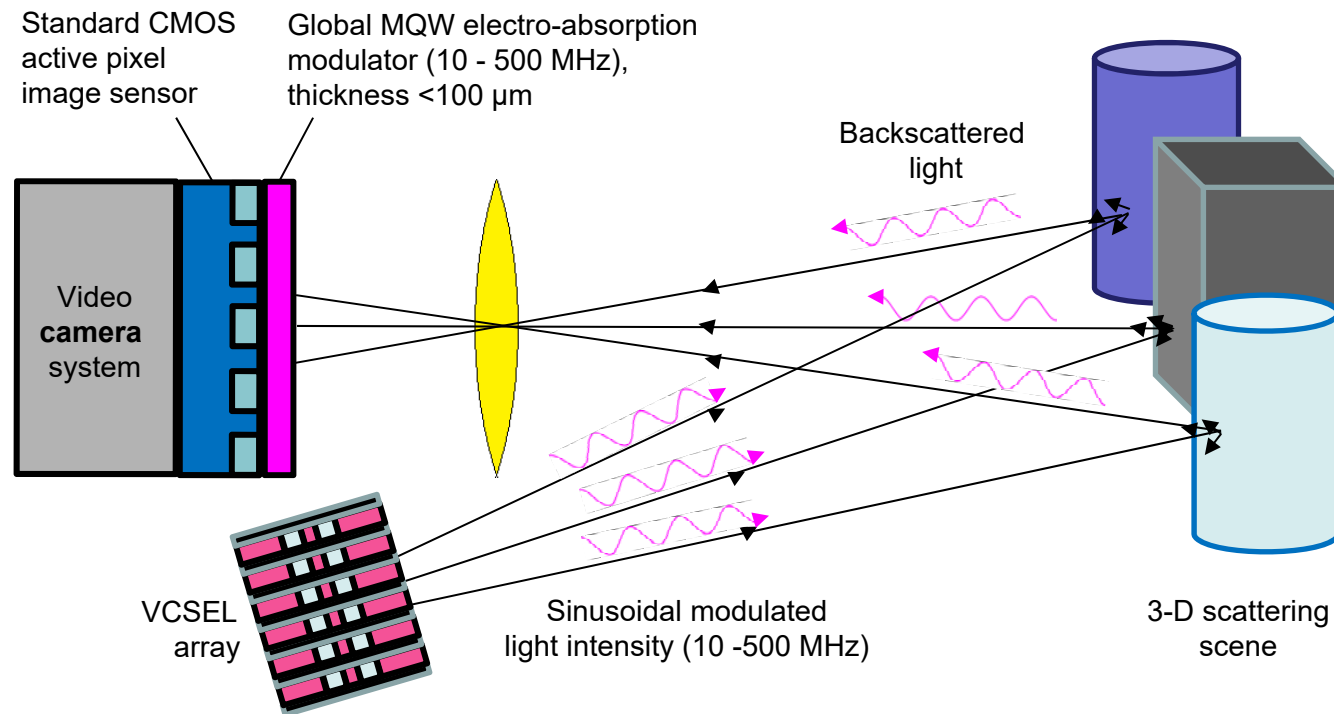


Left: Color-coded 3-D front-view image of a person with measured depth coordinates

Right: Side-view profile calculated from x-, y-, and depth coordinates



Depth Recording Using Sinusoidal Time-of-Flight Signals and Electro-absorption Modulator Placed in front of Lens



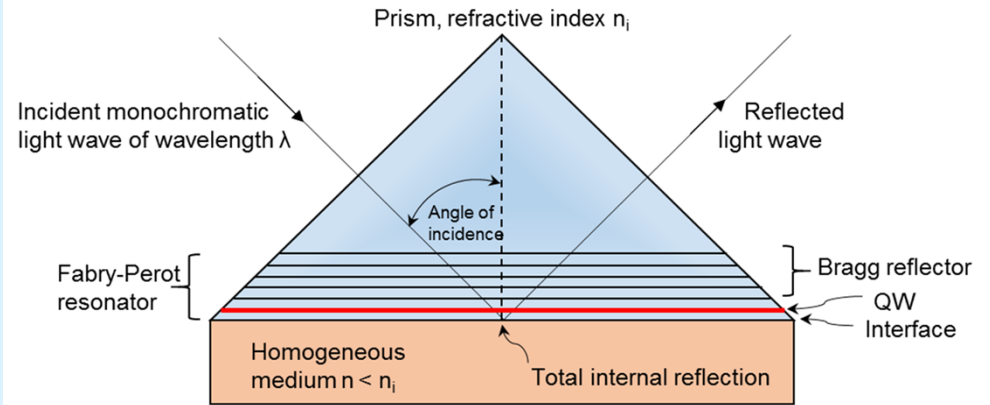
Method:

Sinusoidal intensity modulated light from a VCSEL illuminates a 3-D object. An MQW electro-absorption modulator is applied for a second modulation of the backscattered light before reaching the image sensor. Each pixel records the difference frequency signal of the mixing process that contains information on the depth profile of the scattering object.

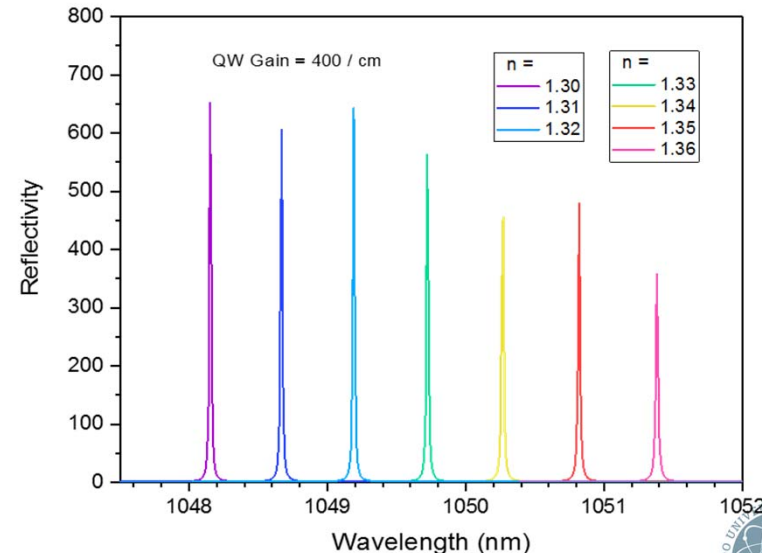
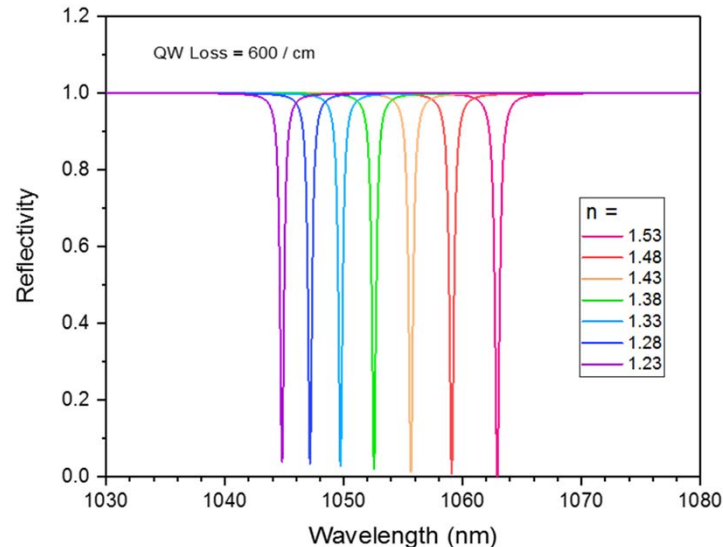
Half-VCSEL and Loss-Gain Refractometry

Inspiration & Idea & Applications

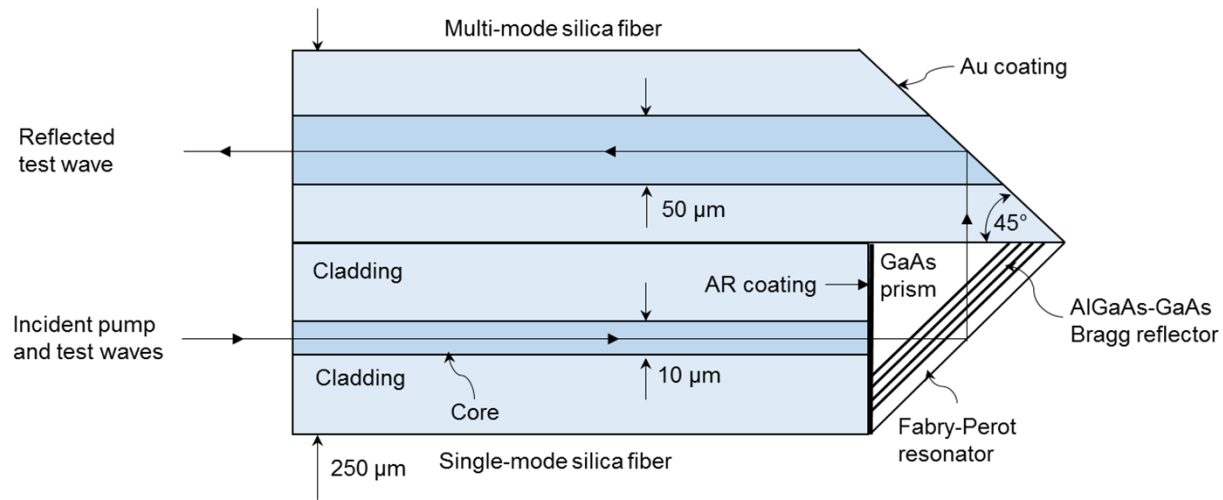
- R.H. Yan, R.J. Simes, L.A. Coldren, IEEE J- QE 25(1989)2272: Surface-Normal Fabry-Perot reflection modulators
- Replace VCSEL bottom mirror by total internal reflection, study oblique incidence
- Chemistry, biotechnology, medicine, or plastics, food, pharmaceutical and paper industries



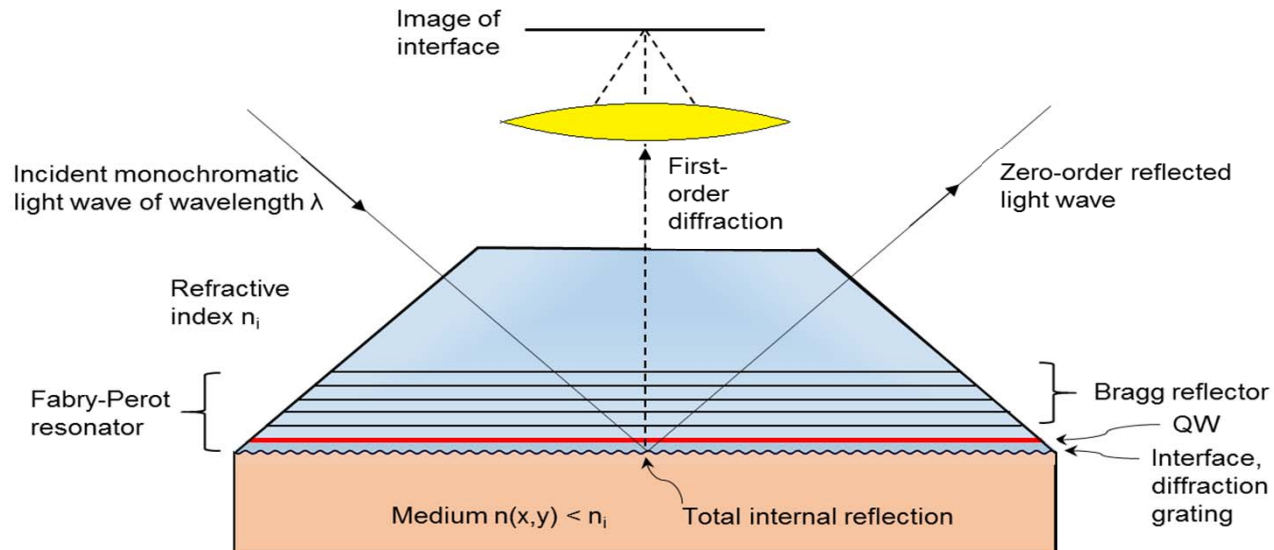
Spectra for 30° angle of incidence, Bragg reflector with 15 GaAs-AlAs $\lambda/4$ -pairs, 10 nm InGaAs QW, TE pol.



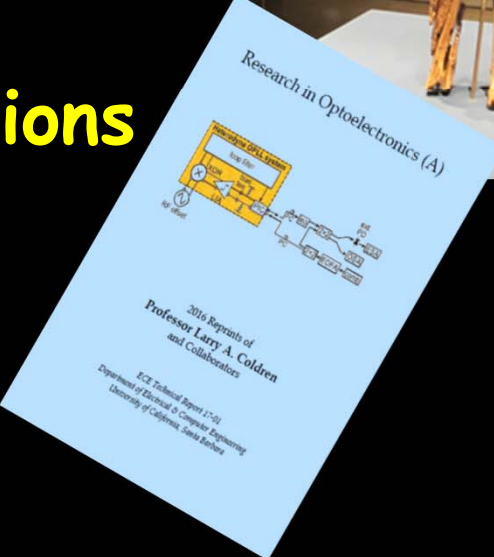
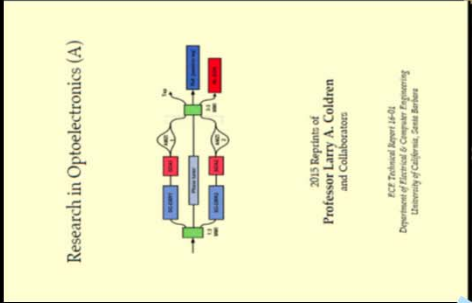
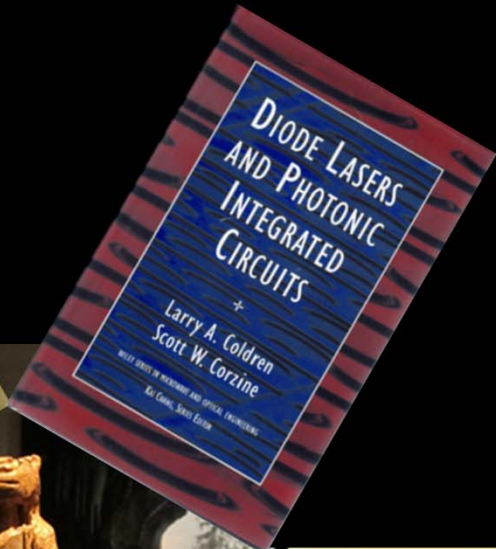
Resonant Micro-Refractometer at Tip of Single-Mode Silica Fiber



Imaging Refractometer with Shallow Sinusoidal Corrugated Interface







Congratulations

and Thanks!