Modern Optical Systems

Optical Engineering

Prof. Elias N. Glytsis

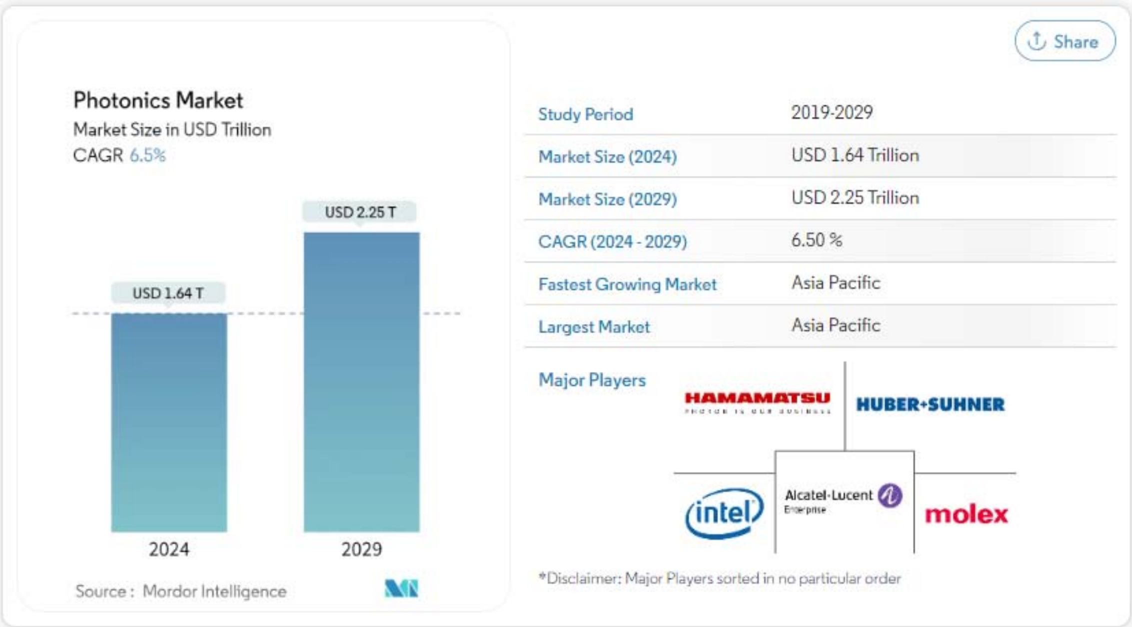
School of Electrical & Computer Engineering
National Technical University of Athens

Photonics For Europe

Photonics technologies, components and solutions play a crucial role in many EU strategic value chains (SVC's).

https://www.photonics21.org/download/ppp-services/photonics-downloads/230421_Supply_Chain_Report_Final_C3.pdf

Photonics Market by Product Type (LED and Lasers, Detectors, Sensors & Imaging Devices), Application (ICT and Production Tech.), End-Use Industry (Media, Broadcasting & Telecommunication and Consumer & Business Automation) - **Global Forecast to 2029**



Study Period	2019-2029
Market Size (2024)	USD 1.64 Trillion
Market Size (2029)	USD 2.25 Trillion
CAGR (2024 - 2029)	6.50 %
Fastest Growing Market	Asia Pacific
Largest Market	Asia Pacific

Major Players

HAMAMATSU, HUBER+SUHNER, intel, Alcatel-Lucent Enterprise, molex

*Disclaimer: Major Players sorted in no particular order

USD **1.64** Trillion in 2024

to USD **2.25** Trillion by 2029

Compound Annual Growth Rate (CAGR) of **6.50%**

https://www.mordorintelligence.com/industry-reports/photonics-market-market

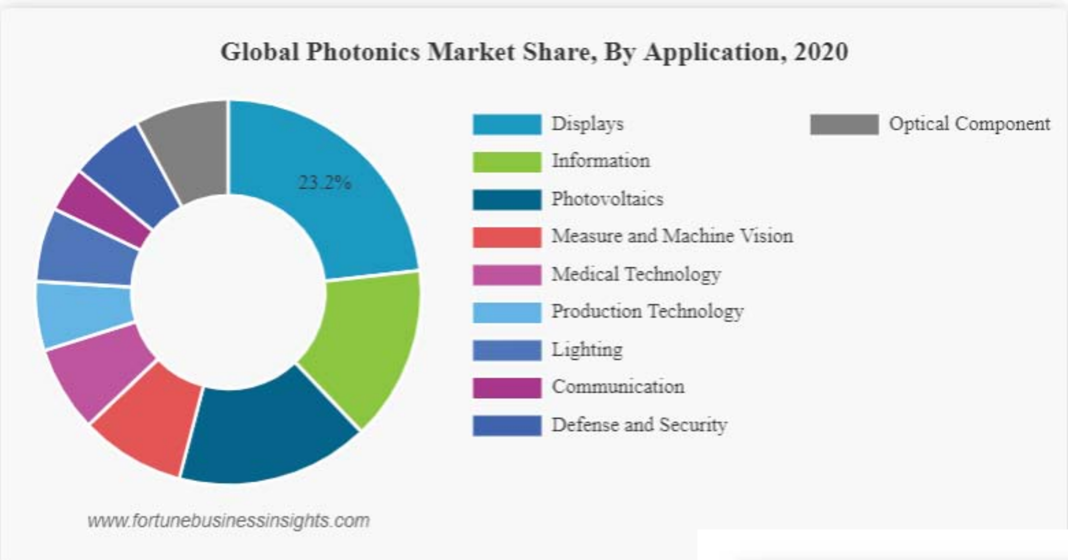
Photonics Market, by Product Type:

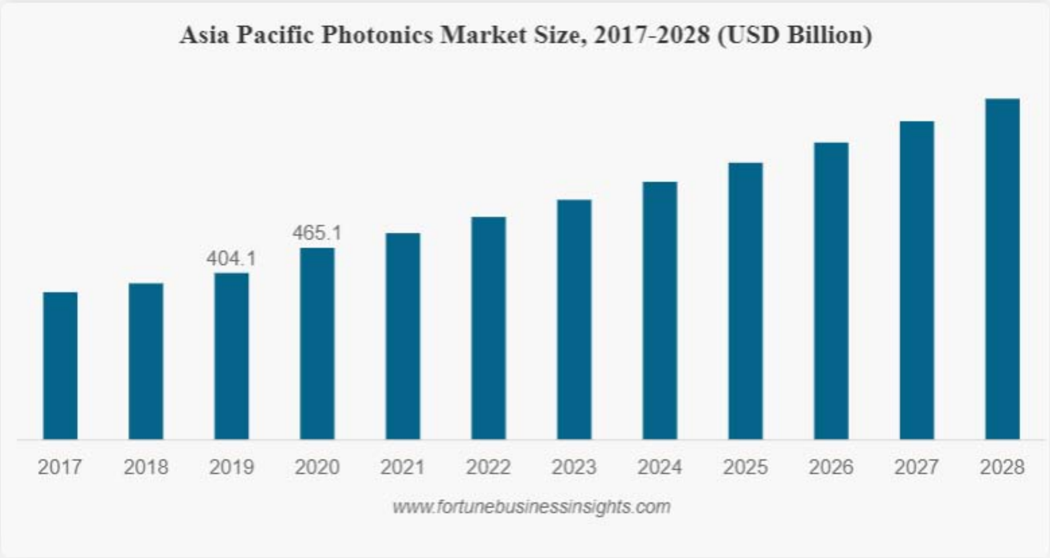
- LED
- Lasers, Detectors, Sensors, & Imaging Devices
- Optical Communication Systems & Components
- Consumer Electronics & Devices
- Others

Photonics Market, by Application:

- Displays
- Information & Communication Technology
- Photovoltaic
- Medical Technology & Life Sciences
- Measurement & Automated Vision
- Lighting
- Production Technology
- Others

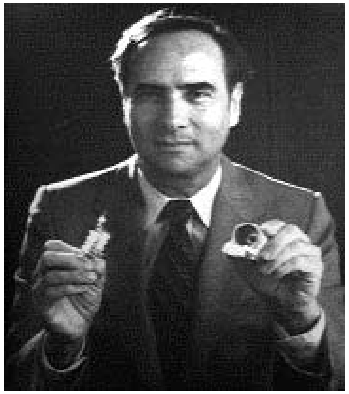
Global Photonics Market Outlook



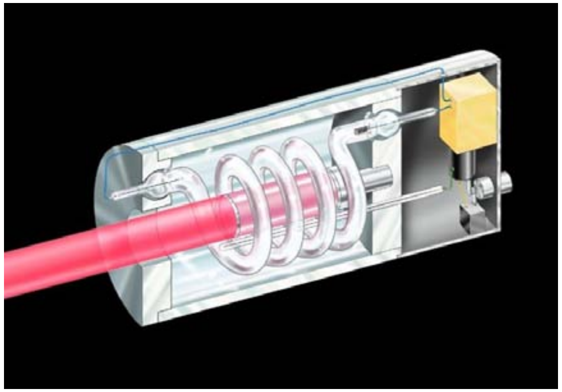


https://www.fortunebusinessinsights.com/photonics-market-106525

Invention of LASER (1960)



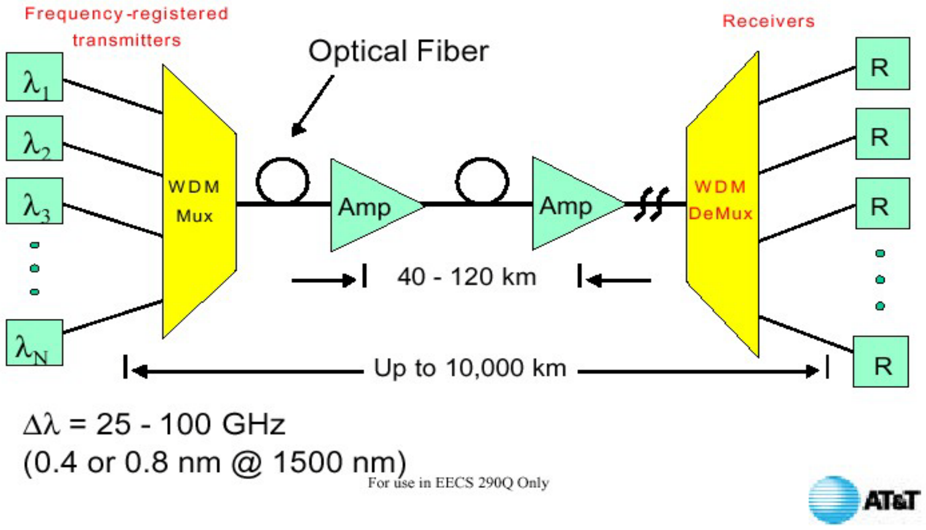
Theodore Harold Maiman
(July 11, 1927 – May 5, 2007)

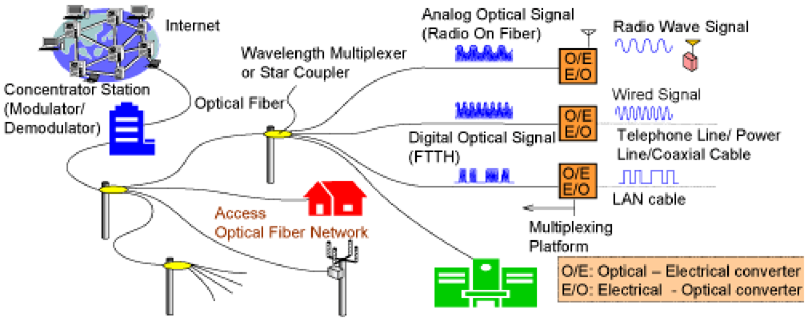


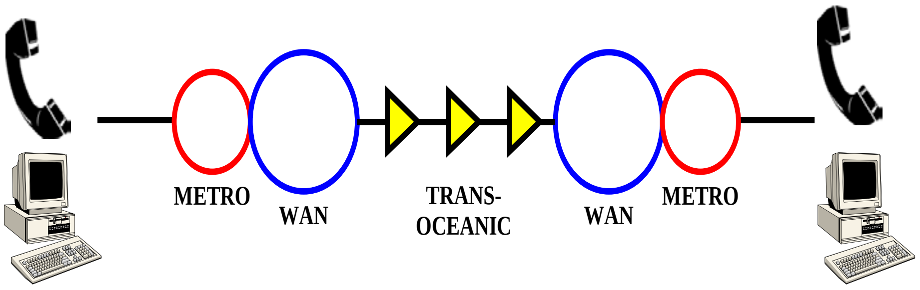
Schematic of first Ruby Laser

https://en.wikipedia.org/wiki/Theodore_Maiman#/media/File:World's_first_laser_out_of_case.jpg

Communication by photons



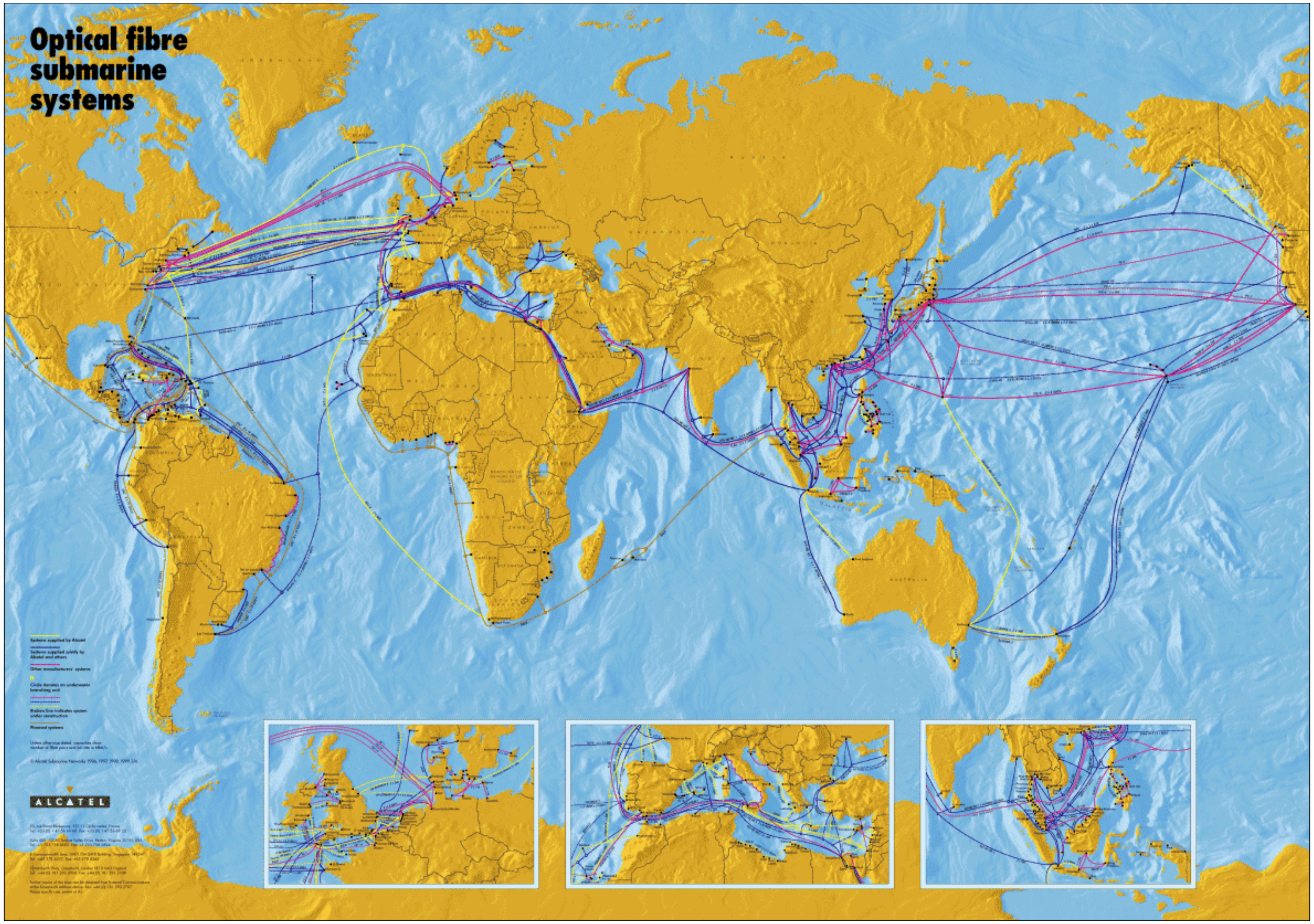




Telephony/data/internet

http://criepi.denken.or.jp/en/system/unit/03/index.html

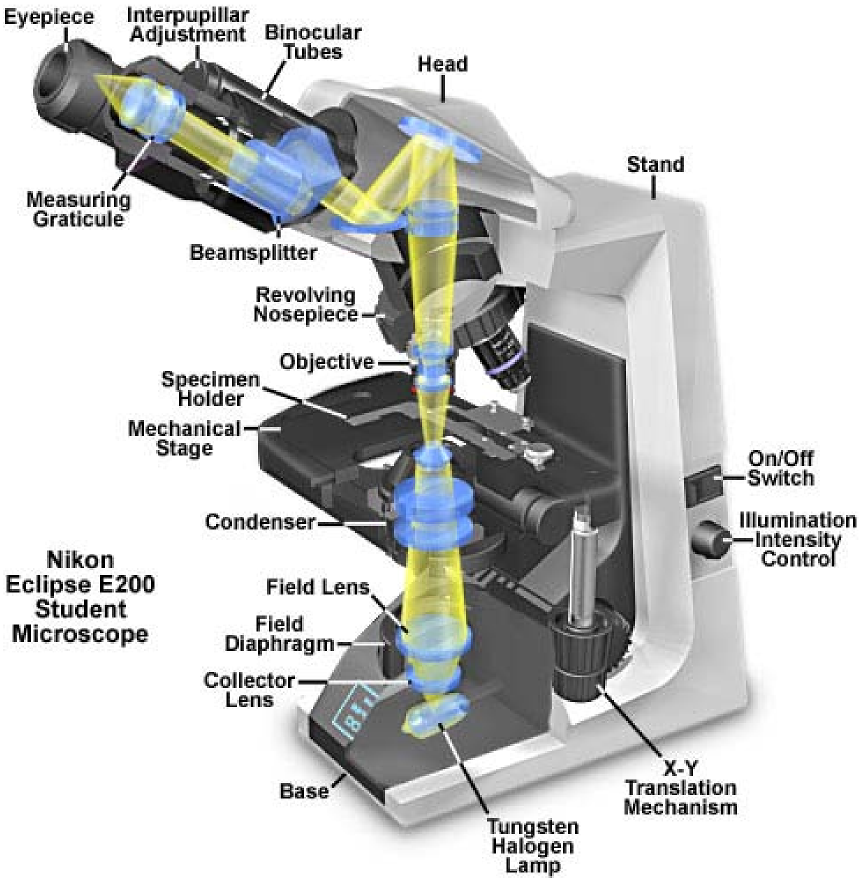
Global Submarine Optical-Fiber Systems



https://personalpages.manchester.ac.uk/staff/m.dodge/cybergeography/atlas/cables.html

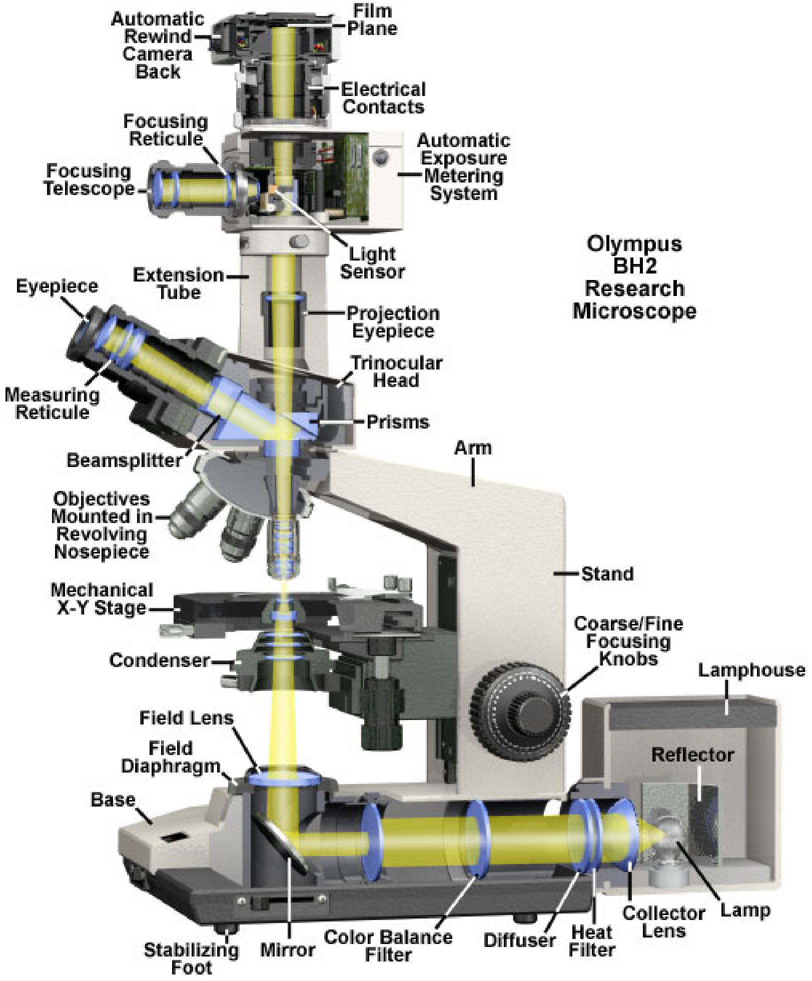
Microscopes

Nikon Eclipse E200 Microscope Cutaway Diagram



https://micro.magnet.fsu.edu/primer/anatomy/nikone200cutaway.html

Olympus BH2 Research Microscope Cutaway Diagram



http://www.olympusmicro.com/primer/anatomy/bh2cutaway.html

Telescopes

A typical 4" refractor

An 8" Newtonian Reflector

http://www.scopereviews.com/begin.html

Hale 5m (200 inch) at Mt. Palomar

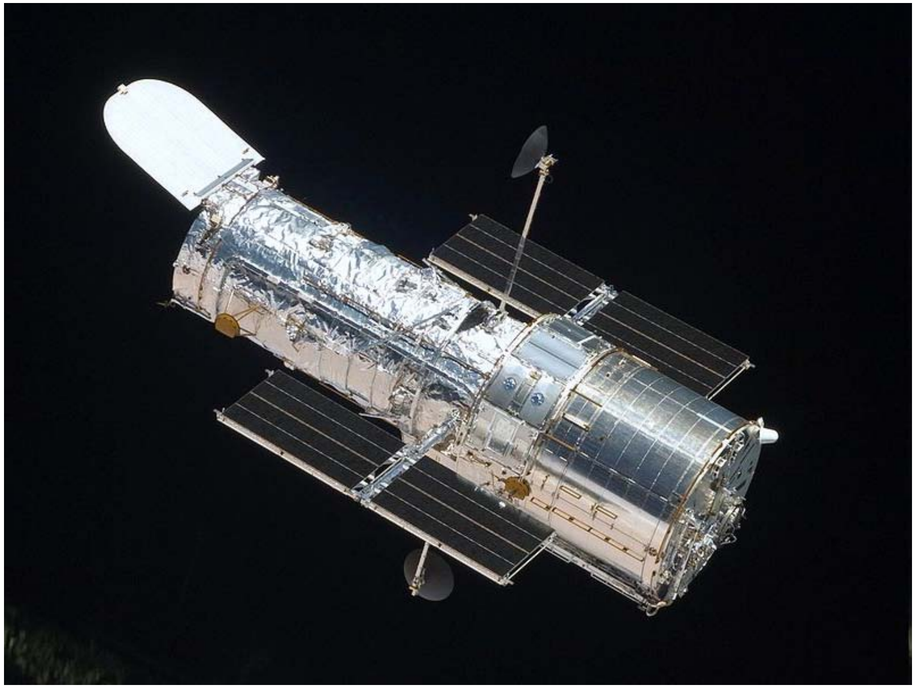
Cassegrain type

http://www.astro.caltech.edu/palomar/hale.html

Hubble Telescope

General Information

Launch: April 24, 1990, from space shuttle Discovery (STS-31)
Deployment: April 25, 1990
First Image: May 20, 1990: Star Cluster NGC 3532
Servicing Mission 1: December 1993
Servicing Mission 2: February 1997
Servicing Mission 3A: December 1999
Servicing Mission 3B: February 2002
Servicing Mission 4: May 2009



http://en.wikipedia.org/wiki/Hubble_Space_Telescope

Size

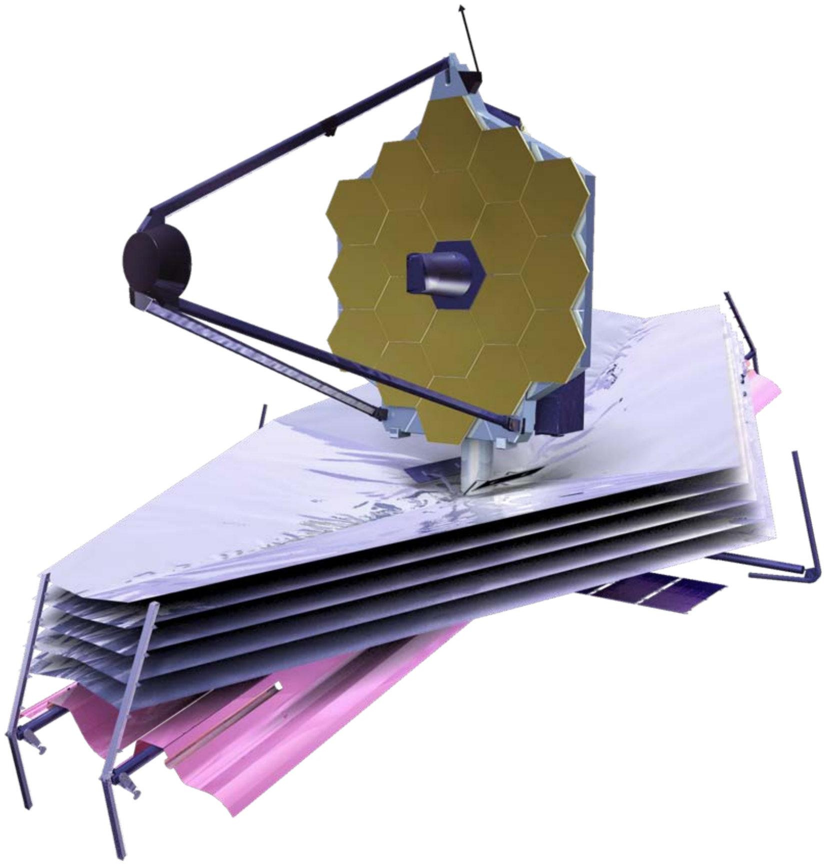
Length: 43.5 ft (13.2 m)
Weight: At Launch: ~24,500 lb (11,110 kg)
Post SM4: ~27,000 lb (~12,247 kg)
Maximum Diameter: 14 ft (4.2 m)

Hubble's Mirrors

Primary Mirror Diameter: 94.5 in (2.4 m)
Primary Mirror Weight: 1,825 lb (828 kg)
Secondary Mirror Diameter: 12 in (0.3 m)
Secondary Mirror Weight: 27.4 lb (12.3 kg)

http://hubblesite.org/the_telescope/hubble_essentials/

James Webb Space Telescope



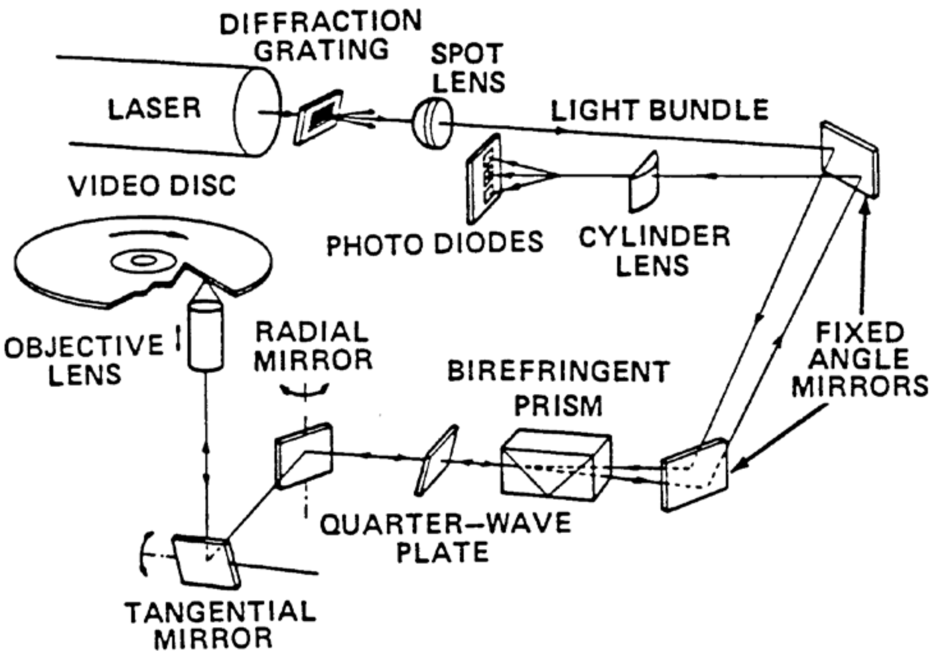
https://en.wikipedia.org/wiki/James_Webb_Space_Telescope

Launched: 25 /12/ 2021

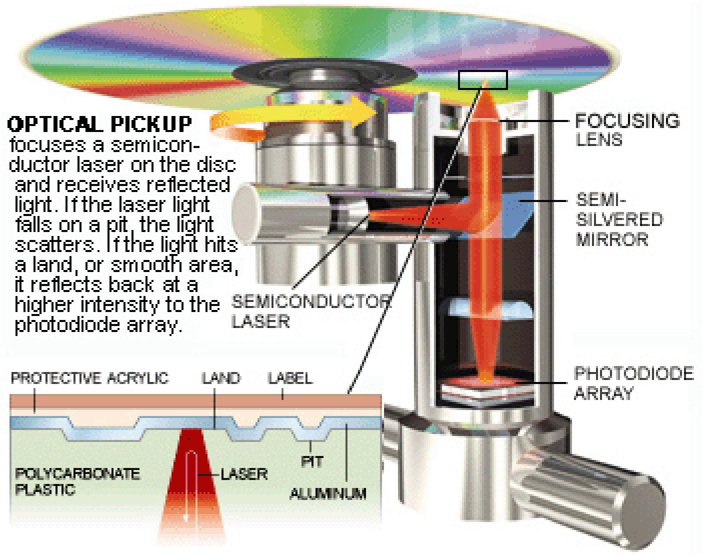
Main telescope	
Type	Korsch telescope
Diameter	6.5 m (21 ft)
Focal length	131.4 m (431 ft)
Focal ratio	*f*/20.2
Collecting area	25.4 m^2 (273 sq ft)[7]
Wavelengths	0.6–28.3 μm (orange to mid-infrared)

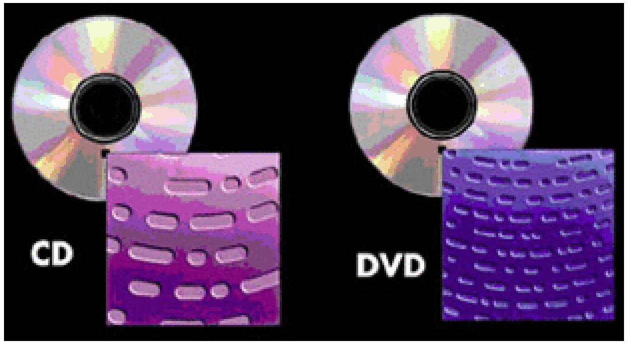
Orbital parameters	
Reference system	Sun–Earth L_2 orbit
Regime	Halo orbit
Periapsis altitude	250,000 km (160,000 mi)[6]
Apoapsis altitude	832,000 km (517,000 mi)[6]
Period	6 months

Bulk Optics Compact Disk Reader



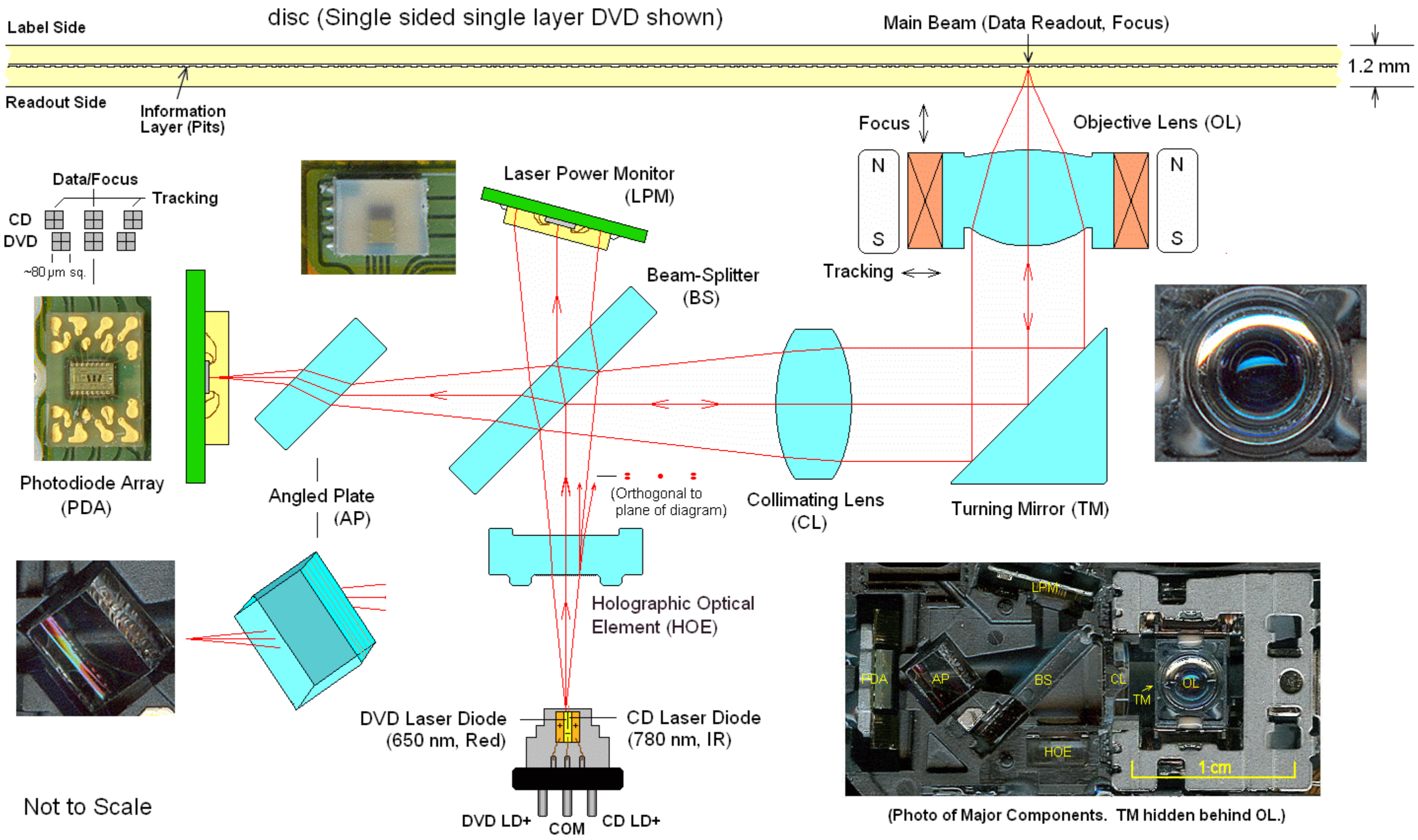
L. Steckler, Radio Electronics 7, 37 (1979).


OPTICAL PICKUP focuses a semiconductor laser on the disc and receives reflected light. If the laser light falls on a pit, the light scatters. If the light hits a land, or smooth area, it reflects back at a higher intensity to the photodiode array.



http://tweak3d.net/articles/opticals/print.shtml

Miniature Optics CD/DVD Reader-Writer



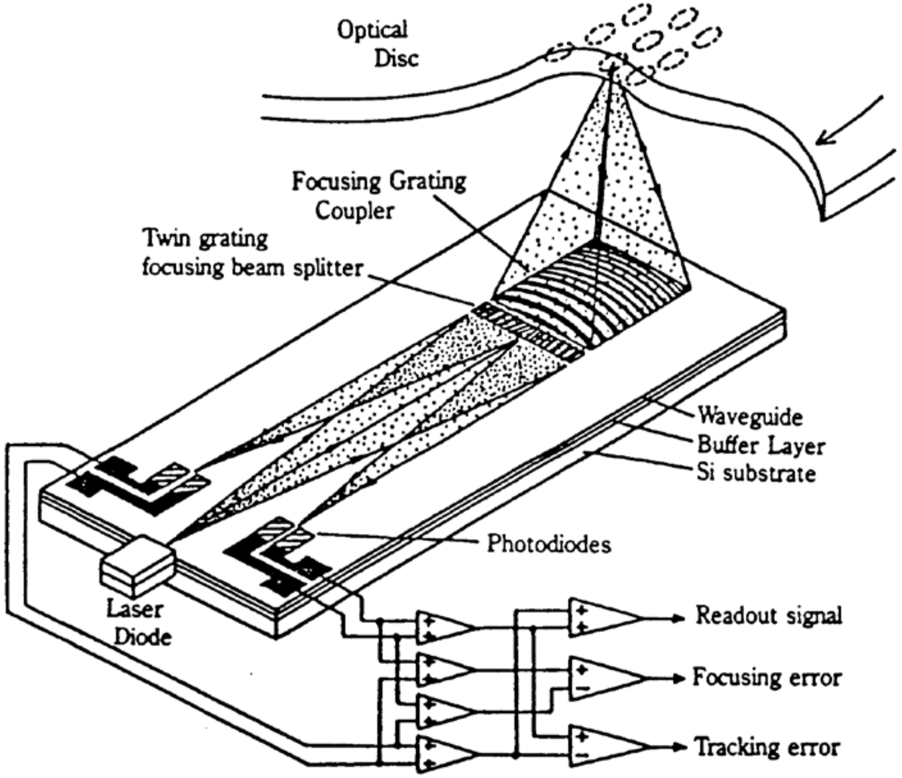
Not to Scale

(Photo of Major Components. TM hidden behind OL.)

Beam Paths of Optical Pickup in Panasonic UJ8D1 CD/DVD RW Drive

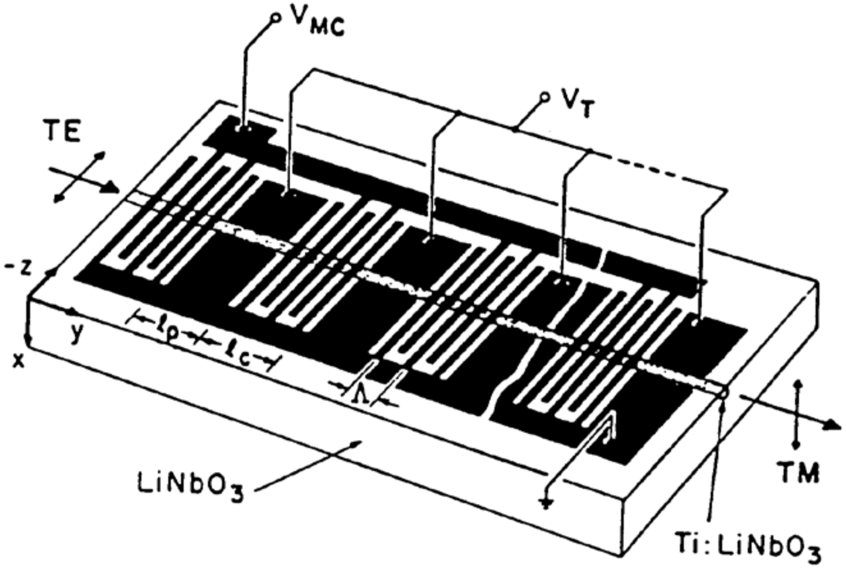
https://www.repairfaq.org/sam/puj8d1bp.gif

Integrated Optics Compact Disk Reader



S. Ura, T. Suhara, and H. Nishihara, Appl. Opt. 26, 4777 (1987).

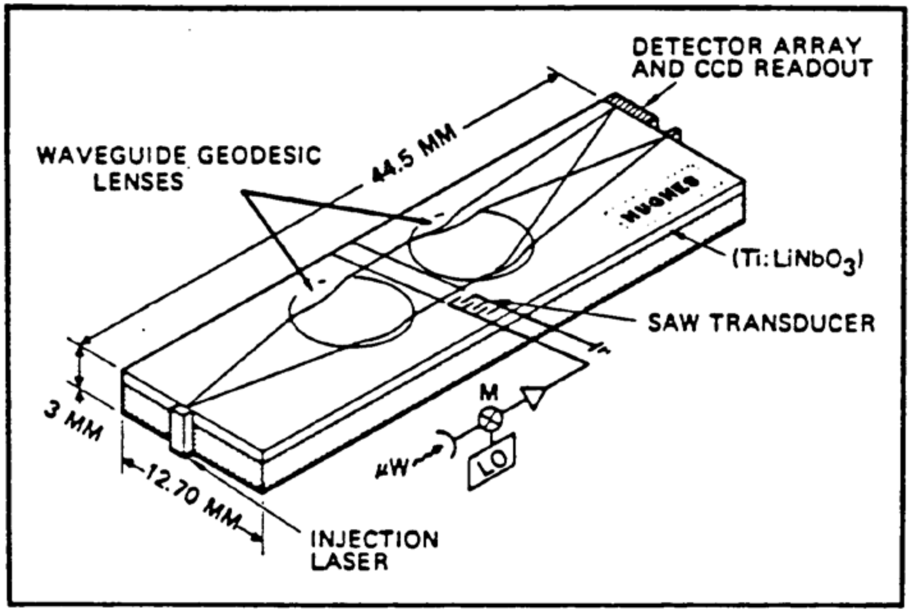
Wavelength-Tunable Electro-Optic Polarization Converter



This device is a cascade of N TE ↔ TM mode converter sections alternated with N birefringent tuning sections implemented in x-cut, y-propagating lithium niobate. The mode converter sections utilize the electric field in the x direction and the tuning sections utilize the field in the z direction.

F. Heismann and R. C. Alferness, IEEE J. Quantum Electron. 24, 83 (1988).

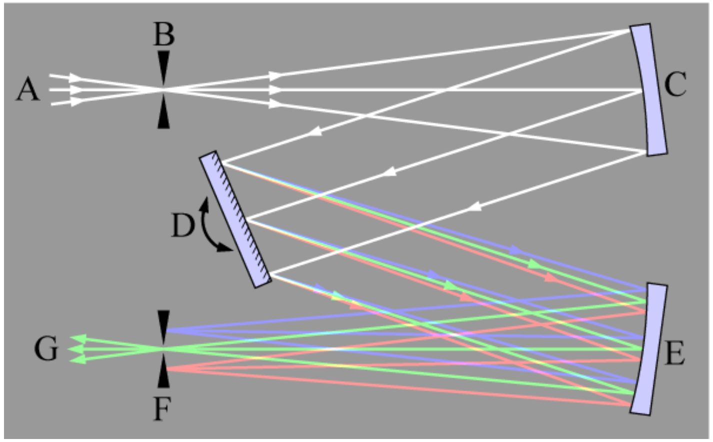
Integrated Optical Spectrum Analyzer

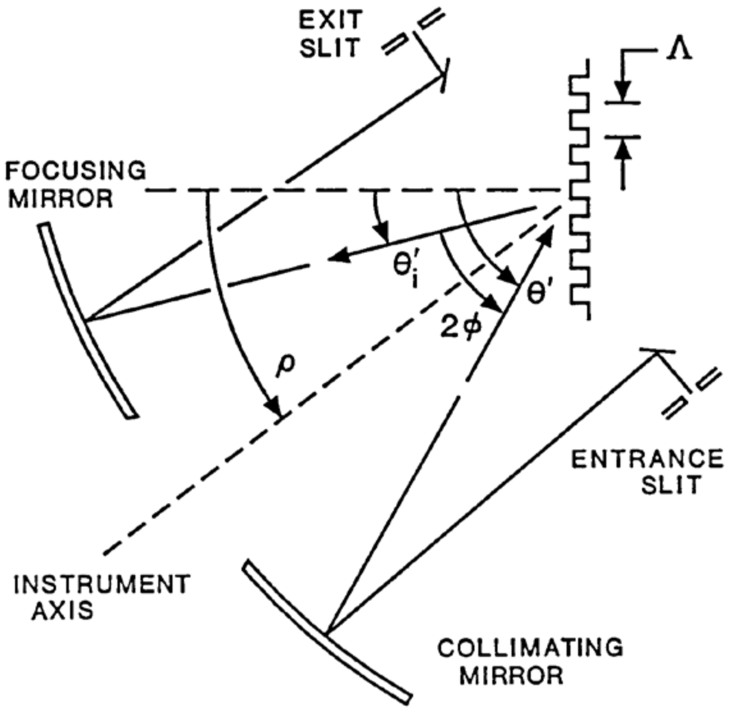


The integrated spectrum analyzer developed at Hughes Aircraft Co. has a bandwidth of a few hundred Megahertz to a few Gigahertz.

Laser Focus <u>16</u>, 44 (1980).

Czerny-Turner Monochrometer

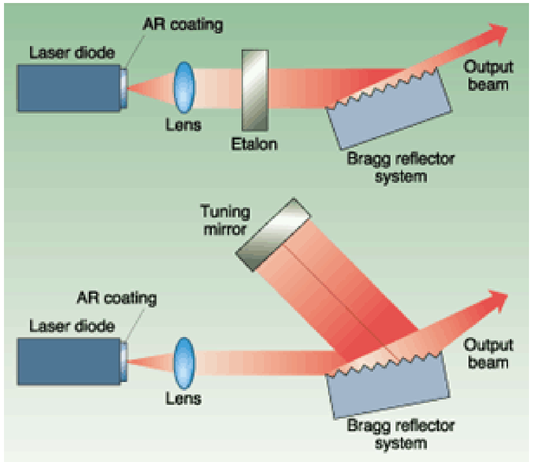


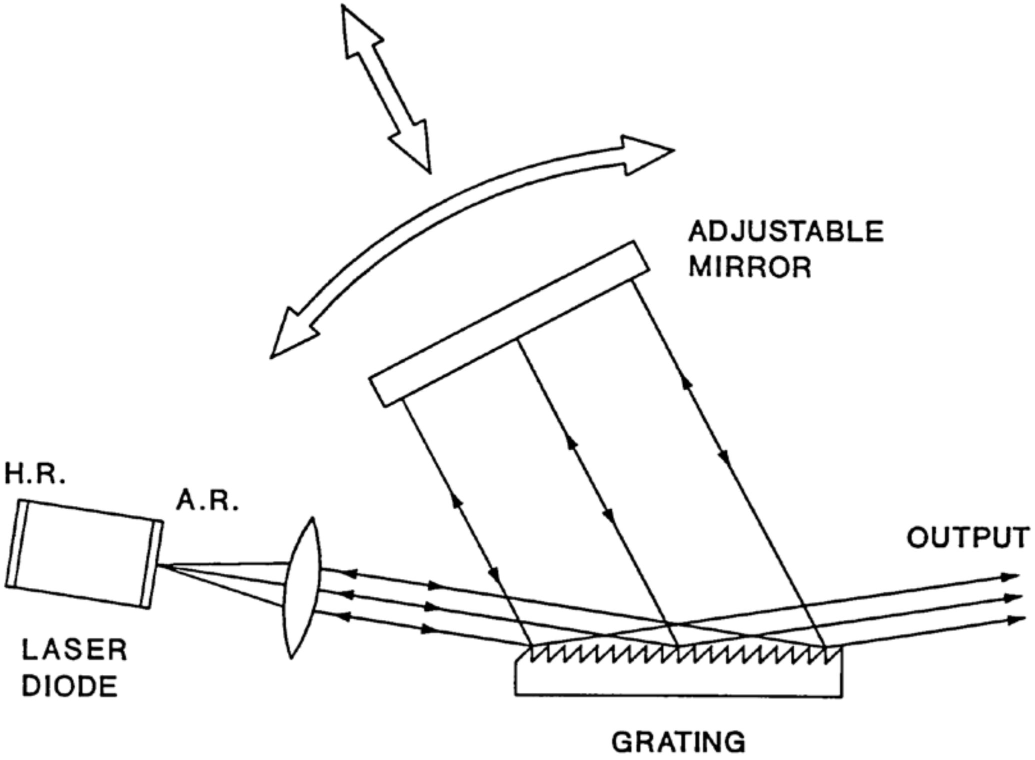


Using a planar grating, the Czerny-Turner monochromator selects out a single wavelength from the entering light beam.

K. M. Rosfjord et al., Appl. Opt. 39, 568 (2000).

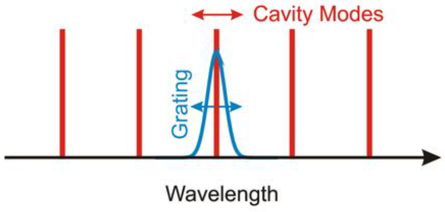
Grating-Tunable Laser Diode
Littman-Metclaf Configuration



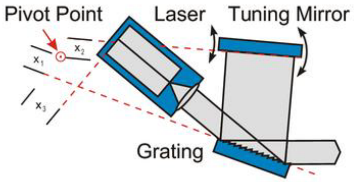


M. G. Littman and H. J. Metcalf, Appl. Optics 17, 2224 (1978).

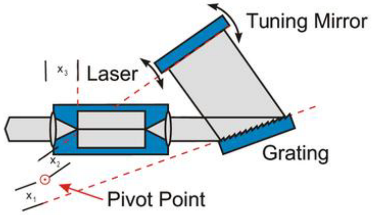
How does our Laser
tune modehop-free ?



Lion
TEC-500

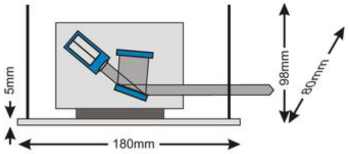


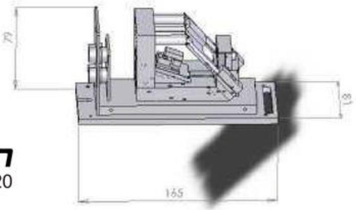
Lion
TEC-520



Dimensions

Lion
TEC-500





Lion
TEC-520

Physical Basics

The emission wavelength of a laser is defined by two features. The first condition is the cavity mode. The second condition is the amplification range of the gain medium. Since diode lasers have an extremely wide gain region, it is necessary to put a wavelength selective medium inside of the cavity like a grating. In order to tune such a laser modehop-free, it is required to synchronize the grating defined wavelength with the cavity defined wavelength [1].

Technical Solution

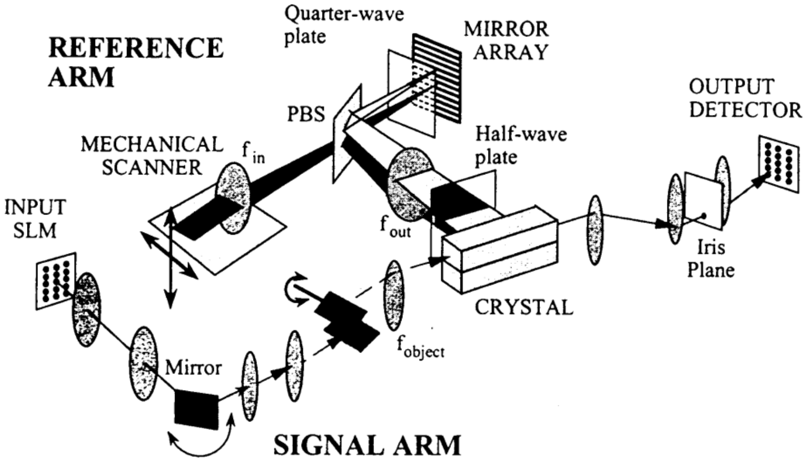
Sacher Lasertechnik has realized the synchronization between grating defined and cavity defined wavelength by only a simple rotation of the mirror. The adjustment of the pivot point is done during the wavelength scanning operation of our Littman/Metcalf laser system according to our patent no. 5,867,512. Due to this special method, we are able to ensure the best modehop free tuning behavior. An increase of the output power and the total performance of the Littman/Metcalf laser is achieved by using a high efficiency grating and outcoupling the light of the rear facet of the laser diode. With this approach, we are able to increase the output power to more than 100mW.

Technical Realization

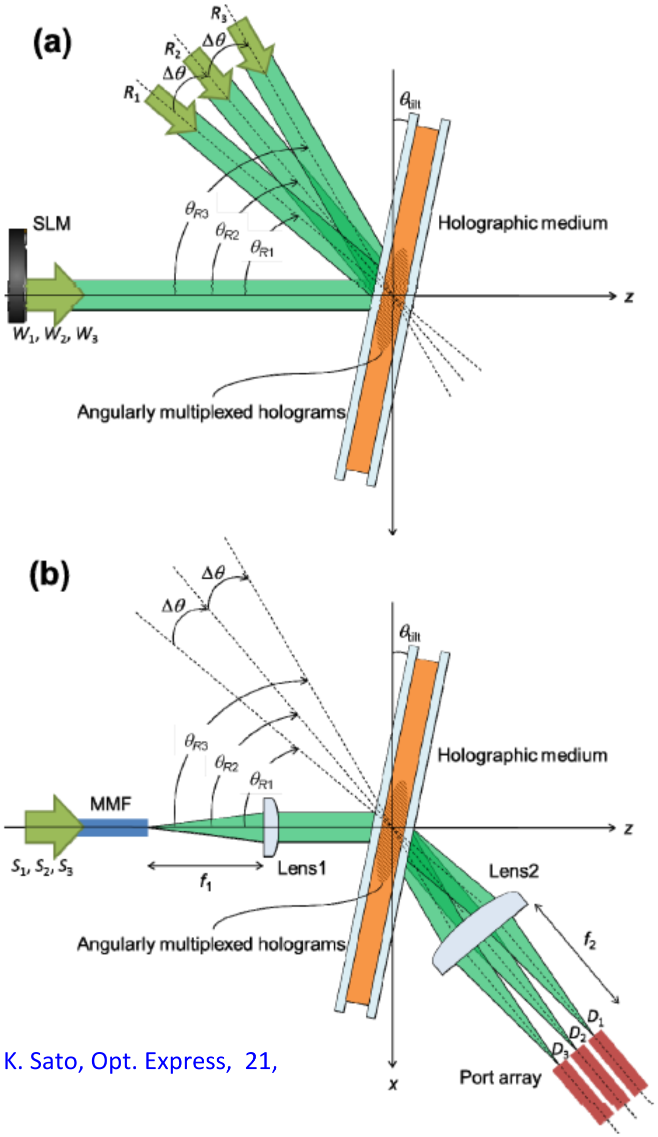
The drawings on the left hand side show the technical realization and the dimensions of the TEC-500 and the TEC-520 external cavity diode laser systems. Due to using a alignment insensitive cavity design and a flexmount concept, our Littman/Metcalf laser diode systems are excellent turn-key devices.

[1] M. G. Littman, H. J. Metcalf, Appl. Opt. 17, 2224, 1978

Angularly Multiplexed Volume Holographic Memory

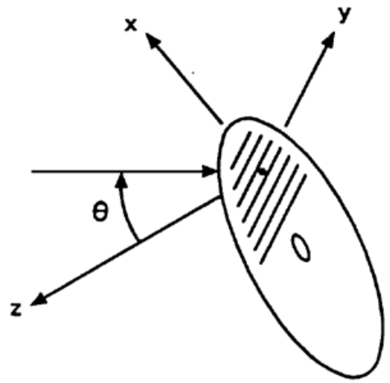


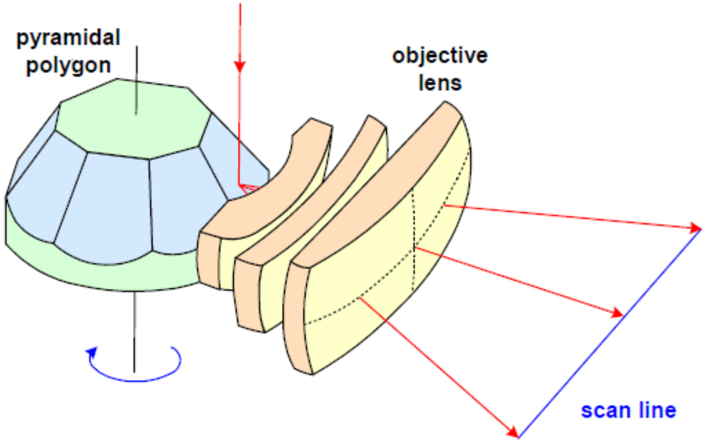
X. An, D. Psaltis, and G. W. Burr, Appl. Opt. 38, 386 (1999).

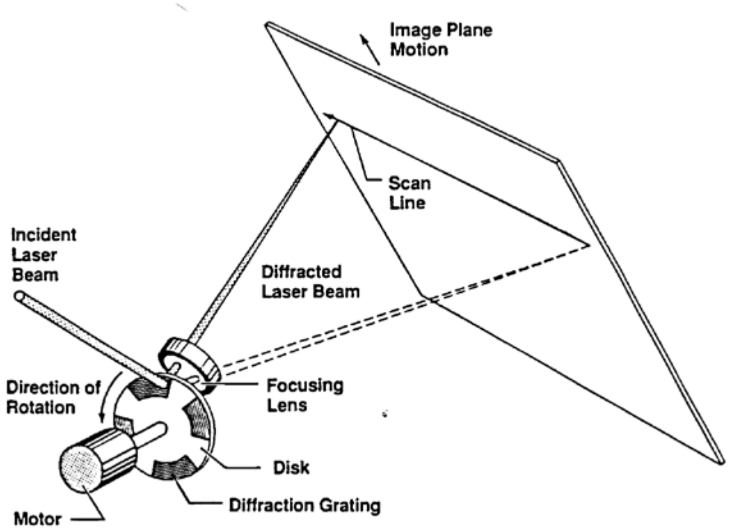


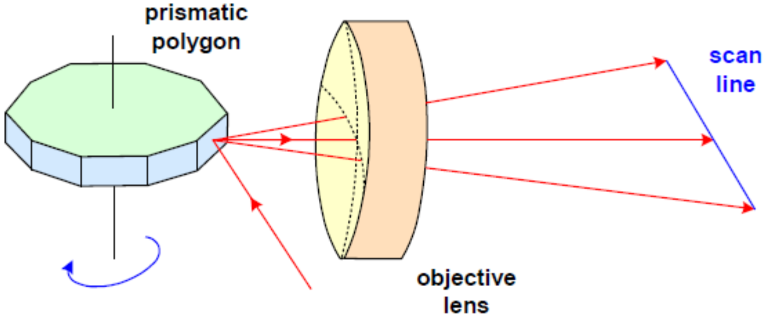
Y. Wakayama, A. Okamoto, K. Kawabata, A. Tomita, and K. Sato, Opt. Express, 21, 12920 (2013)

Diffractive Deflector/Scanner







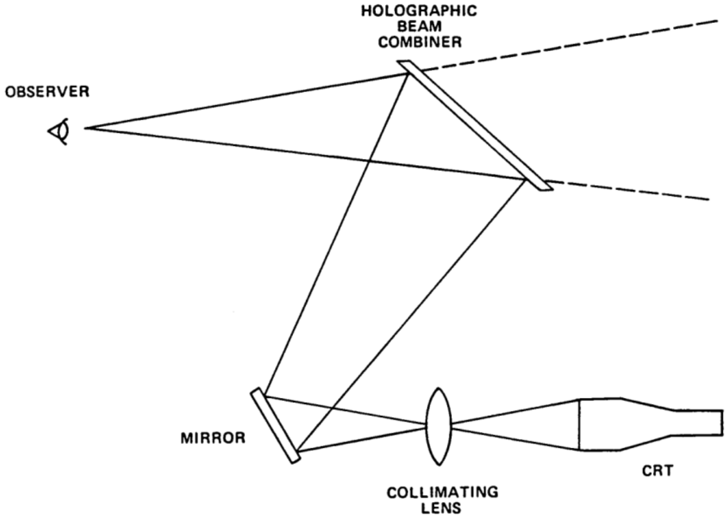


https://html2-f.scribdassets.com/8i38i8fuio2xmm43/images/37-5678c30532.jpg

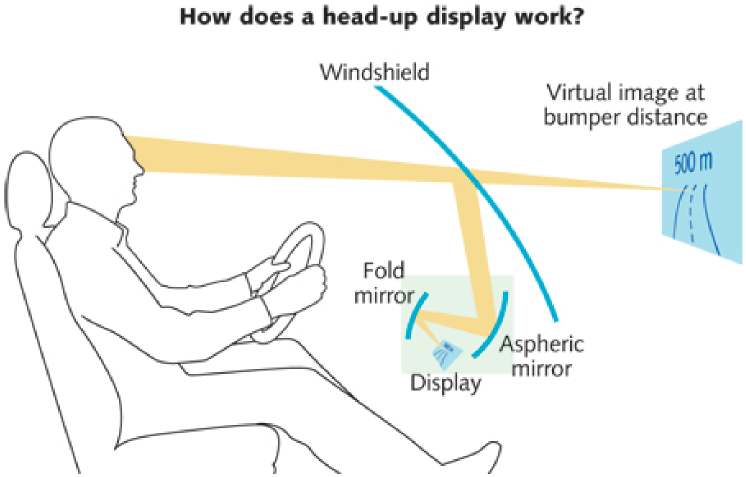
e.g. G. F. Marshall, *ed.*, Optical Scanning. New York: Marcel Dekker (1991).

Diffractive Head-Up Display

https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcQ6JdMlNRaPt42adiifT9psIkOqoIBUIH0vwxUMt8XXN0eQkoef

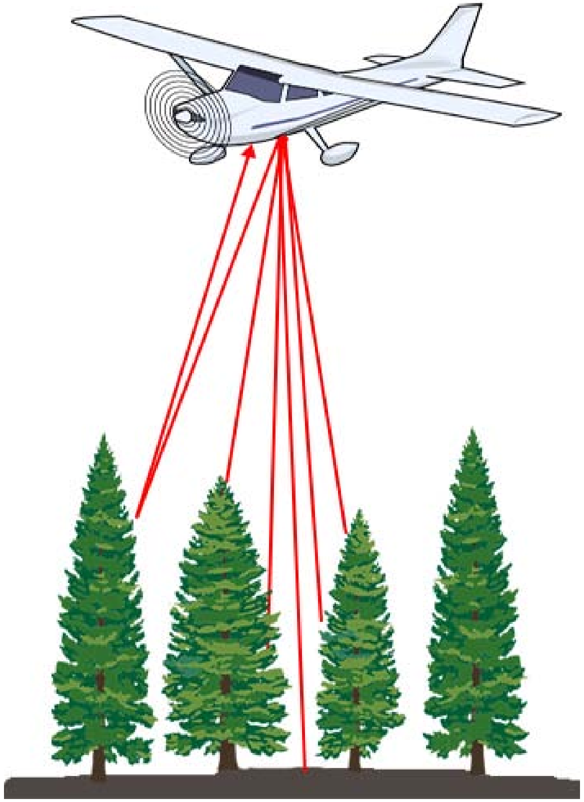


https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSMxEi6CrQlWZqprtUfOEd17MFC1lb1HO_4louwyjPRu6rB3gv9



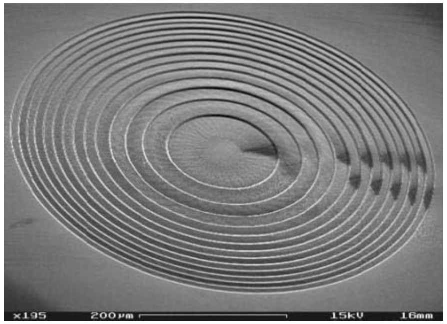
https://aemstatic-ww1.azureedge.net/content/dam/lfw/print-articles/2014/12/1412LFW05f1.jpg

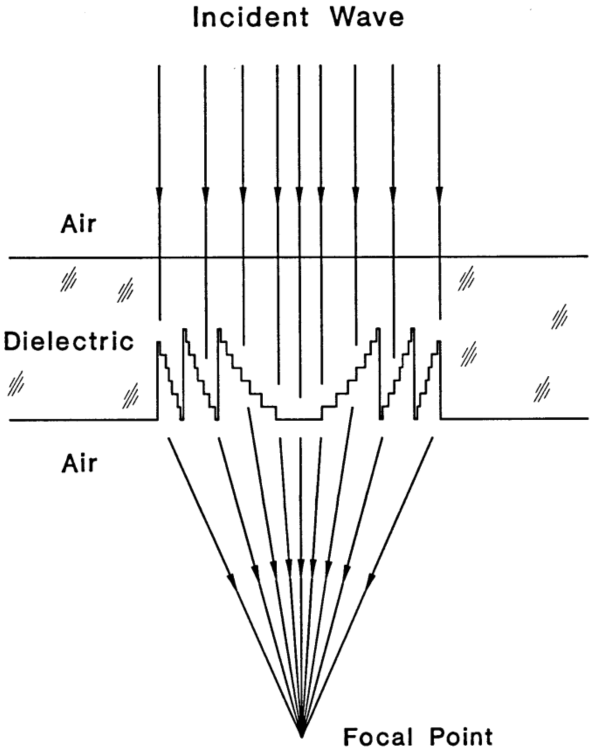
Light Detection and Ranging (LIDAR or LADAR)



http://gsp.humboldt.edu/OLM/Courses/GSP_216_Online/lesson7-1/overview.html

Diffractive Lenses

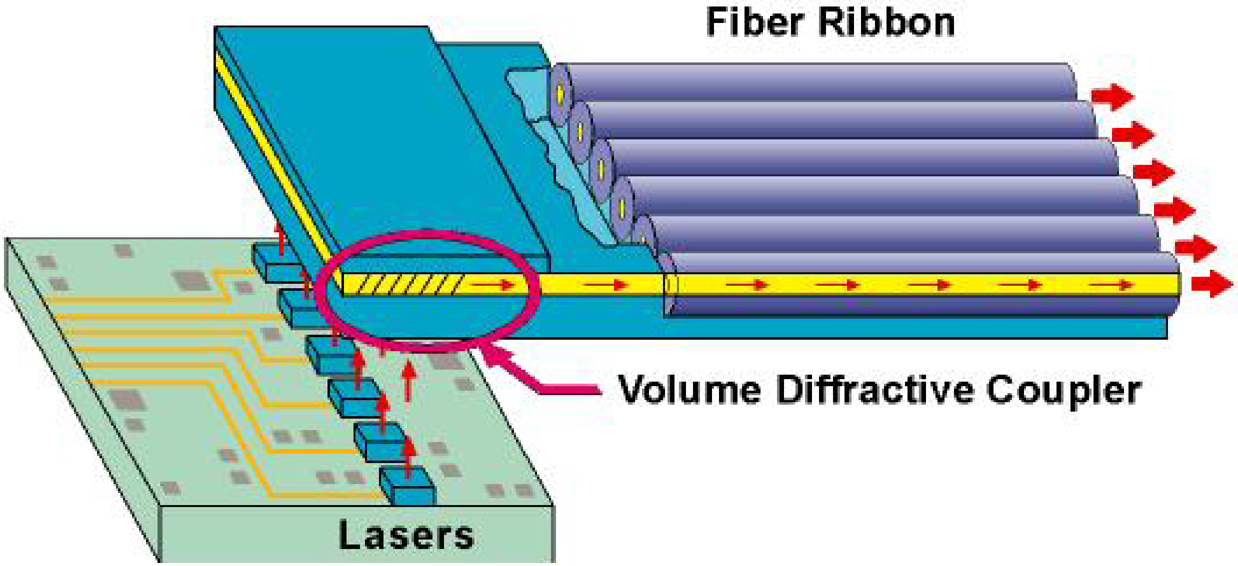




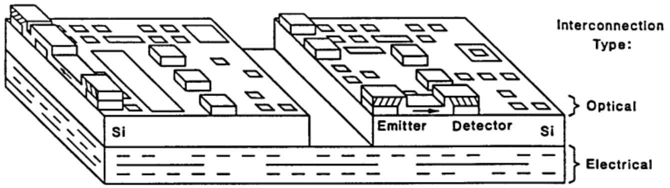
K. Hirayama *et al.*, J. Opt. Soc. Amer. A 13, 2219 (1996).

Light House Fresnel Lens-Paris Maritime Museum

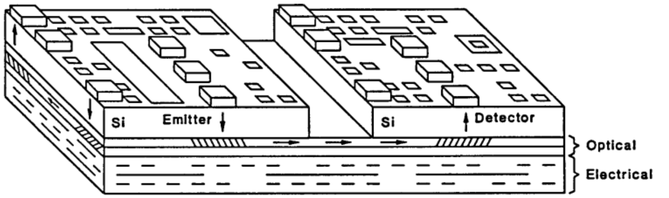
Optical Interconnects
Chip-to-Fiber Ribbon



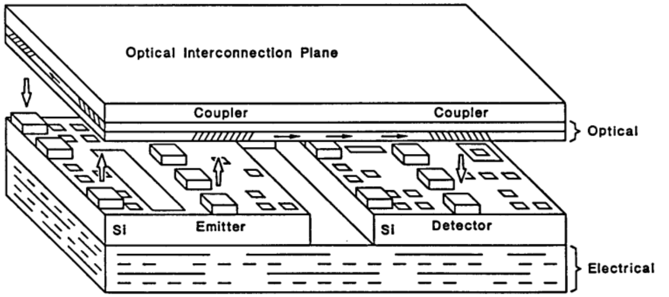
Optical Interconnects
Inter-Chip & Intra-Chip



(a) Intra-Chip Interconnections Through Waveguides on Silicon

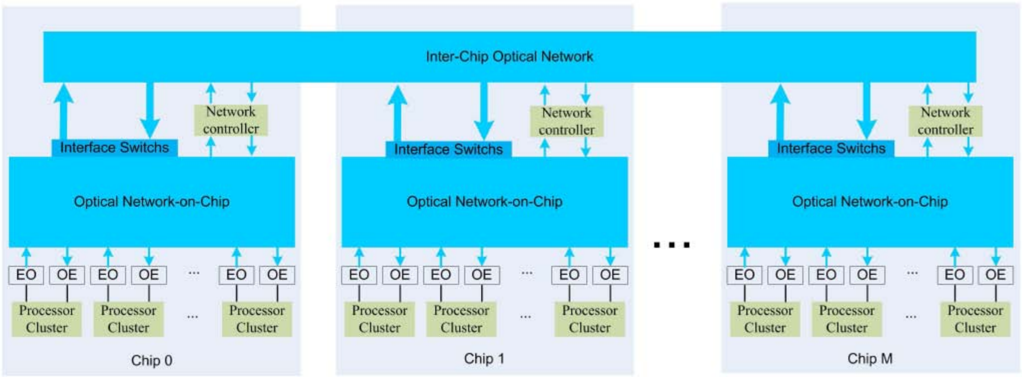


(b) Intra-Chip and Inter-Chip Interconnections Through Substrate

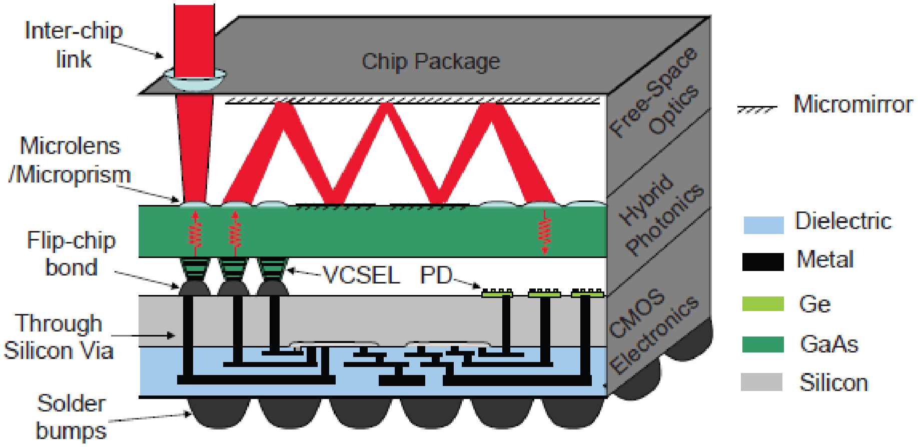


(c) Intra-Chip and Inter-Chip Interconnections Through Optical Plane

J. L. Cruz - Rivera *et al.* in R. Tummala, ed., Fundamentals of Microelectronics Systems Packaging. New York: McGraw - Hill (2001).



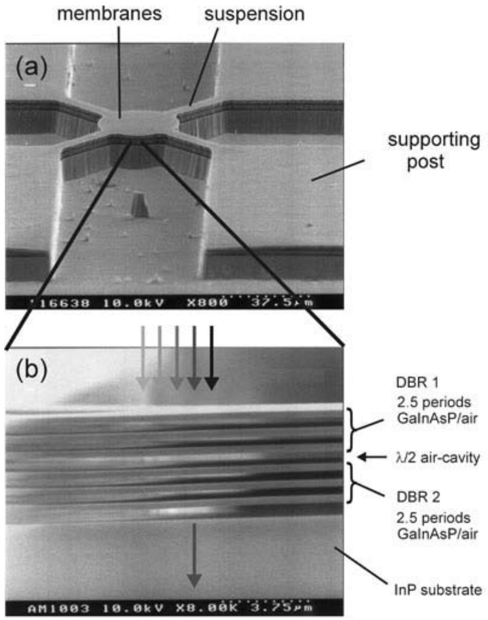
https://www.ece.ust.hk/~eexu/publications/NanoArch2010.pdf



https://www.osapublishing.org/oe/abstract.cfm?uri=oe-20-4-4331

Deformable-Mirror Tunable MQW VCSEL

Hartmut Hillmer, Soren Irmer, and Friedhard Romer, SPIE Newsroom 2006



Scanning-electron micrographs of multiple air-gap filters with membranes 40μm in diameter and four suspensions. (a) An In(GaAs)P/air-gap filter with 30μm-long suspensions. (b) A closer view of the layers (c) A spiral-shaped suspension InP/air-gap filter. (d) An InP/air-gap filter with 10μm-long suspensions.

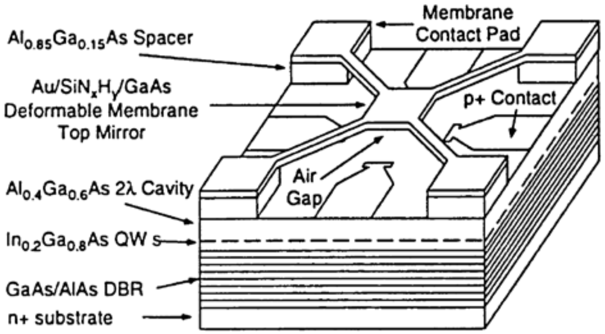
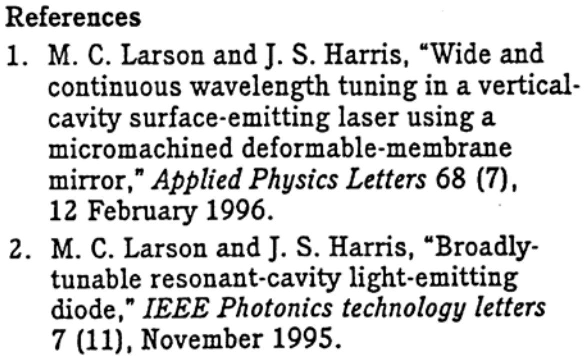


Figure 1. The new, tunable VCSEL has the same basic structure as a conventional device, except for the deformable micromirror at the top. A voltage across the mirror and the p-layer pulls the central reflector down into the air gap, so shortening the resonant cavity of the laser.



References

1. M. C. Larson and J. S. Harris, "Wide and continuous wavelength tuning in a vertical-cavity surface-emitting laser using a micromachined deformable-membrane mirror," *Applied Physics Letters* 68 (7), 12 February 1996.
2. M. C. Larson and J. S. Harris, "Broadly-tunable resonant-cavity light-emitting diode," *IEEE Photonics technology letters* 7 (11), November 1995.

Deformable-Mirror Tunable MQW VCSEL

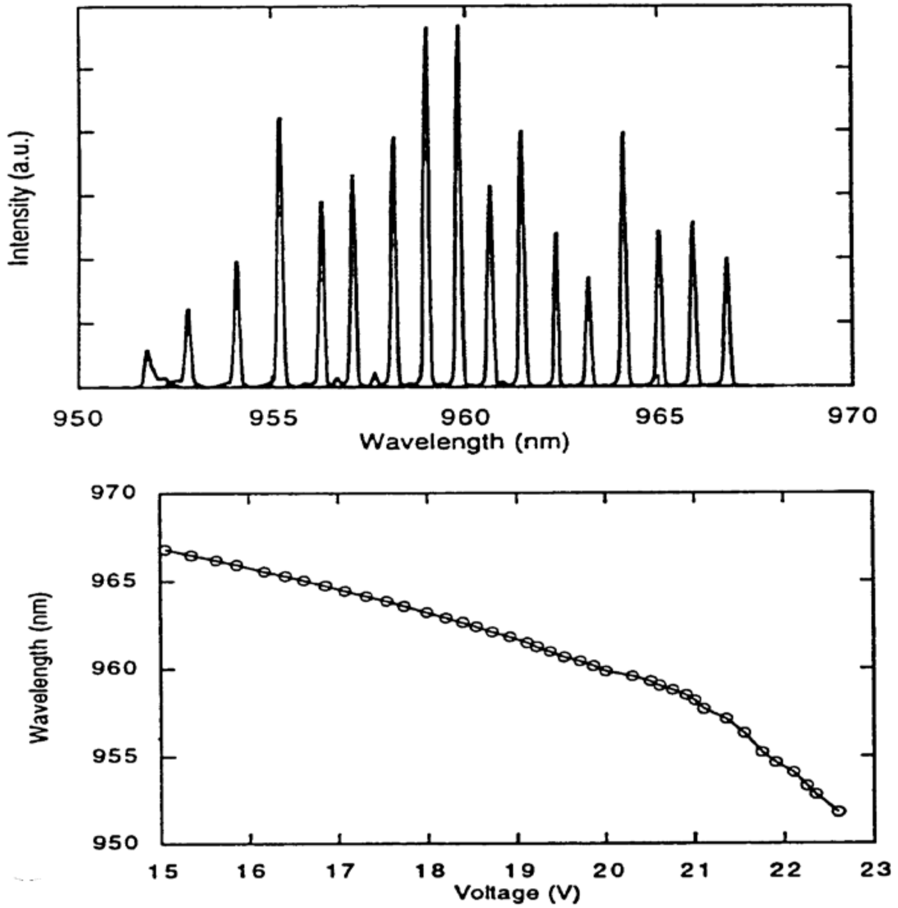
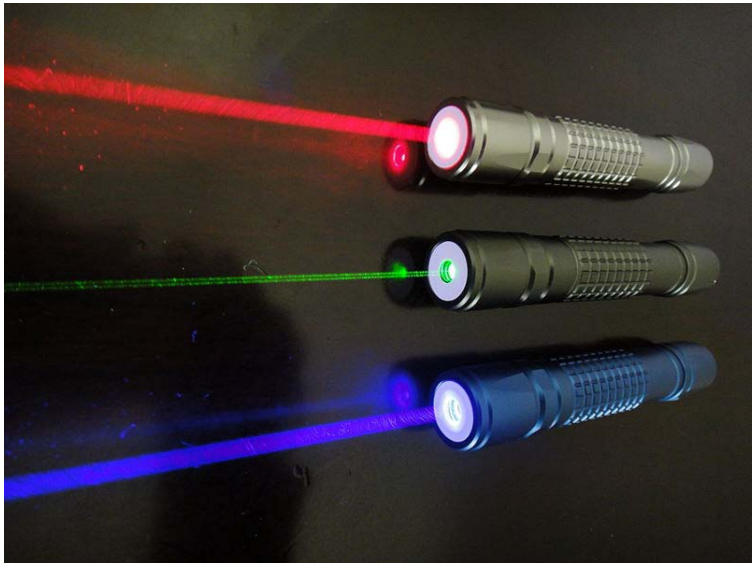


Figure 2. Stanford researchers were able to tune through 15 nm by electrostatically moving the micromirror. Shown in (a) is the output intensity at each wavelength. In (b) we see how this wavelength varies with the applied voltage.

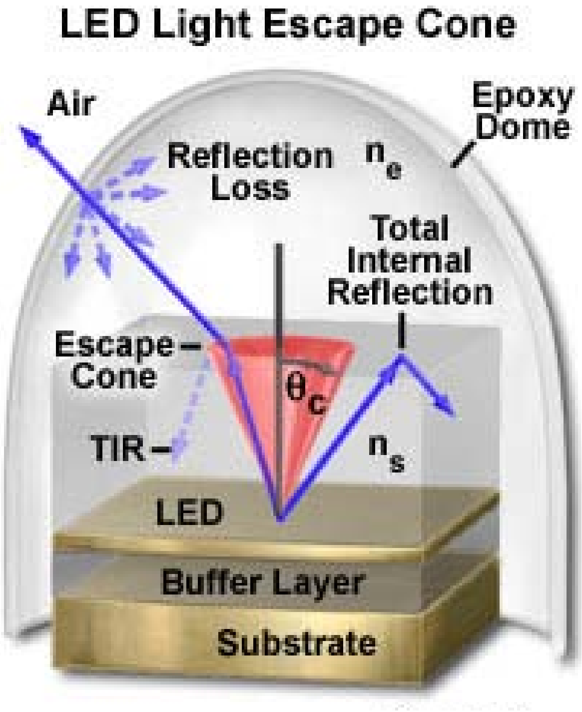
Laser Pointers

http://preventdisease.com/images/red-laser-pointer-with-key-chain.jpg



https://commons.wikimedia.org/wiki/File:Laser_pointers.jpg

Light Emitting Diodes (LED)

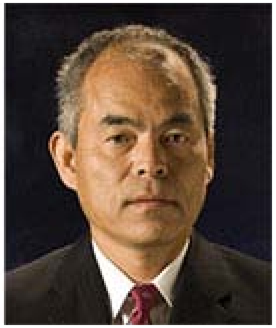


2014 Nobel Prize for Physics

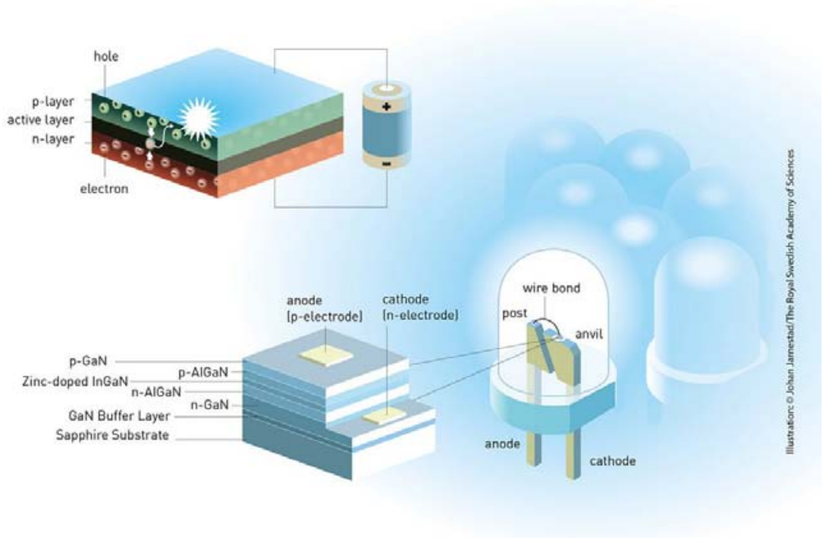
"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

Isamu Akasaki

Hiroshi Amano



Shuji Nakamura

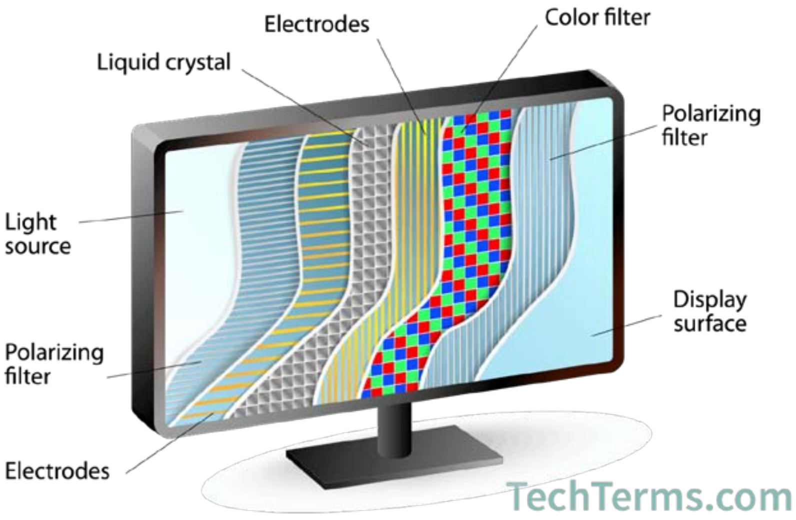


Illustrations © Johan Jarnestad/The Royal Swedish Academy of Sciences

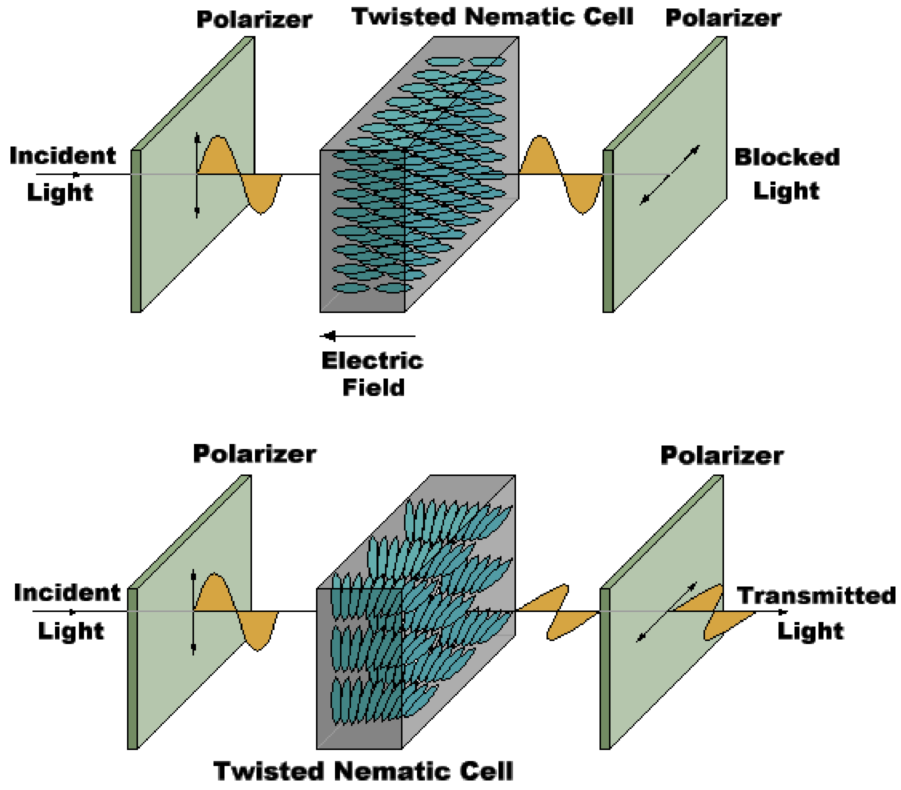
http://www.theguardian.com/science/live/2014/oct/07/nobel-prize-physics-2014-stockholm-live

http://physicsworld.com/cws/article/news/2014/oct/07/isamu-akasaki-hiroshi-amano-and-shuji-nakamura-win-2014-nobel-prize-for-physics

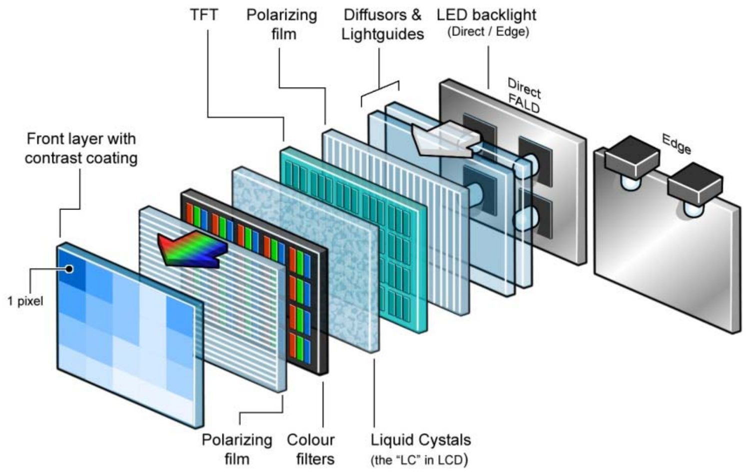
Liquid Crystal Displays



https://cdn.techterms.com/img/lg/lcd_81-2.png

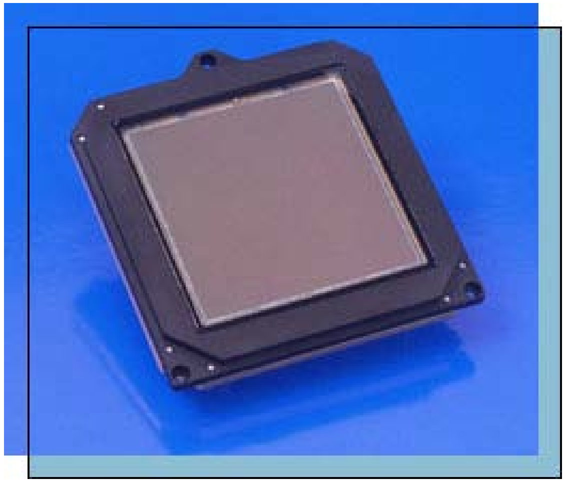


http://groups.csail.mit.edu/graphics/classes/6.837/F01/Lecture01/Slide16.html



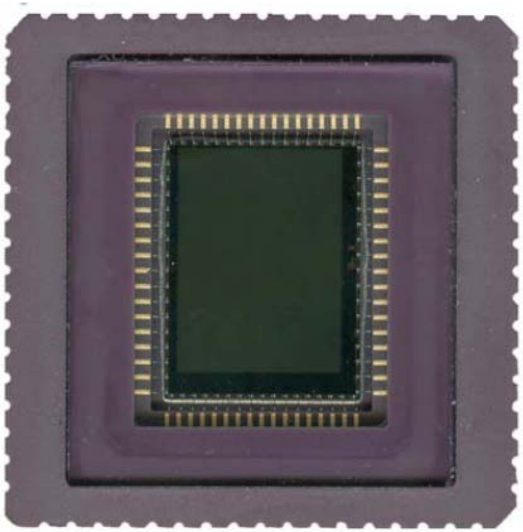
https://data.kemt.fei.tuke.sk/DigitalnaTelevizia/prednasky/15_11_2016/Obrazky_15_11_2016/OLED_LCD_lcd_panel.jpg

Charge-Coupled Device (CCD)

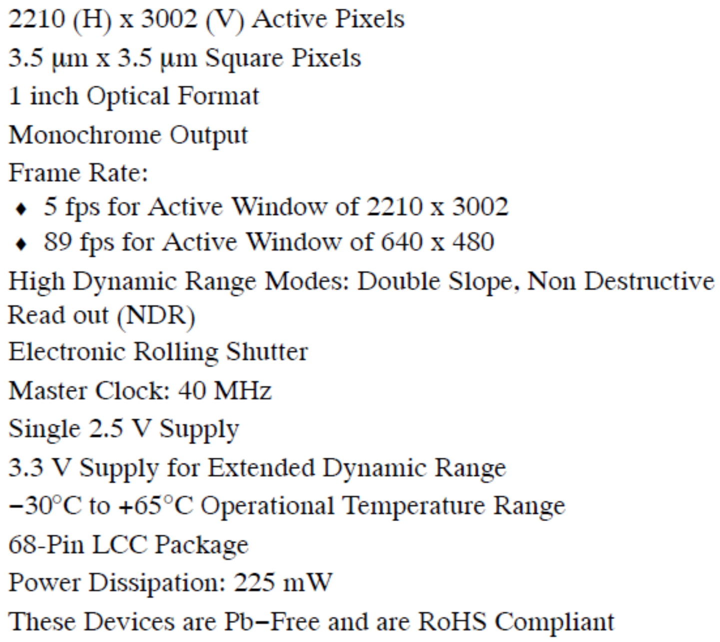


CCD 595 Fairchild Imaging

9216 x 9216 full frame CCD array
8.75μm x 8.75μm pixels
80.64mm x 80.64mm image area
100% fill factor
Non multi-pinned phase (MPP) operation
8 outputs (4 on each side)
Readout noise less than 30 e- at 100MHz (25MHz x 4)



On Semiconductor CMOS 6.6Mpixel Array



2210 (H) x 3002 (V) Active Pixels
3.5 μm x 3.5 μm Square Pixels
1 inch Optical Format
Monochrome Output
Frame Rate:
- 5 fps for Active Window of 2210 x 3002
- 89 fps for Active Window of 640 x 480

High Dynamic Range Modes: Double Slope, Non Destructive Read out (NDR)
Electronic Rolling Shutter
Master Clock: 40 MHz
Single 2.5 V Supply
3.3 V Supply for Extended Dynamic Range
−30°C to +65°C Operational Temperature Range
68-Pin LCC Package
Power Dissipation: 225 mW
These Devices are Pb−Free and are RoHS Compliant

Canon PowerShot SD890 IS Digital ELPH

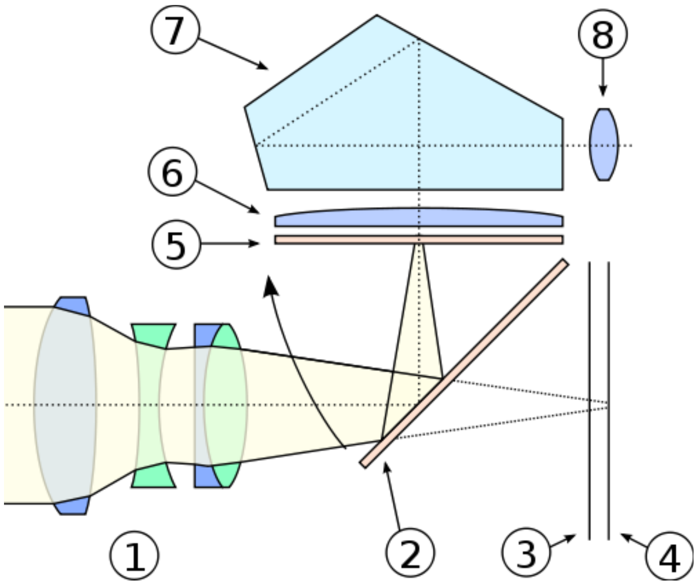
Canon today added a trio of new ultra-compact cameras to their Digital ELPH lineup. Canon's model numbering for the ELPHs is about as confusing as humanly possible, but I think I can safely say that the PowerShot SD770 and SD790 replace the SD750, with the SD890 more-or-less replacing the SD850. Here are the highlights on the SD890, which has more "zoom" than any ELPH yet.

PowerShot SD890 IS Digital ELPH - Specifications

10.0 effective Megapixel CCD
F3.2-5.7, 5X optical zoom lens, equivalent to 37 - 185 mm
Optical image stabilization
2.5" PureColor II LCD display with 230,000 pixels; optical viewfinder also available
Point-and-shoot operation
Face detection AF/AE/FE/WB
AF-point zoom feature enlarges the selected face or focus point
High ISO Auto mode has been enhanced to use Motion Detection; if the subject is moving, the sensitivity is boosted higher than it would if it was stationary
Automatic redeye reduction feature
Records movies at 640 x 480 (30 fps) for up to 32 minutes
Memory card slot supports SD, SDHC, MMC, MMCplus, and HC MMCplus media
Uses NB-5L lithium-ion battery; 320 shots per charge
USB 2.0 High Speed support; camera now uses a standard mini-B connector

SLR (Single-Lens-Reflex) Digital Cameras

Nikon D5000

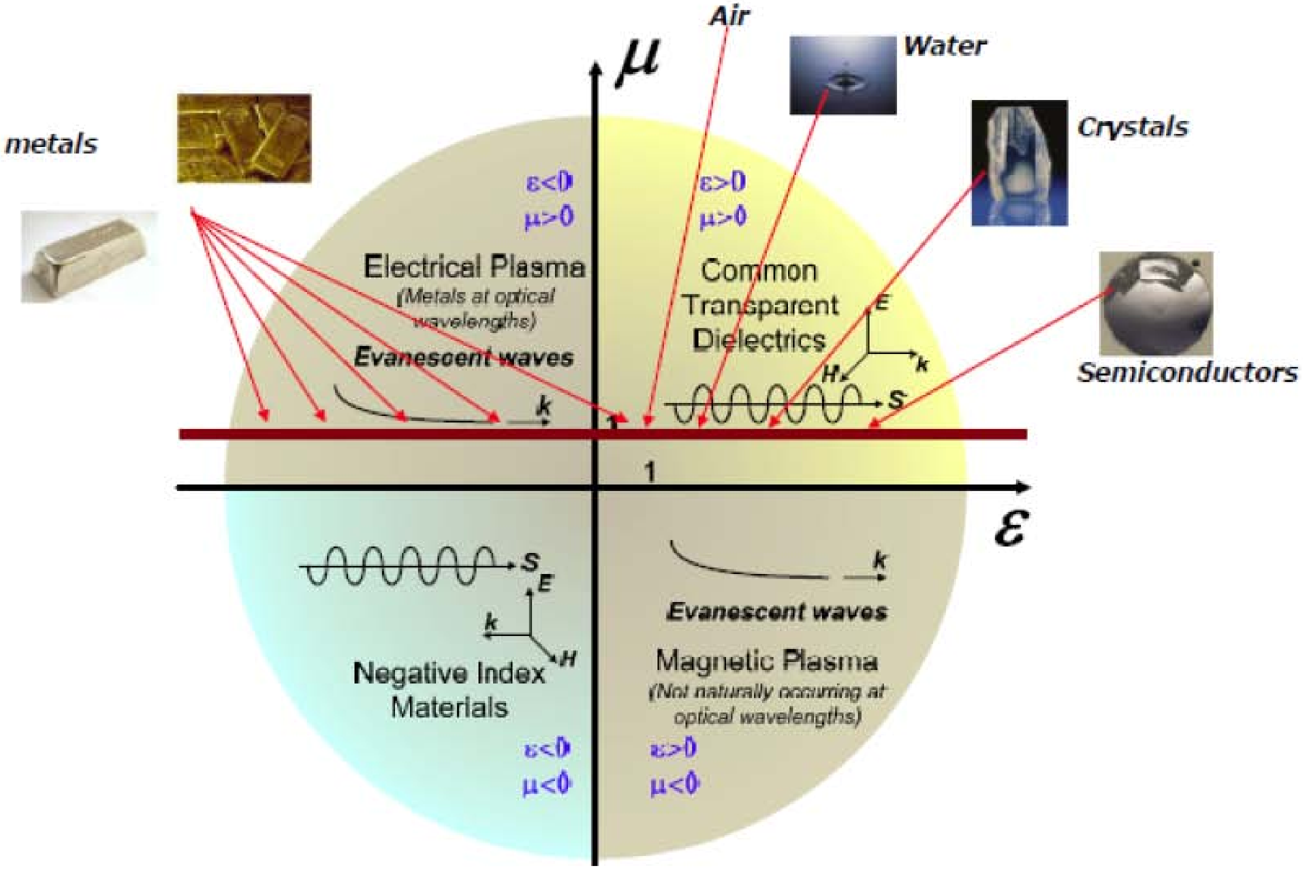


Cross-section of SLR
1. Lens assembly
2. Mirror in down position (image visible in viewfinder)
3. Focal-plane shutter
4. Sensor/Film
5. Focusing screen
6. Condensing lens
7. Pentaprism or Pentamirror
8. Eyepiece

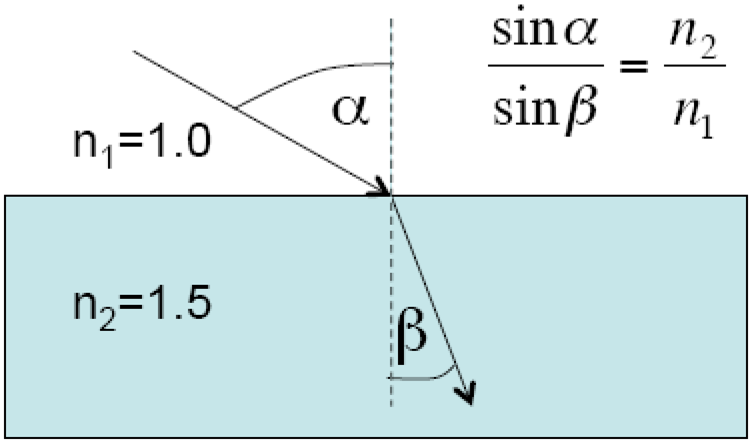
Specifications

12.3 megapixel DX CMOS sensor
1280x720 24fps HD D-Movie mode
2.7-inch Live View LCD display, variable angle
Secure Digital memory storage (SD/SDHC)

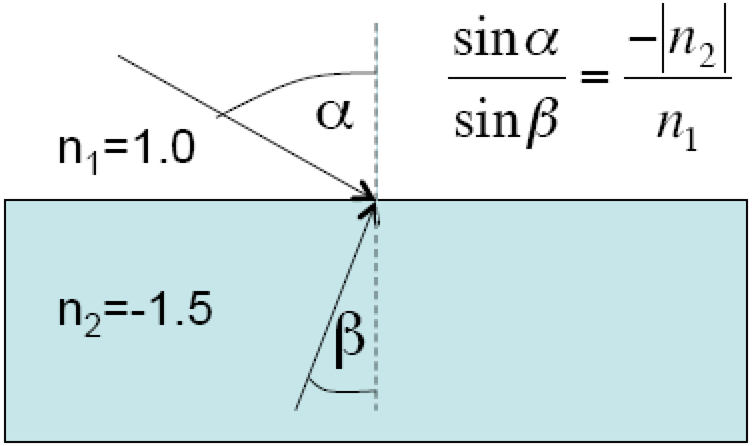
Overview of materials



Negative Index Material



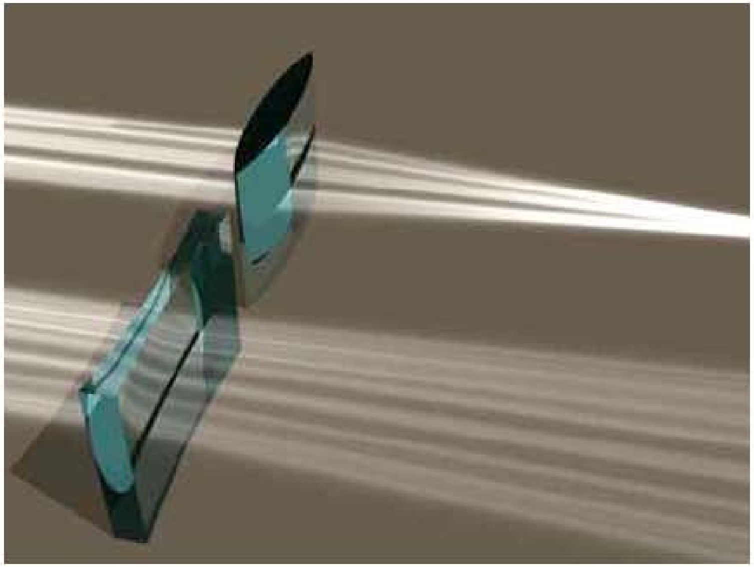
$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1}$$



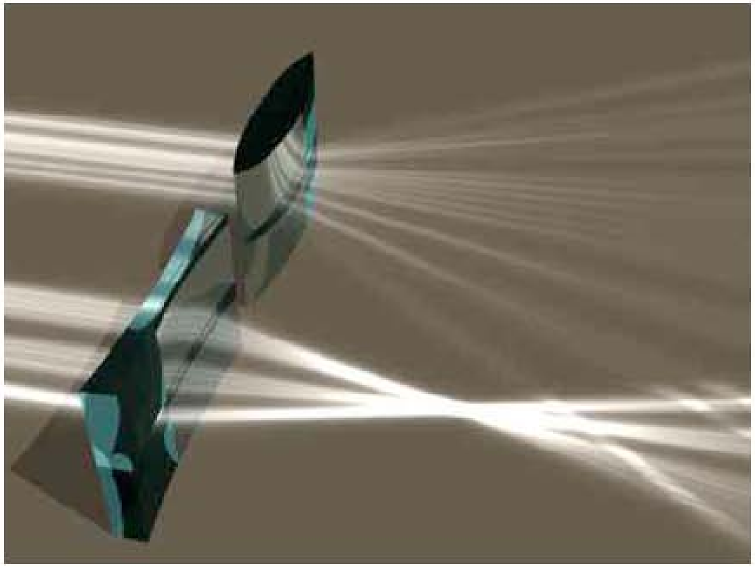
$$\frac{\sin\alpha}{\sin\beta} = \frac{-|n_2|}{n_1}$$

Ray tracing - lenses

Positive refractive index



Negative refractive index



Ray tracing - glasses

Pov-ray is a ray-tracing software that can represent negative refractive indices

n=1.3

n=-1.3

G. Dolling *et al.*, Opt. Express 14, 1842 (2006)

Negative index materials

So far, we have looked at negative ε and negative μ separately. For example, we have looked at splitrings in terms of their magnetic resonance leading to a negative μ, whereas nnanoantennas have a negative ε dueto their “electric” resonance.
The ”fishnet structure” puts the two together.

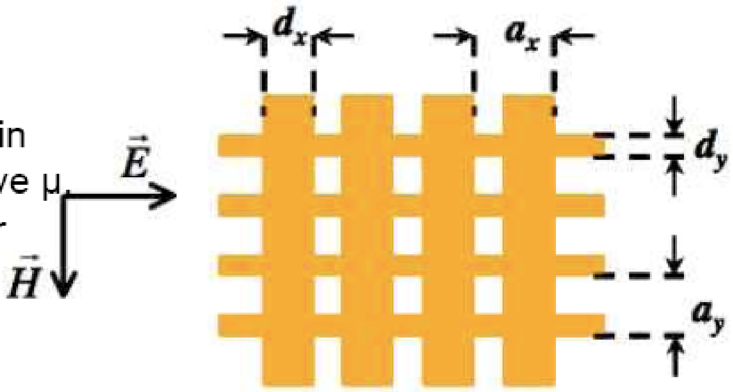
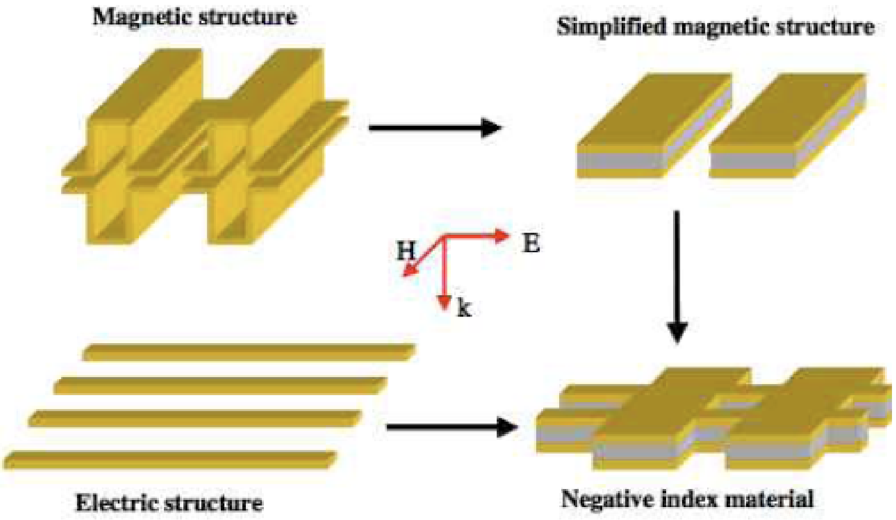
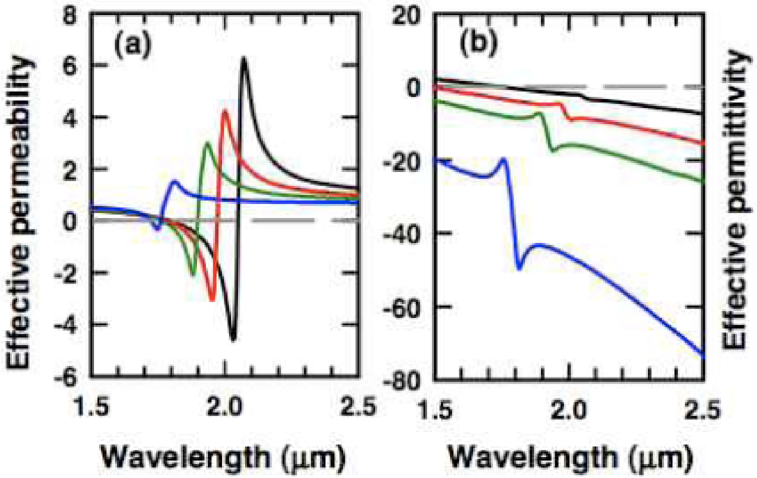


Fig. 2. Top view of the structure with geometrical parameters indicated.





dx= 500nm.

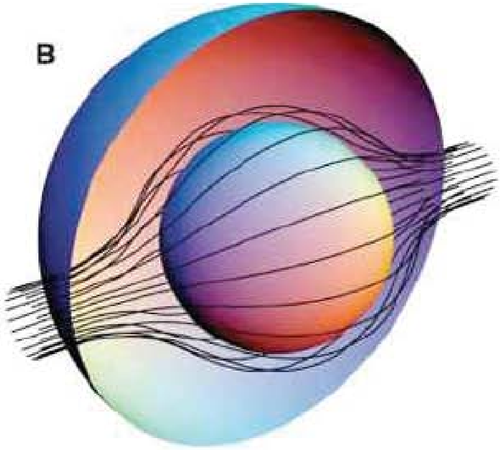
dy=500 nm (blue)
dy=300 nm (green)
dy=200 nm (red)
dy=100 nm (black)

S. Zhang, W. Fan, K. J. Malloy, S. R. Brueck, N. C. Panoiu, and R. M. Osgood, "Near-infrared double negative metamaterials," Opt. Express 13, 4922-4930 (2005)

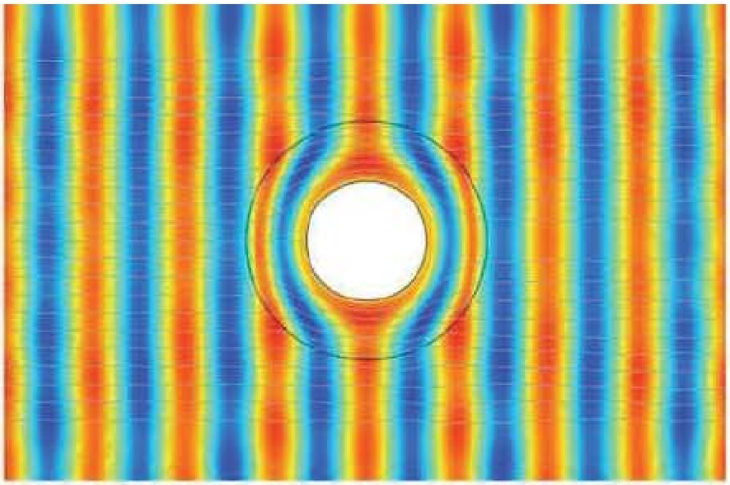
What dimension do you choose for d_y ?

Optical Cloaking

Ray trajectories in the cloak



Electric field distribution



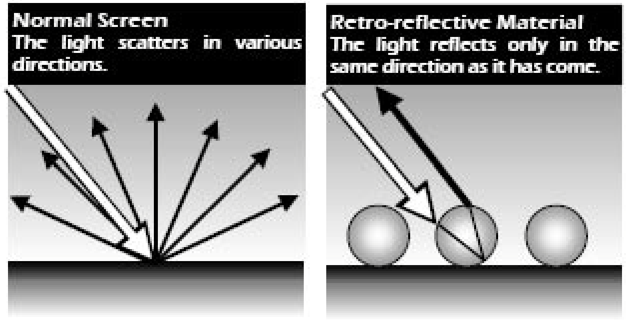
Optical cloaking relies on the fact that a metamaterial allows us to engineer the refractive index over a wide range, such that light-rays can be bent around an object.

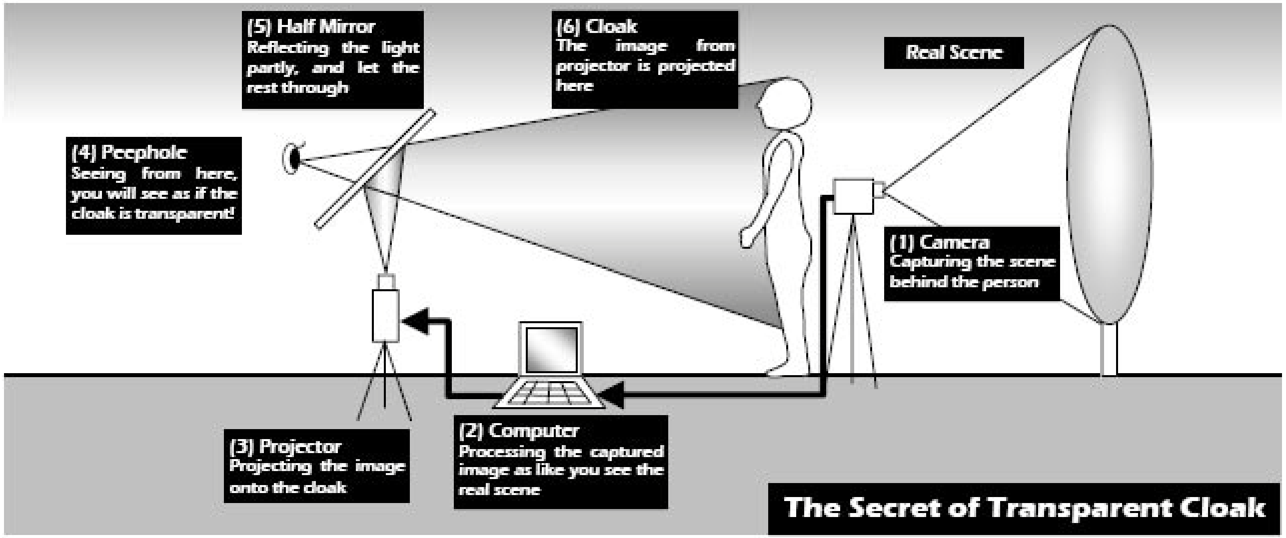
J. B. Pendry, Science. 312, 1780 (2006)

Invisible Man become a reality?

Prof. Susumu Tachi, Keio University, Japan http://thecreatorsproject.vice.com/blog/an-invisibility-cloak-you-have-to-see-to-believe-video

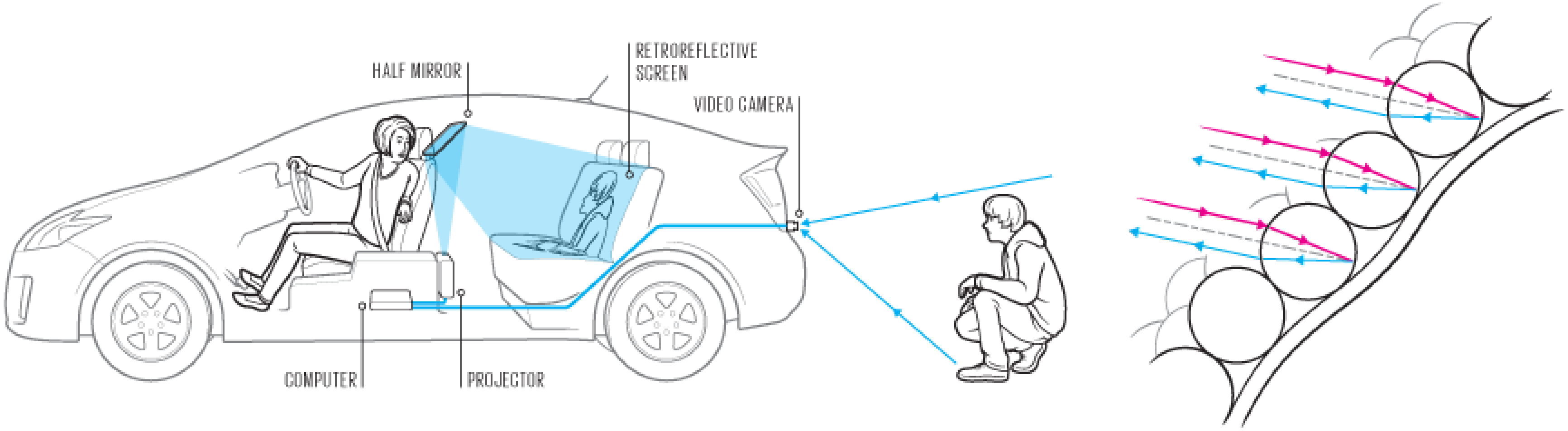
Retro-Reflecting Projection Technology





http://www.brainsturbator.com/posts/147/diy-invisibility-suits-optical-camouflage-source-documents

Retro-Reflecting Projection Technology
IEEE Spectrum November 2014



http://spectrum.ieee.org/transportation/advanced-cars/augmented-reality-helps-drivers-see-around-blind-spots

Military Applications

Laser Guided Bombs

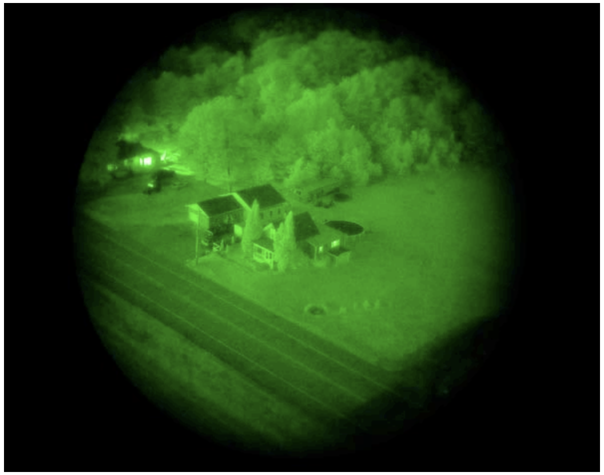
http://science.howstuffworks.com/smart-bomb1.htm

Diagram showing the operation of a laser-guided ammunition round. From a CIA report, 1986.

https://en.wikipedia.org/wiki/Precision-guided_munition

Military Applications

Night Vision Goggles



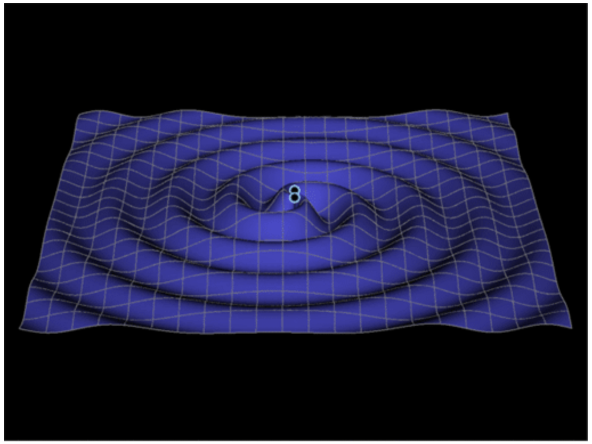
http://media3.washingtonpost.com/wp-srv/photo/gallery/090820/GAL-09Aug20-2504/media/PHO-09Aug20-175212.jpg

Laser Weapons

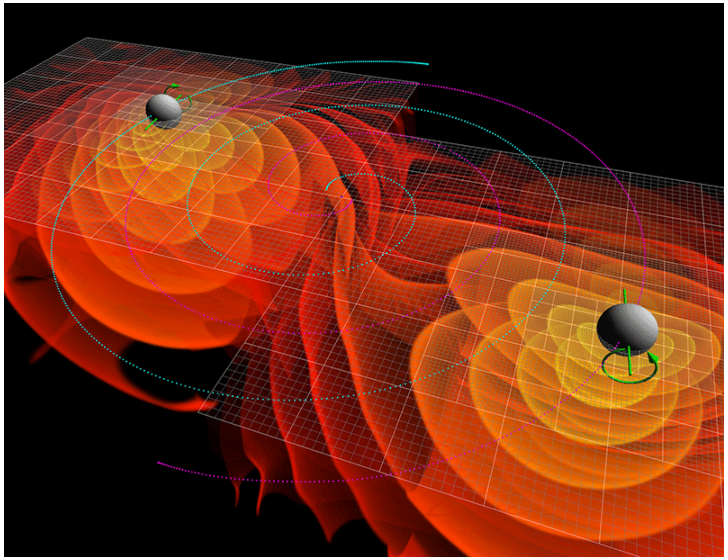
http://image.slidesharecdn.com/laser-140918011516-phpapp02/95/laser-42-638.jpg?cb=1411003058

Gravitational Waves Measurement

LIGO (Light Interferometer Gravitational-Wave Observatory)



Video: A schematic depiction of LIGO’s interferometric gravitational wave detector. Light from a laser is split in two by a beam splitter; one half travels down the vertical arm of the interferometer, the other half travels down the horizontal arm. The detector is designed so that in the absence of gravitational waves (top left) the light takes the same time to travel back and forth along the two arms and interferes destructively at the photodetector, producing no signal. As the wave passes (moving clockwise from top right) the travel times for the lasers change, and a signal appears in the photodetector. (The actual distortions are extremely small, but are exaggerated here for easier viewing.) Inset: The elongations in a ring of particles show the effects of a gravitational wave on spacetime.



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. 116, 061102 (2016)

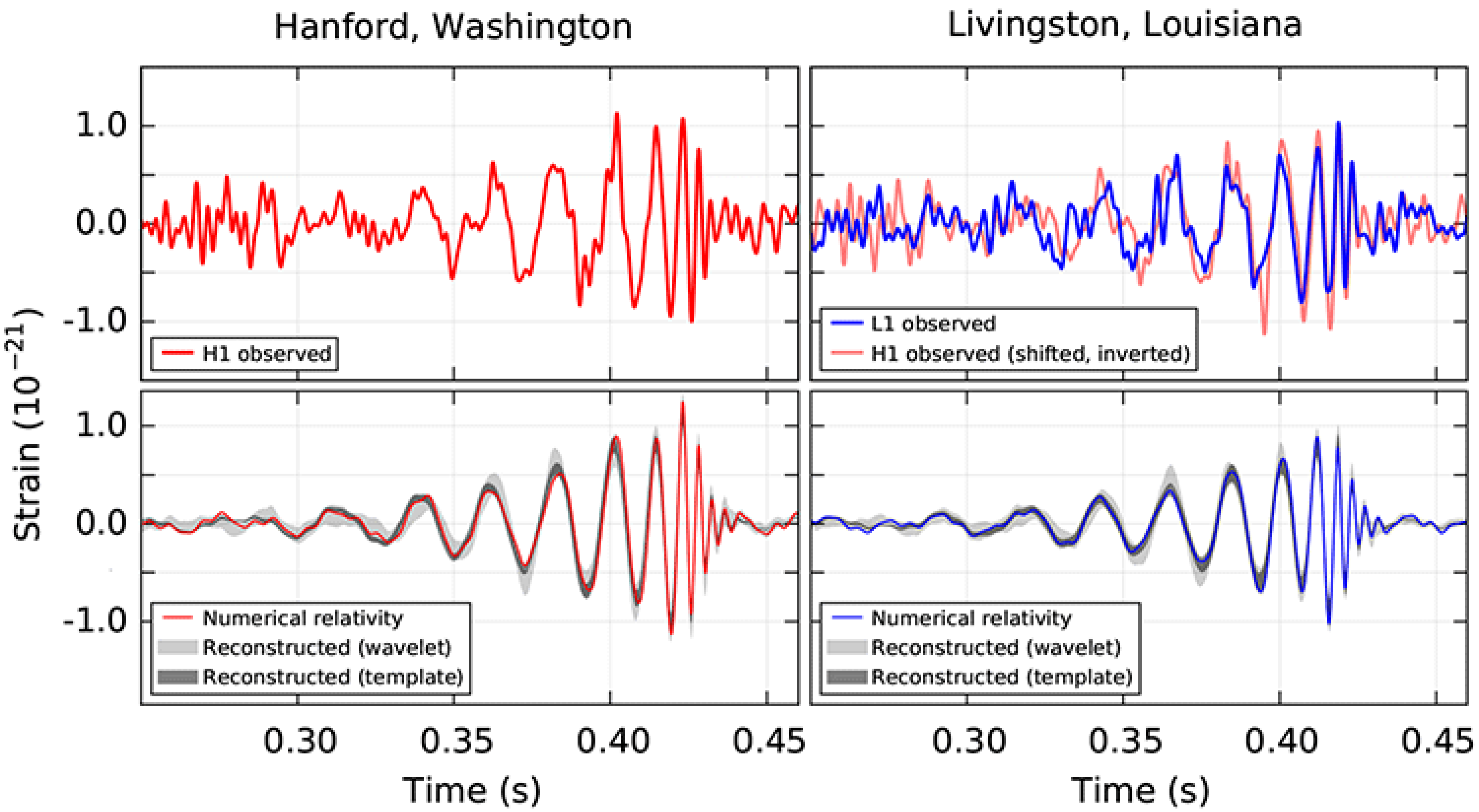
http://physics.aps.org/articles/v9/17

Gravitational Waves Measurement

LIGO (Light Interferometer Gravitational-Wave Observatory)

First Experimental Measurement of Gravitational Waves

on September 14, 2015 at 09:50:45 UTC (coordinated universal time)



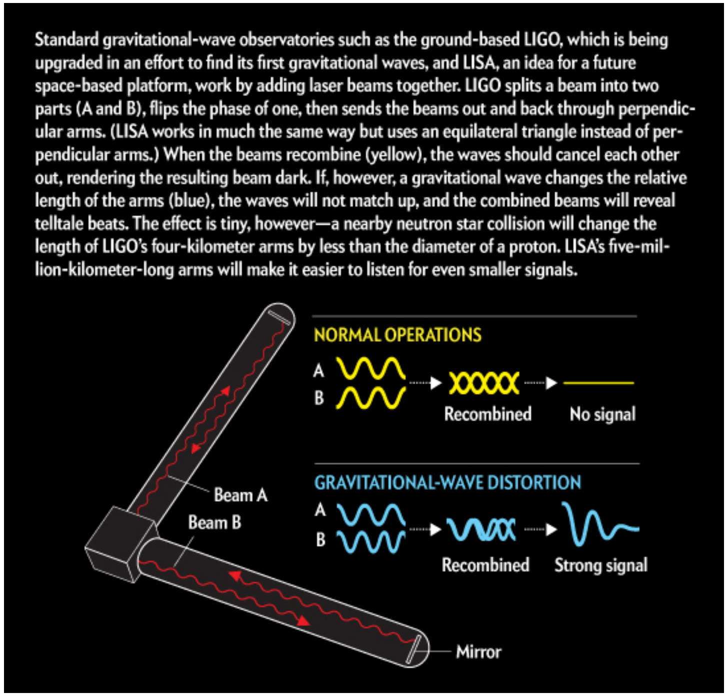
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. 116, 061102 (2016)

Gravitational Waves Measurement

LIGO (Light Interferometer Gravitational-Wave Observatory)



Standard gravitational-wave observatories such as the ground-based LIGO, which is being upgraded in an effort to find its first gravitational waves, and LISA, an idea for a future space-based platform, work by adding laser beams together. LIGO splits a beam into two parts (A and B), flips the phase of one, then sends the beams out and back through perpendicular arms. (LISA works in much the same way but uses an equilateral triangle instead of perpendicular arms.) When the beams recombine (yellow), the waves should cancel each other out, rendering the resulting beam dark. If, however, a gravitational wave changes the relative length of the arms (blue), the waves will not match up, and the combined beams will reveal telltale beats. The effect is tiny, however—a nearby neutron star collision will change the length of LIGO's four-kilometer arms by less than the diameter of a proton. LISA's five-million-kilometer-long arms will make it easier to listen for even smaller signals.

http://blogs.scientificamerican.com/sa-visual/ligo-and-gravitational-waves-a-graphic-explanation/

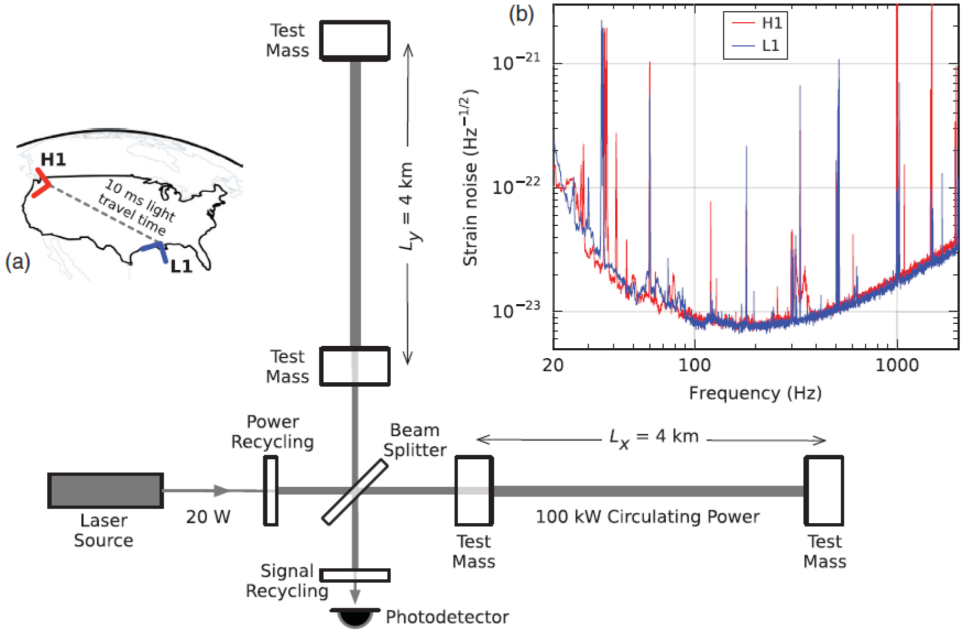
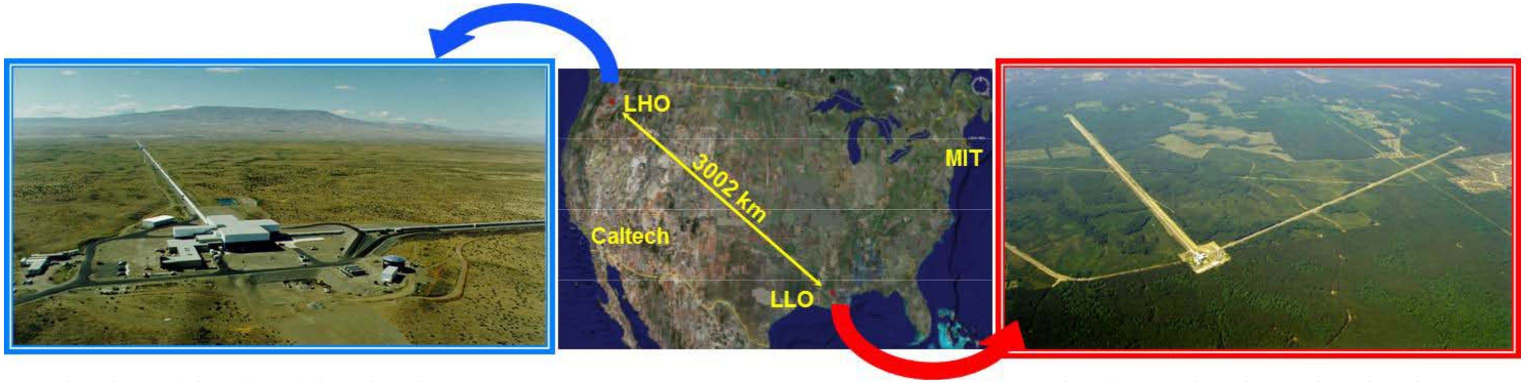


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

Observation of Gravitational Waves from a Binary Black Hole Merger
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 116, 061102 (2016)

Gravitational Waves Measurement

LIGO and VIRGO Detectors



Aerial view of the site of the Ligo (at Hanford, WA, USA)(4 km-long arms)

Aerial view of the site of the Ligo (at Livingston LA, USA) (4 km-long arms)

Aerial view of the site of the Virgo (near Pisa, Italy) experiment showing the central building, the Mode-Cleaner building, the full 3 km-long west arm and the beginning of the north arm (on the right).

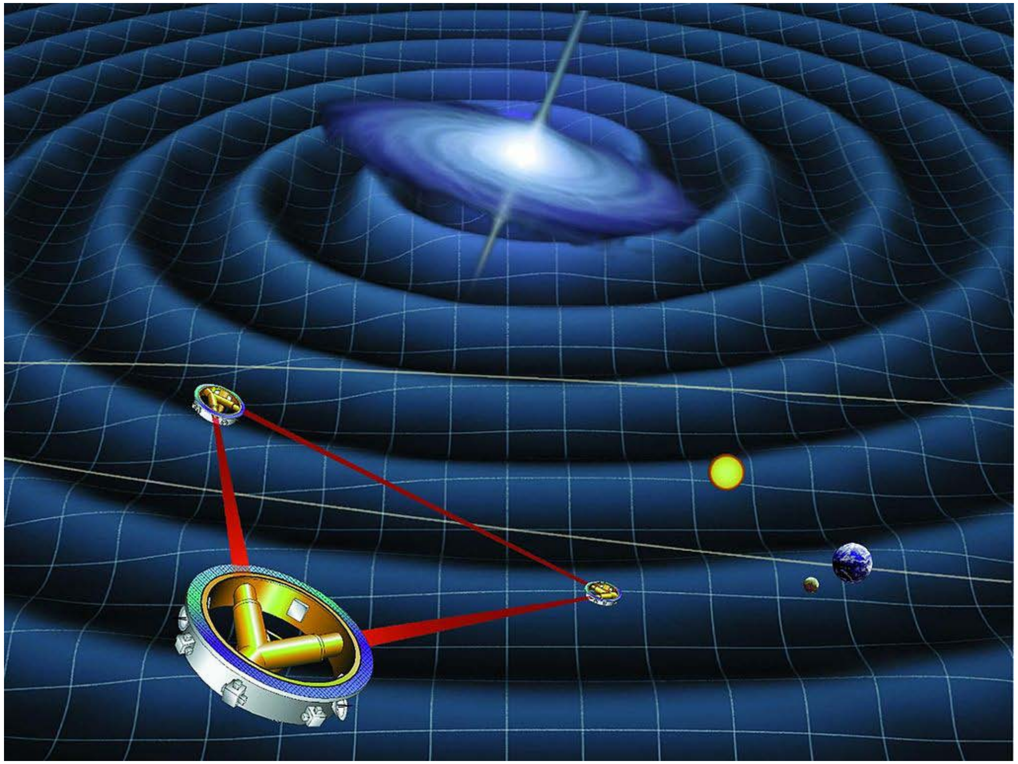
https://www.ligo.caltech.edu/page/press-release-gw170817?highlight=GW170817

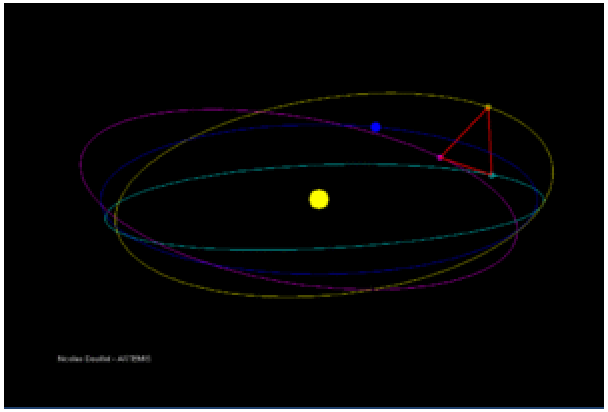
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 119, 161101 (Oct. 20, 2017)

Evolved Laser Interferometer Space Antenna (eLISA)

Proposed for launch in 2034

eLISA would be the first dedicated space-based gravitational wave detector. It aims to measure gravitational waves directly by using laser interferometry. The LISA concept has a constellation of three spacecraft, arranged in an equilateral triangle with million-kilometre arms (5 million km for classic LISA, 1 million km for eLISA) flying along an Earth-like heliocentric orbit.





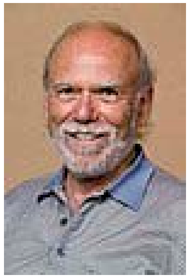
https://en.wikipedia.org/wiki/Evolved_Laser_Interferometer_Space_Antenna

2017 Nobel Prize for Physics

″for decisive contributions to the LIGO detector and the observation of gravitational waves”

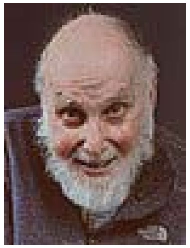
Reiner Weiss

Kip Thorne



Barry Barish

2018 Nobel Prize for Physics



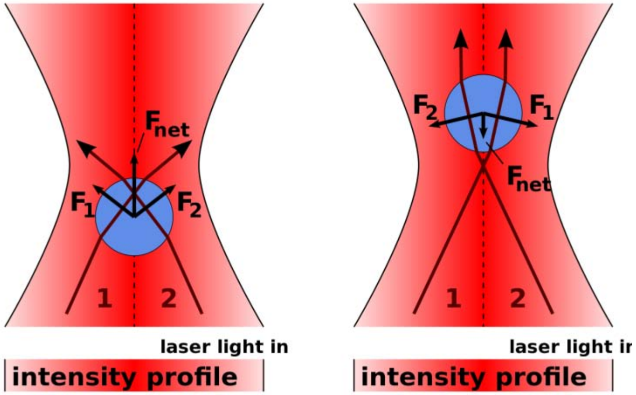
Arthur Ashkin

Gerard Mourou

Donna Strickland

For the invention of optical tweezers and their application to biological systems

For the invention of generation of high-intensity, ultra-short optical pulses



https://en.wikipedia.org/wiki/Optical_tweezers

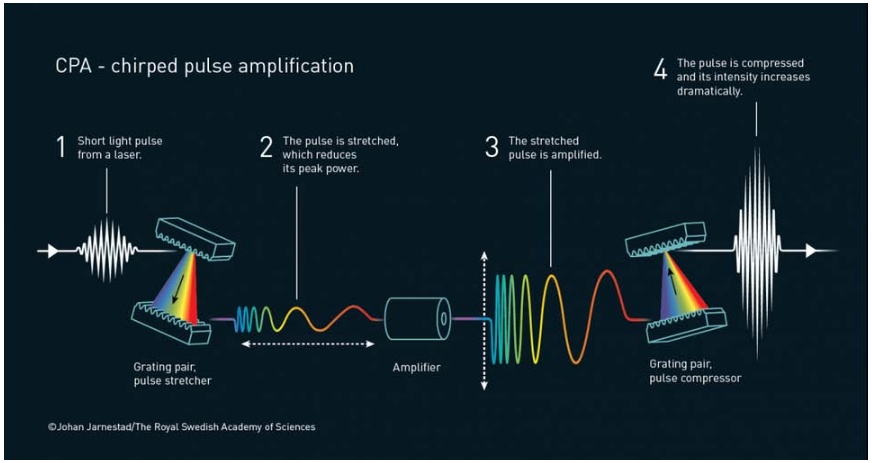


Illustration of Chirped Pulse Amplification from press materials released by the Royal Swedish Academy of SciencesJOHAN JARNESTAD FOR THE ROYAL SWEDISH ACADEMY OF SCIENCES

Nobel Laureates Related to the Field of Optics

Laureates Names	Contribution	Field	Year
W. Röntgen	X-Rays	*Physics*	**1901**
H. Lorentz, P. Zeeman	Magnetism/Radiation Phenomena	*Physics*	**1902**
J. W. Strut (Lord Rayleigh)	Gases Densities - Argon	*Physics*	**1904**
A. Michelson	Optical Precision Instruments and Spectroscopy	*Physics*	**1907**
G. Lippman	Reproduction of Photographic Colors/Interference	*Physics*	**1908**
W. H. Bragg, W. L. Bragg	Crystal Structure with X-Rays	*Physics*	**1915**
A. Einstein	Photo-electric Effect	*Physics*	**1921**
C. V. Raman	Light Scattering	*Physics*	**1930**
F. Zernicke	Phase Contrast Microscopy	*Physics*	**1953**
C. H. Townes, N. G. Basov, A. M. Prokhorov	Maser Principle	*Physics*	**1964**
A. Kastler	Optical Methods for Hertzian Resonances in Atoms	*Physics*	**1966**

Nobel Laureates Related to the Field of Optics			
Laureates Names	**Contribution**	**Field**	**Year**
D. Gabor	Holography	*Physics*	**1971**
M. Ryle, A. Hewish	Radio Astrophysics	*Physics*	**1974**
A. A. Penzias, R. W. Wilson	Cosmic Microwave Background Radiation	*Physics*	**1978**
A. Cormack, G. Housefield	Computer Assisted Tomography	*Physiology or Medicine*	**1979**
N. Bloembergen, A. Schawlaw, K. Siegbahn	Laser Spectroscopy	*Physics*	**1981**
E. Ruska	Electron Optics/Electron Microscope	*Physics*	**1986**
S. Chu, C. Cohen-Tannoudji, W. Phillips	Cooling and Trapping of Atoms with Lasers	*Physics*	**1997**
A. Zewail	Transitions in Chemical Reactions with Femtosecond Spectroscopy	*Chemistry*	**1999**

Nobel Laureates Related to the Field of Optics

Laureates Names	Contribution	Field	Year
Z. Alferov, H. Kroemer	Semiconductor Heterostructures, High-Speed Optoelectronics	*Physics*	**2000**
P. C. Lauterbur, P. Mansfield	Magnetic Resonance Imaging	*Physiology or Medicine*	**2003**
R. J. Glauber, J. L. Hall, T. W. Hänsch	Quantum Theory of Optical Coherence, Laser Precision Spectroscopy	*Physics*	**2005**
O. Shinomura, M. Chalfie, R. Y. Tsien	Green Fluorescent Protein	*Chemistry*	**2008**
C. K. Kao, W. S. Boyle, G. E. Smith	Light Transmission in Optical Fibers, CCD Sensors	*Physics*	**2009**
I. Akasaki, H. Amano, S. Nakamura	Blue Light Emitting Diodes	*Physics*	**2014**
E. Betzig, S. W. Hell, W. E. Moerner	Super-Resolved Fluorescence Microscopy	*Chemistry*	**2014**
R. Weiss, B. C. Barish, K. S. Thorne	LIGO Detector for Gravitational Waves	*Physics*	**2017**
A. Ashkin, G. Mourou, D. Strickland	Optical Tweezers, High-Intensity Ultr-Short Optical Pulses	*Physics*	**2018**

Nobel Laureates Related to the Field of Optics			
Laureates Names	**Contribution**	**Field**	**Year**
A. Aspect, J. F. Clauser, and A. Zeilinger	For experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information sciences	*Physics*	**2022**
F. Krausz, P. Agostini, and A. L'Huiller	For experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter	*Physics*	**2023**