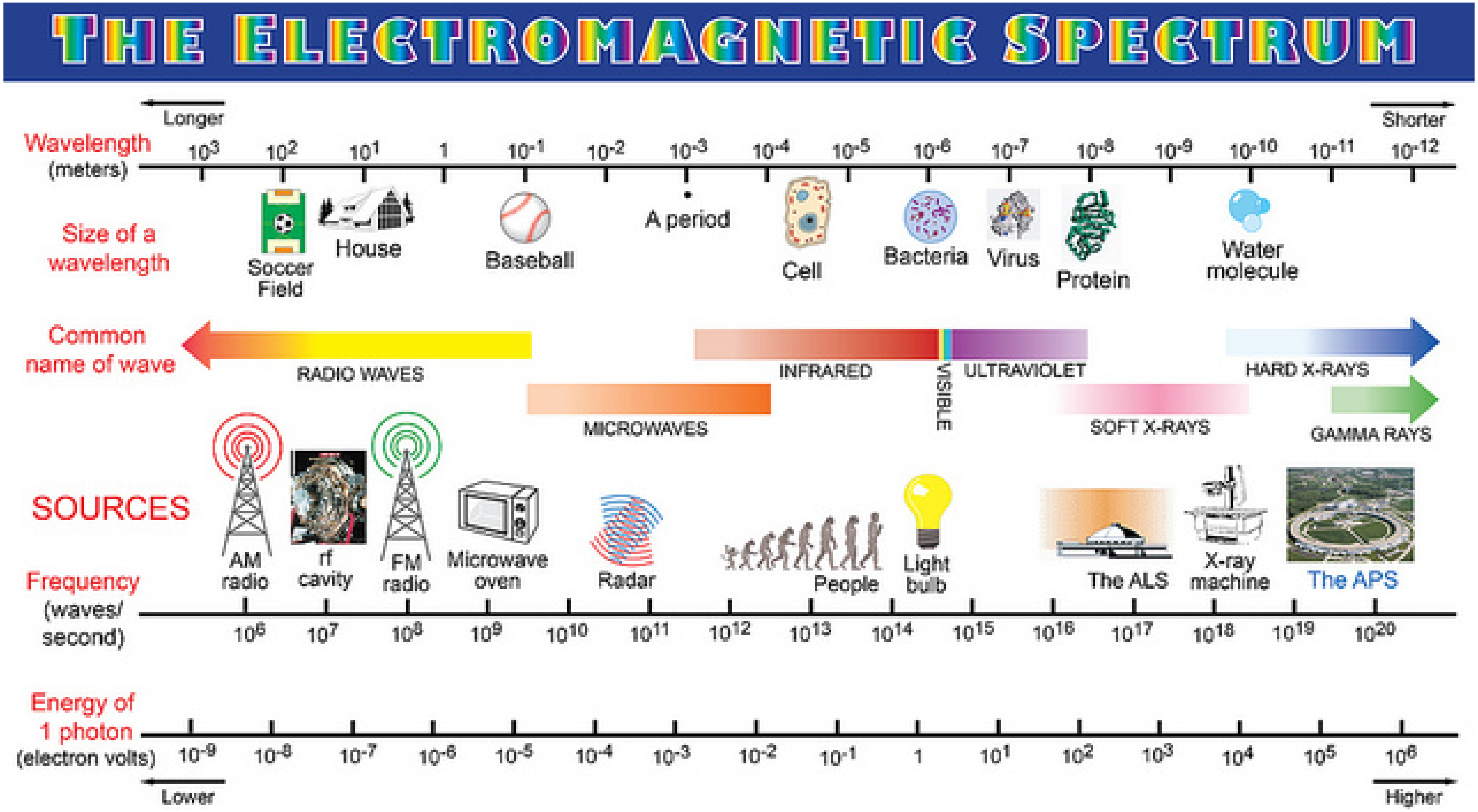
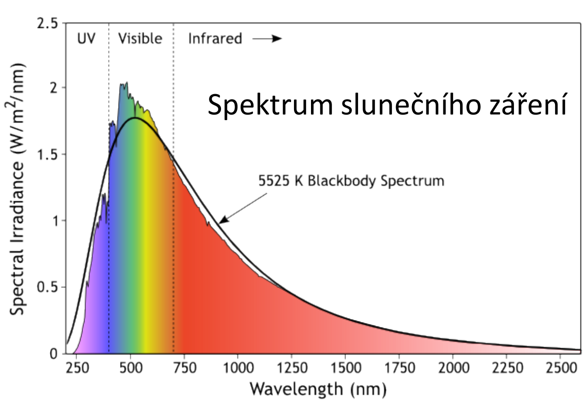
Světelné vlny

Petr Malý

Katedra chemické fyziky a optiky
Matematicko-fyzikální fakulta
Univerzita Karlova

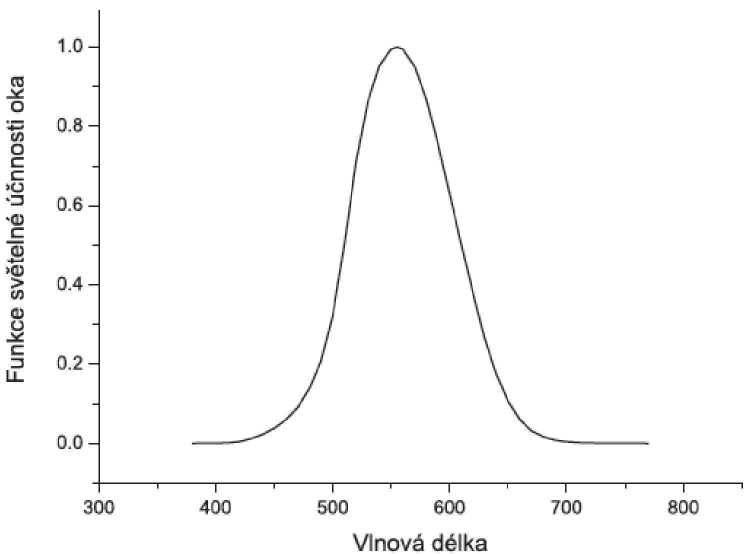




Světelné vlny odpovídají svou frekvencí (energií fotonu) řízení elektronových přechodů v molekulách a pevných látkách

Zrak

vnímání světa



Funkce světelné citlivosti oka

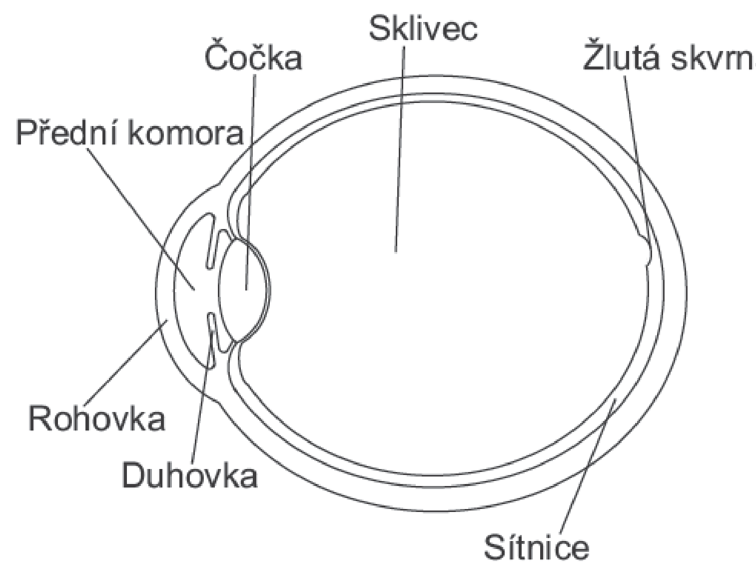
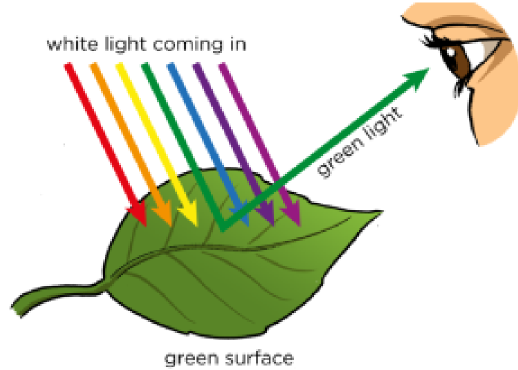


Schéma lidského oka

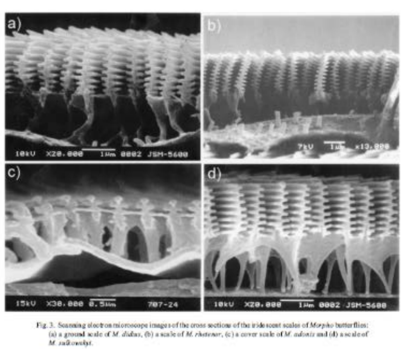
Jak vidíme?

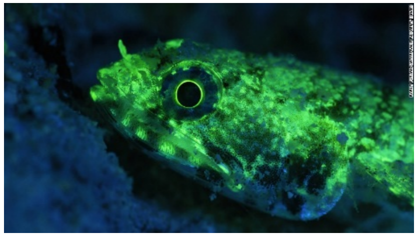


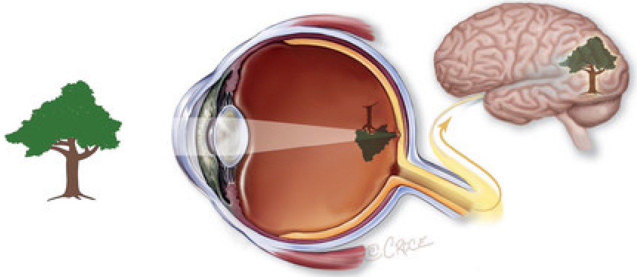
Světlo se šíří od zdroje a osvětluje předmět

Světlo se na povrchu předmětu částečně

- Odrazí (odraz od plochy, mnohonásobný odraz)
- Rozptýlí
- Absorbuje
- Interferuje
- Předmět vyzařuje (tepelné záření, luminiscenci,…)





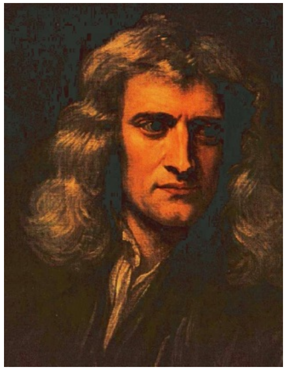


Světlo se šíří od předmětu do oka

Oko světlo fokusuje a detekuje

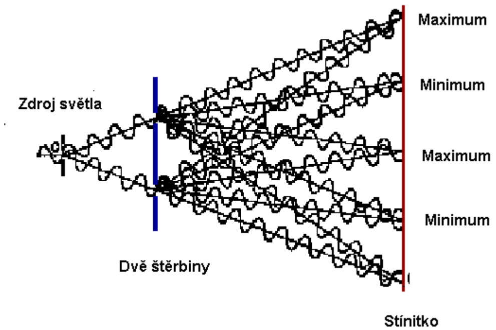
Co je světlo: vlnově částicový dualismus

Světlo složeno z částic

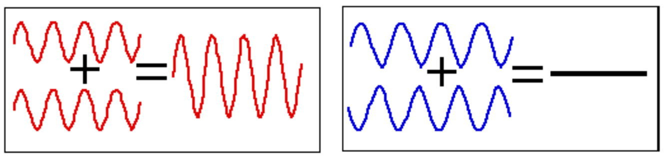
Isaac Newton (1643 - 1727)

Světlo jsou vlny



Youngův experiment

Thomas Young 1802



Konstruktivní interference

Destruktivní interference

Christian Huygens

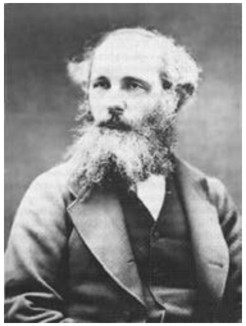
MAXWELLOVY ROVNICE

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$$

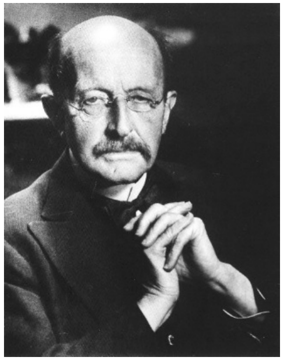
$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \cdot \vec{B} = 0$$



James Clerk Maxwell
1864

Kvantová teorie – světlo: kvanta (fotony)



Max Planck

1900 záření černého tělesa

Albert Einstein

1905 fotoefekt

Paul Dirac

1927 kvantování světla

Vybrané oblasti

- Optická vlákna
- Optické metamateriály
- Lasery (s krátkými optickými pulsy)
- Duha

Světlo - vlna

$$\vec{E}(\vec{r},t) = \vec{E}_0 \cos\left(\omega t - \vec{k}\cdot\vec{r} + \varphi\right).$$

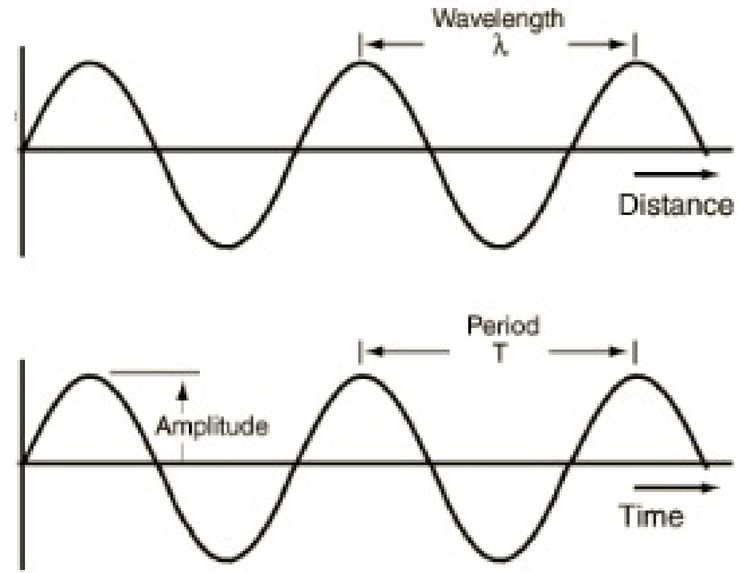
$$\vec{k} = k\,\vec{s} = \frac{2\pi}{\lambda}\vec{s}$$

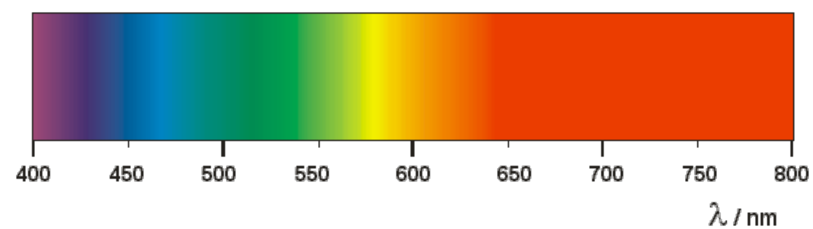
$$\omega T = 2\pi$$

$$k\lambda = 2\pi$$

$$\nu = \frac{1}{T} = \frac{\omega}{2\pi}$$

$$\lambda = \frac{c}{\nu}$$





Příklad:

$$\lambda = 500\ \mathrm{nm}$$

$$\nu = 6 \times 10^{14}\ \mathrm{Hz} \qquad T = 1{,}7 \times 10^{-15}\ \mathrm{s} = 1{,}7\ \mathrm{fs}$$

$$\omega = 3{,}8 \times 10^{15}\ \mathrm{s}^{-1} \qquad k = 1{,}26 \times 10^{7}\ \mathrm{m}^{-1}$$

Šíření světla

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 ,$$

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j} ,$$

$$\nabla \cdot \vec{D} = \rho ,$$

$$\nabla \cdot \vec{B} = 0 ,$$

Vakuum
(nebo isotropní, homogenní neztrátová dielektrika)

$$\vec{B} = \mu \vec{H}$$

$$\vec{D} = \varepsilon_0 (1 + \vec{\chi}) \vec{E} = \vec{\varepsilon} \vec{E}$$

$$\Delta \vec{E} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

c_0
$2{,}9979 \times 10^8$ m s^{-1}

$$n = \frac{c_0}{c}$$

$$c^2 = \frac{1}{\varepsilon \mu}$$

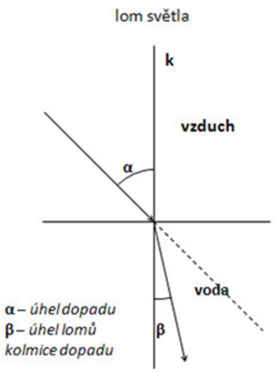
$$n^2 = \varepsilon_r \mu_r .$$

$$n = \frac{c_0}{c} = \sqrt{\varepsilon_r}$$

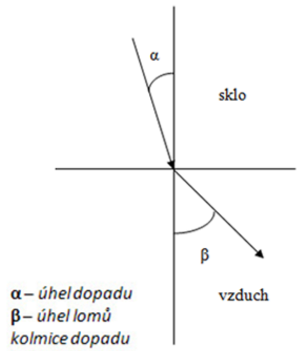
Optická vlákna

Zákon lomu

lom světla ke kolmici



lom světla od kolmice



$$n_1 \sin \alpha = n_2 \sin \beta$$

úplný odraz

$$sin\alpha_m = \frac{1}{n}$$

vzduch - voda

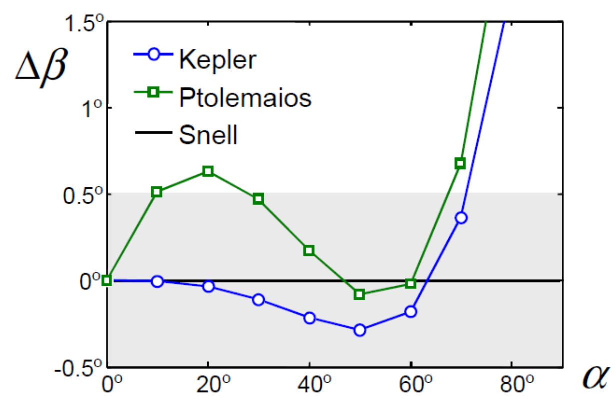
$$\beta = \frac{33}{40}\alpha - \frac{1}{400}\alpha^2$$

Ptolemaios 140

$$\alpha - \beta = \frac{n-1}{n}\frac{\alpha}{\cos\beta}$$

J. Kepler 1604

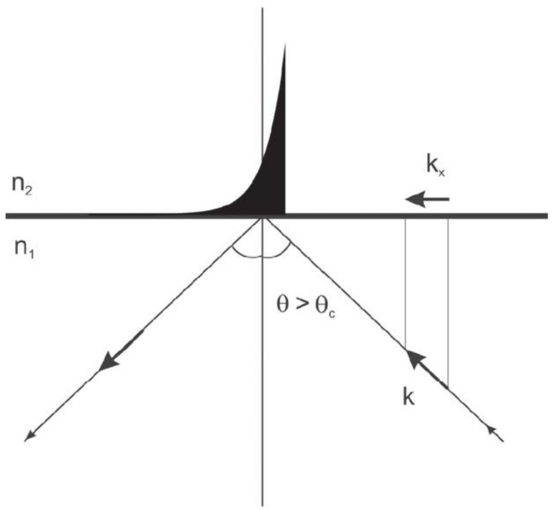
W. Snell 1621

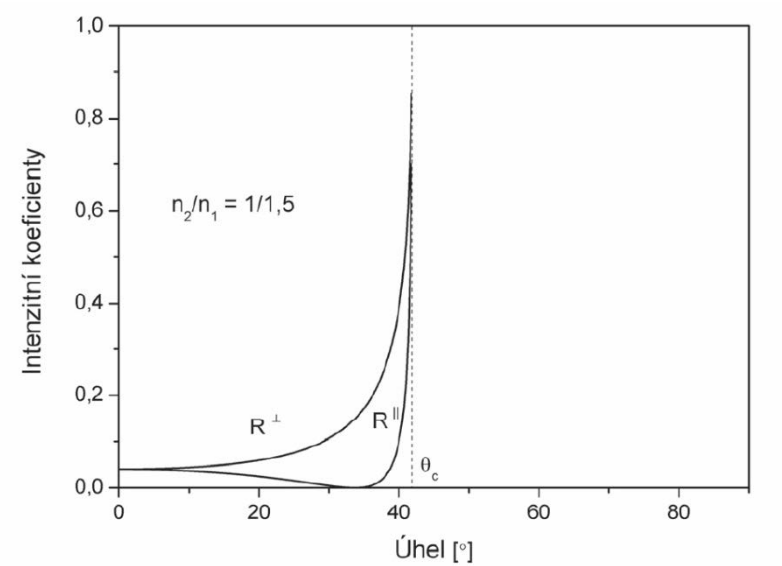


Srovnání chyby $\Delta\beta$ Keplerova a Ptolemaiova zákona lomu oproti přesnému zákonu Snella pro $n = 4/3$. Podotkněme, že chyba půl stupně je pod hranicí přesnosti tehdejších měření.

J. Bajer, Optika 1, UP Olomouc 2015

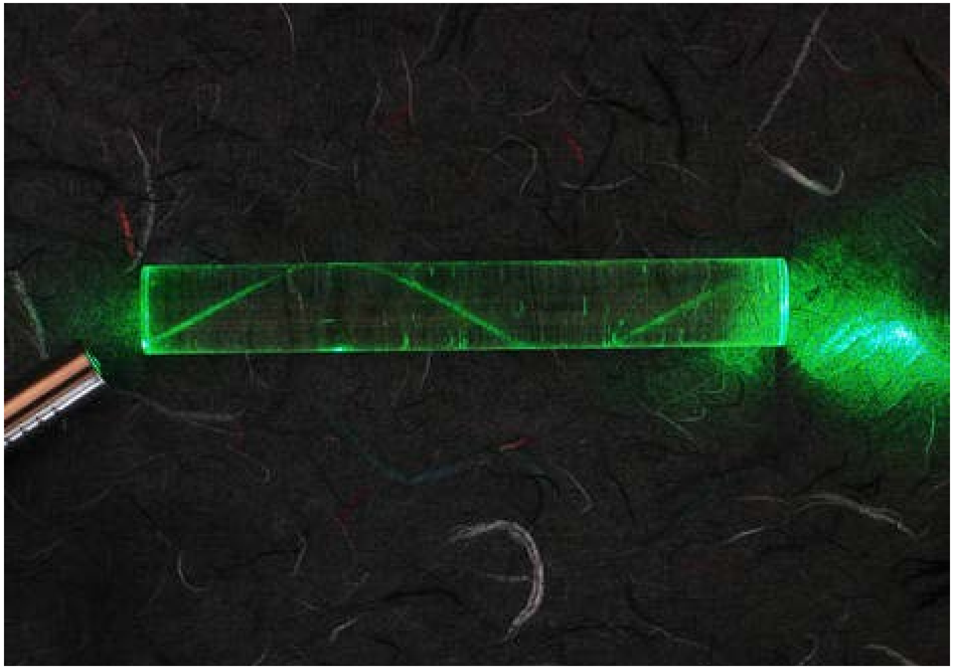
Totální odraz

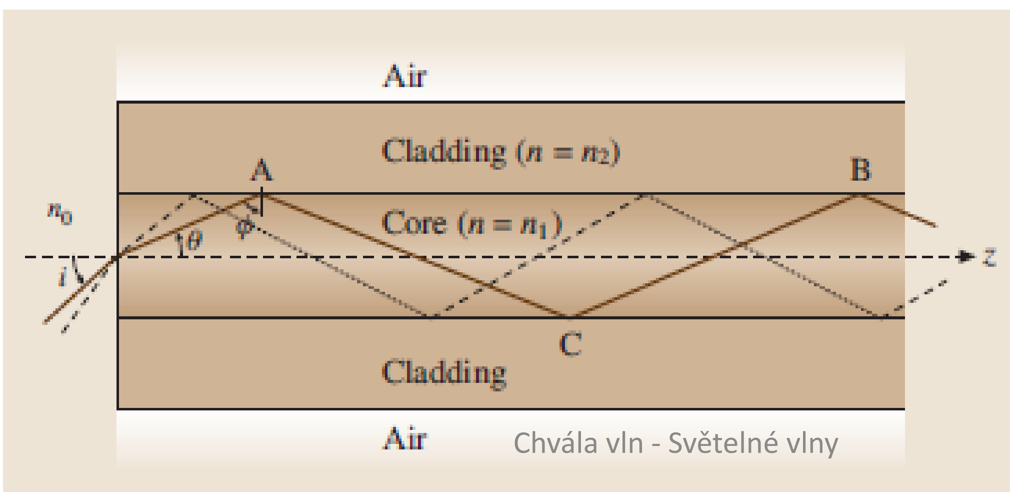




Totální odraz

Světlo lze držet například ve skleněné desce nebo optickém vlákně



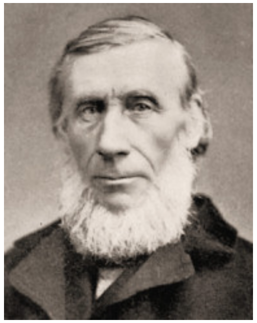


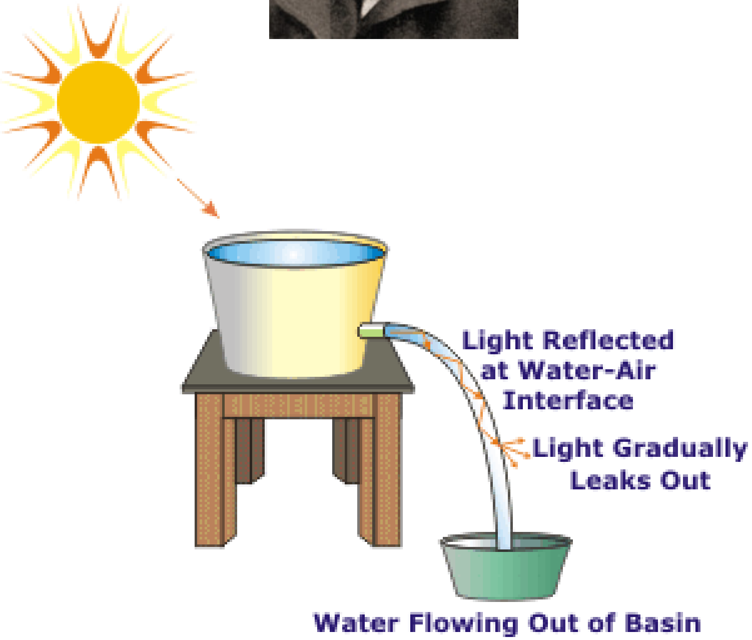
Chvála vln - Světelné vlny

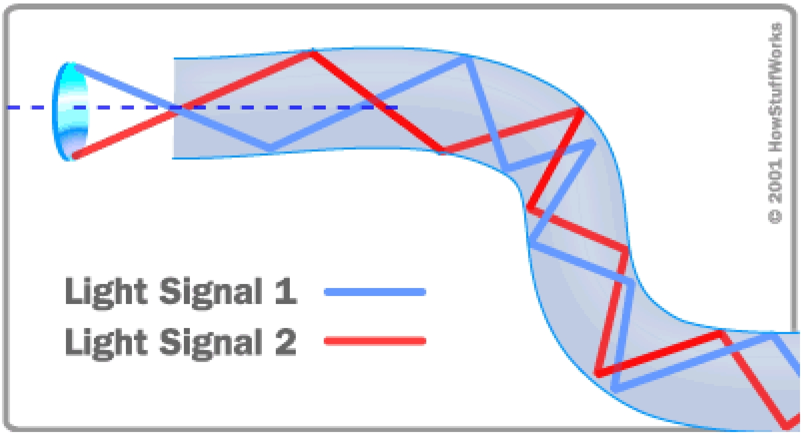
Vedení světla v proudu kapaliny:

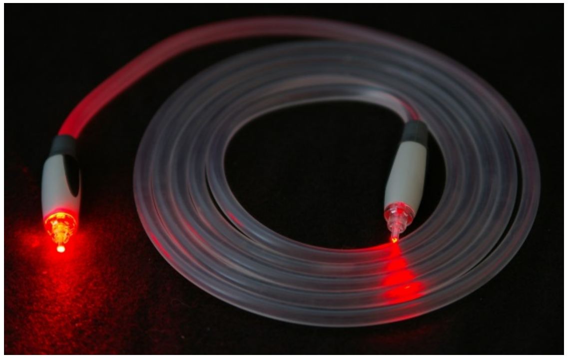
Jean-Daniel Colladon 1841, Jacques Babinet

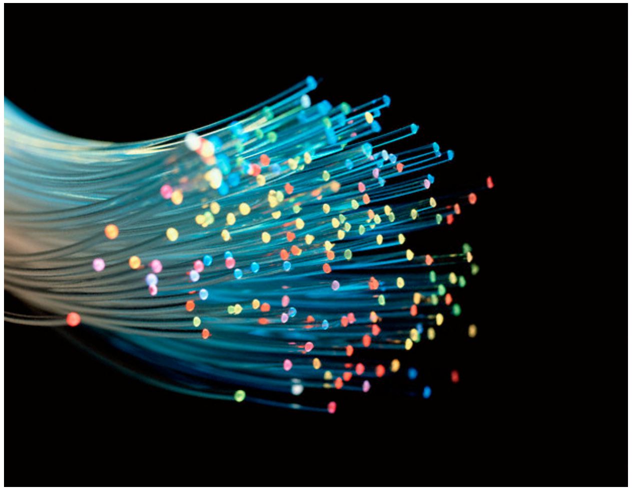
John Tyndall, 1870

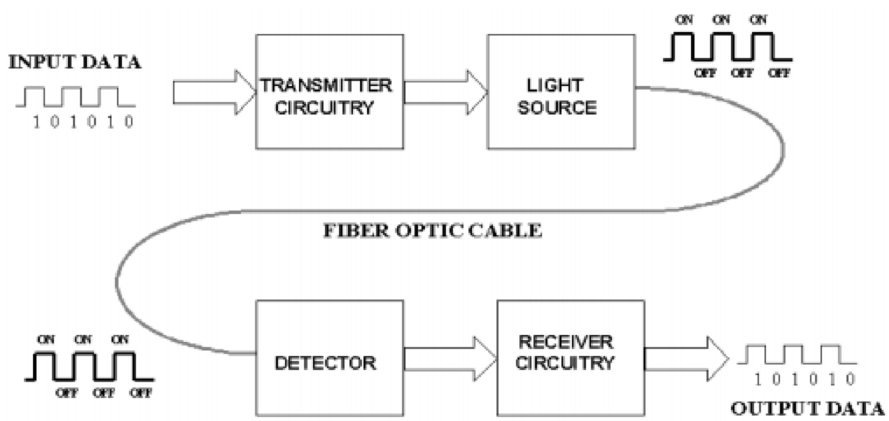


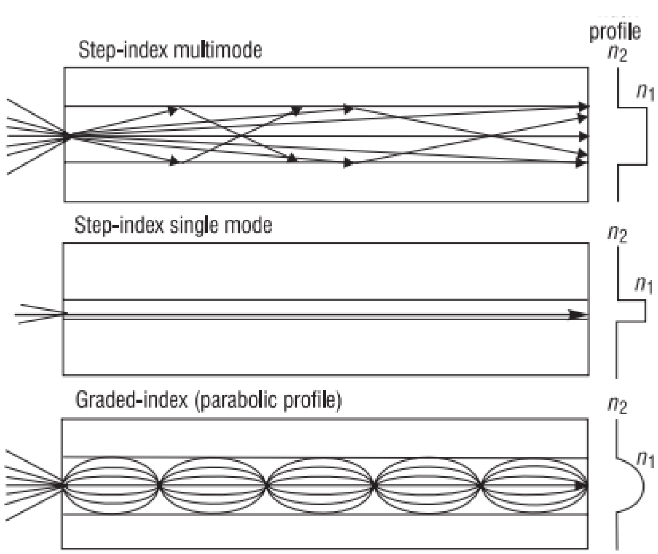



© 2001 HowStuffWorks
Light Signal 1
Light Signal 2







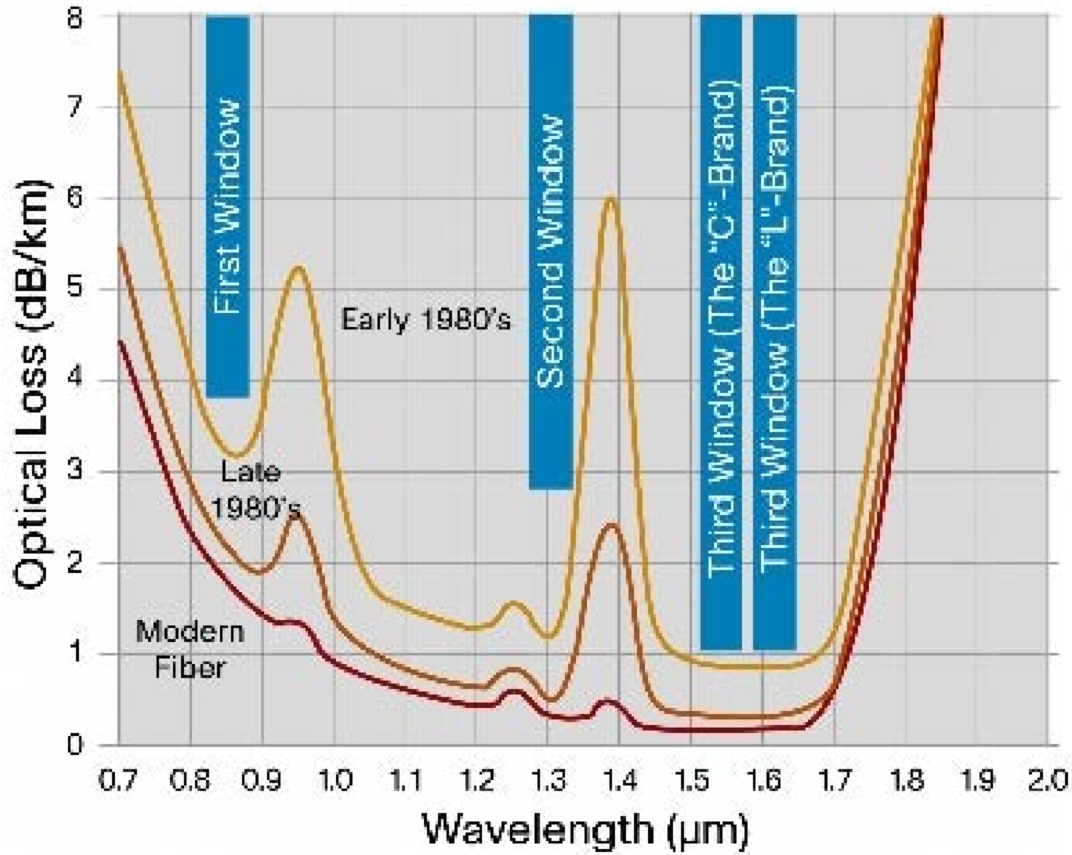


Comments

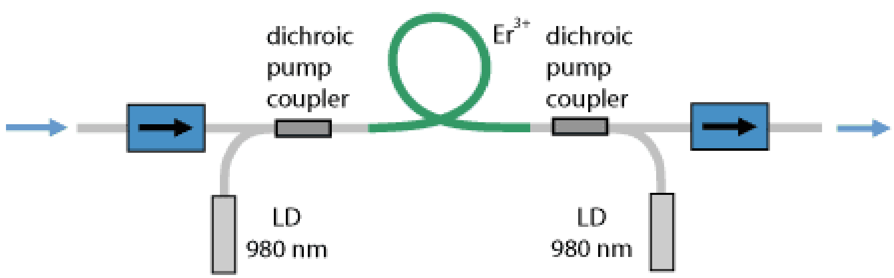
- Large N.A.
- Easy coupling
- Modal dispersion
- Lower data rates
- Shorter distances

- Small N.A.
- Coupling more difficult
- No modal dispersion
- High data rates
- Long distances

- Large N.A.
- Easy coupling
- Less modal dispersion
- Good compromise between multimode and single-mode fiber



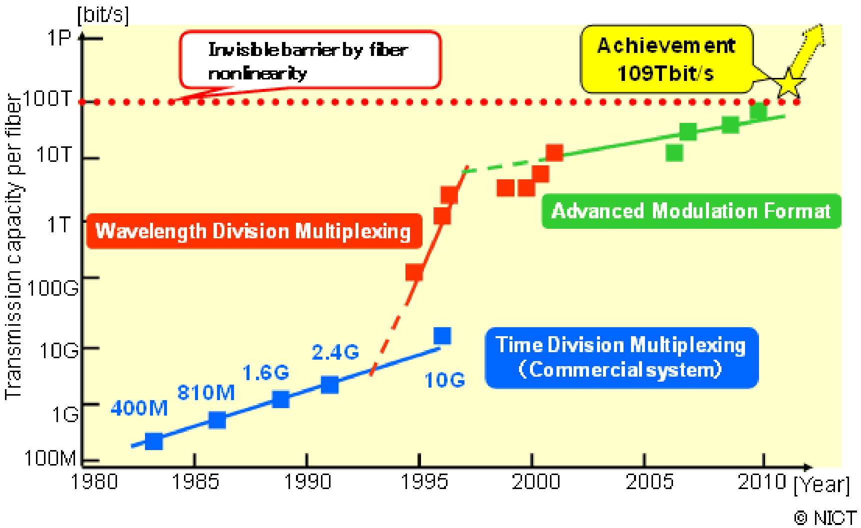
útlum



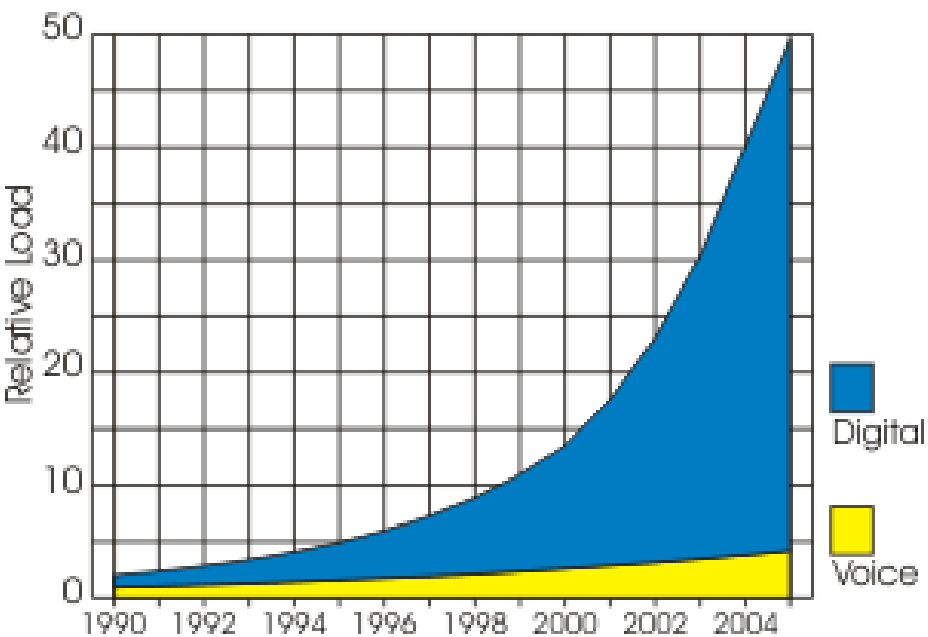
zesilovač

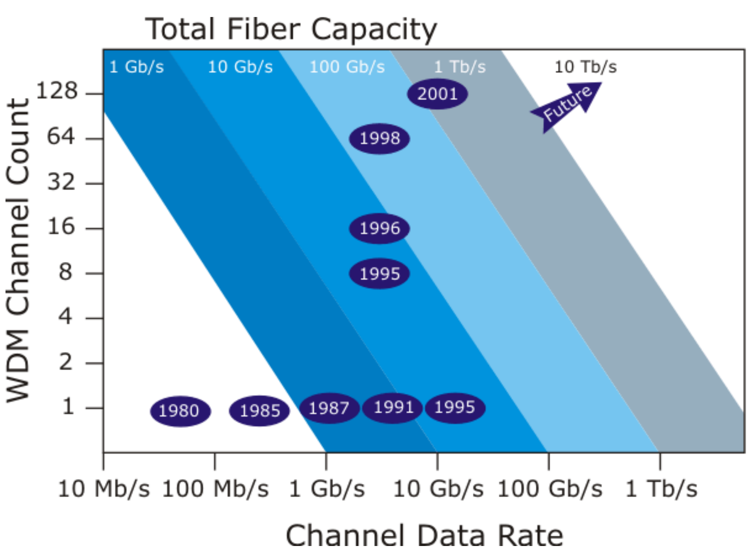
Charles Kuen Kao

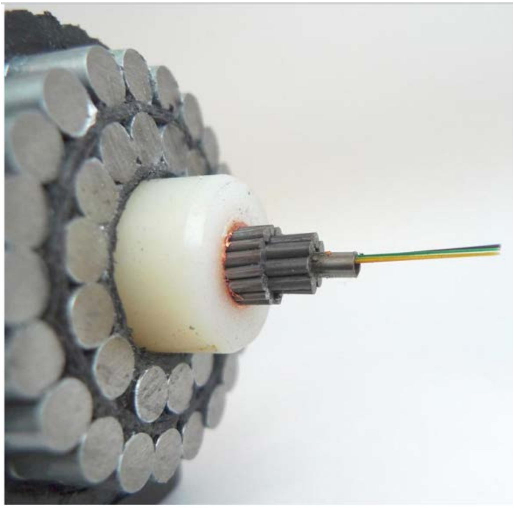
Nobelova cena za fyziku 2009



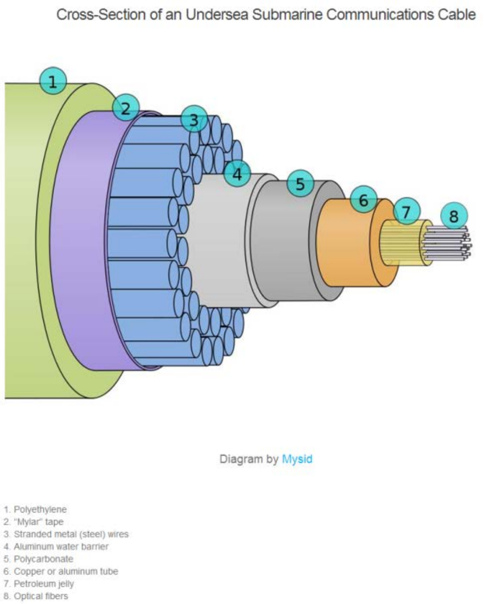
Přenosová kapacita

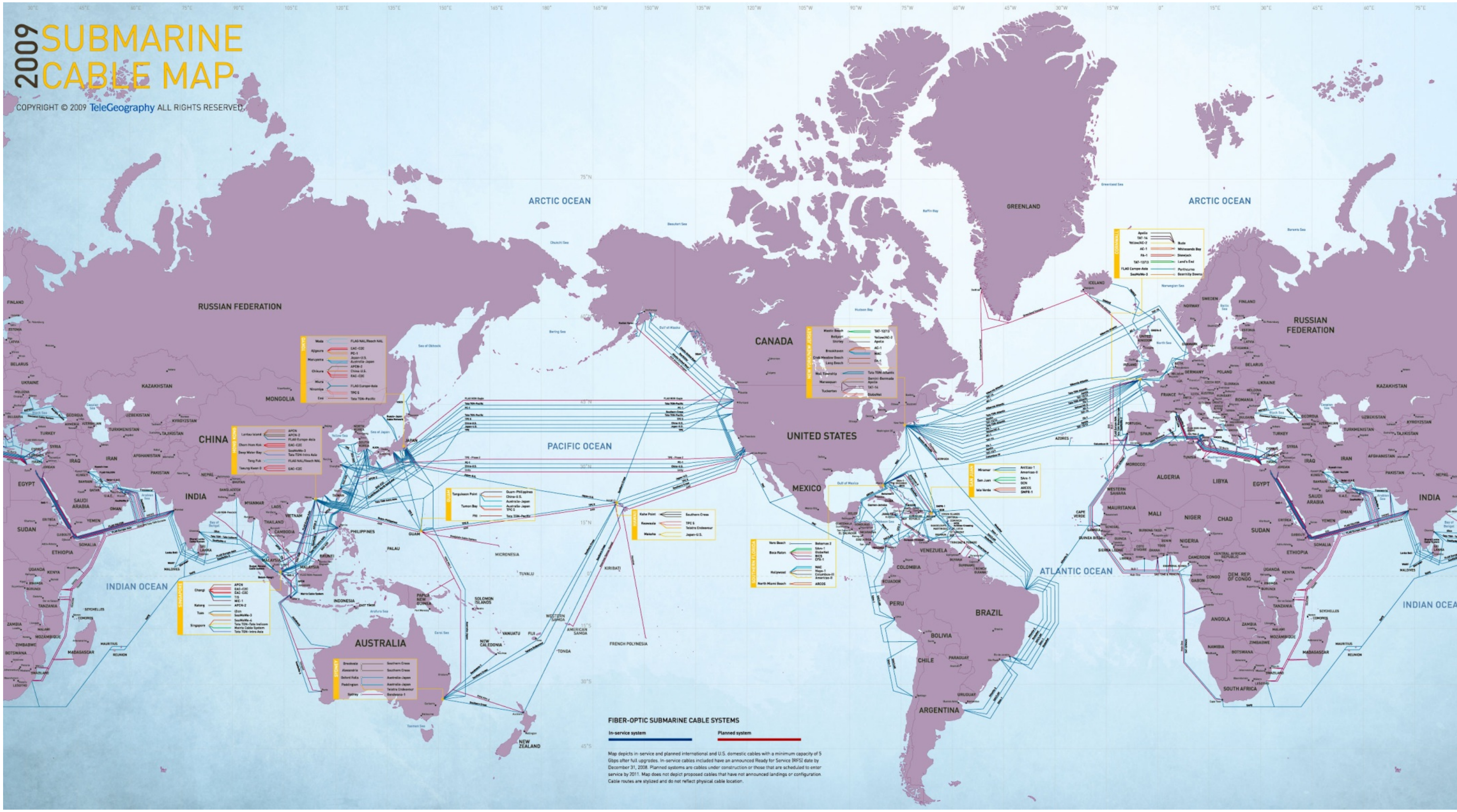


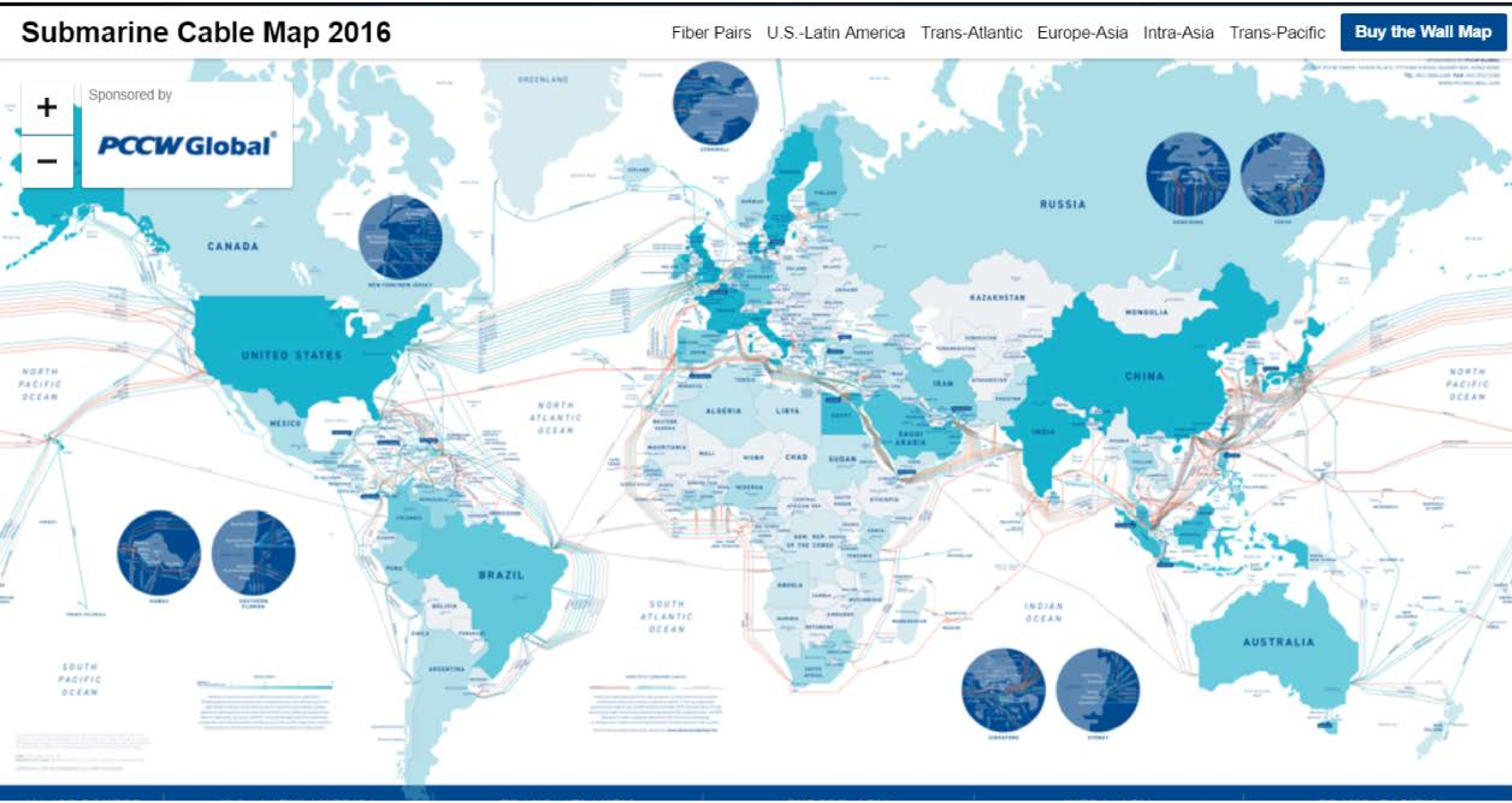




diameter of 69 millimeter (2.7 inches)




2009 SUBMARINE CABLE MAP
COPYRIGHT © 2009 TeleGeography ALL RIGHTS RESERVED
ARCTIC OCEAN
PACIFIC OCEAN
ATLANTIC OCEAN
INDIAN OCEAN
RUSSIAN FEDERATION
CHINA
INDIA
CANADA
UNITED STATES
MEXICO
BRAZIL
AUSTRALIA
GREENLAND
FIBER-OPTIC SUBMARINE CABLE SYSTEMS
In-service system
Planned system
Map depicts in-service and planned international and U.S. domestic cables with a minimum capacity of 5 Gbps after full upgrades. In-service cables included have an announced Ready for Service (RFS) date by December 31, 2008. Planned systems are cables under construction or those that are scheduled to enter service by 2011. Map does not depict proposed cables that have not announced landings or configuration. Cable routes are stylized and do not reflect physical cable location.



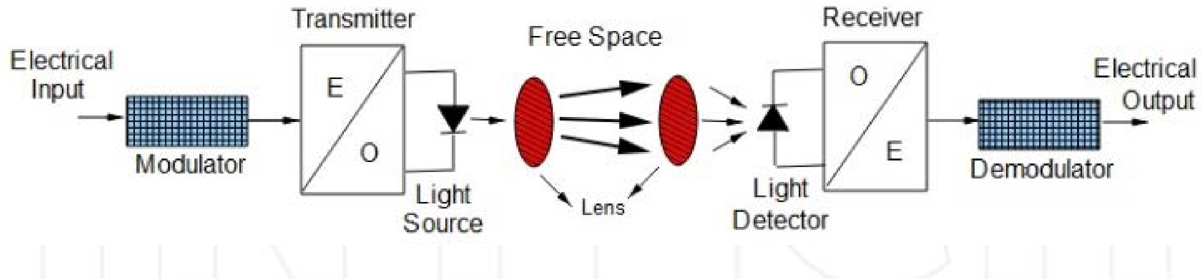
V roce 2017 plánován trans Atlantický kabel : 8 párů vláken, každé 20 Tbit/s (Microsoft a Facebook)

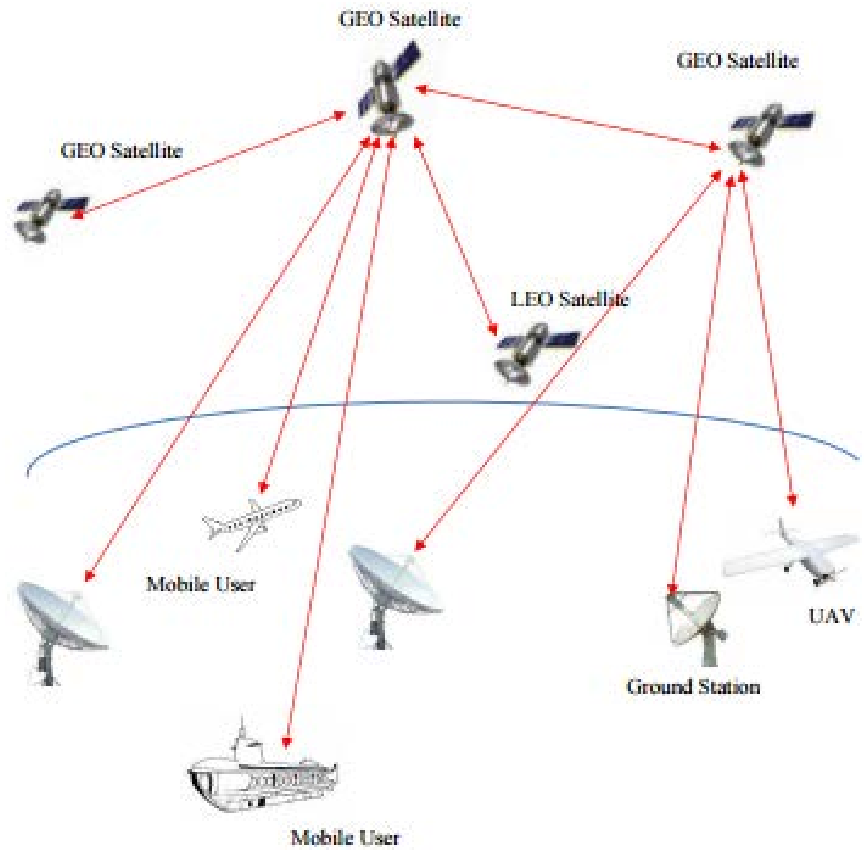
Optické komunikace: od starověku- ohně, záblesky odraženého slunečního světla

Ve Francii konec 18. stol. – telegraf – vlajkové semafory, věže , několik slov/minutu

Vedení světelného signálu – volným šířením
- vedenou vlnou – vlnovody, vlákna

A. G. Bell – 1880 photophone (200 m, volné šíření, selenový odpor/detektor,
B. chvějící se clona na mluvítku)





Weather attenuation coefficient of FSO.

Weather conditions	α[dB/km]
Clear air	0.43
Haze	4.2
Moderate rain (12.5 mm/h)	5.8
Heavy rain (25 mm/h)	9.2
Light fog	20
Moderate fog	42.2
Heavy fog	125

Očekávaný růst
Již nyní města, banky …

Optické metamateriály

Šíření světla

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0\,,$$

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}\,,$$

$$\nabla \cdot \vec{D} = \rho\,,$$

$$\nabla \cdot \vec{B} = 0\,,$$

Vakuum
(nebo isotropní, homogenní dielektrika)

$$\vec{B} = \mu \vec{H}$$

$$\vec{D} = \varepsilon_0 \left(1 + \vec{\vec{\chi}}\right) \vec{E} = \vec{\vec{\varepsilon}}\, \vec{E}$$

$$\Delta \vec{E} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$c_0$$
$$2{,}9979 \times 10^8 \text{ m s}^{-1}$$

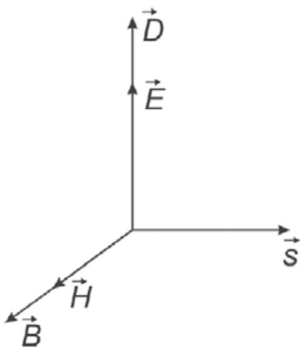
$$n = \frac{c_0}{c}$$

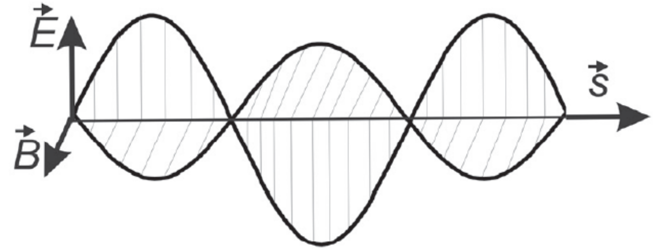
$$c^2 = \frac{1}{\varepsilon \mu} \qquad c = \frac{1}{\sqrt{\mu \varepsilon}}$$

$$n^2 = \varepsilon_r \mu_r.$$

$$n = \frac{c_0}{c} = \sqrt{\varepsilon_r}$$

Světelná vlna
(harmonická, rovinná)





$$E(z,t) = E_0 \cos(\omega t - k z)$$

$$\vec{k} = k\vec{s} = \frac{2\pi}{\lambda}\vec{s} = \frac{\omega}{c}\vec{s} = \frac{\omega}{c_0} n\vec{s} = k_0 n\vec{s}$$

$$\vec{k}\cdot\vec{B}_0 = 0\,,$$

$$\vec{k}\cdot\vec{D}_0 = 0\,,$$

$$\omega\vec{B}_0 = \vec{k}\times\vec{E}_0\,,$$

$$\omega\vec{D}_0 = -\vec{k}\times\vec{H}_0\,.$$

příčná vlna

$$\vec{k}\times\overrightarrow{E_0} = \omega\mu\overrightarrow{H_0}$$

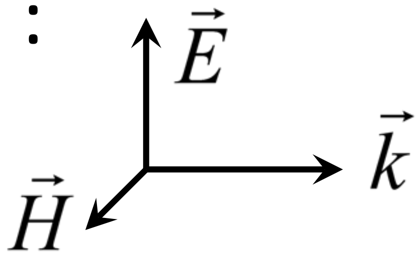
Poyntingův vektor $\vec{S}(\vec{r},t) = \vec{E}(\vec{r},t)\times\vec{H}(\vec{r},t)$

$$\vec{k}\times\overrightarrow{H_0} = -\omega\varepsilon\overrightarrow{E_0}$$

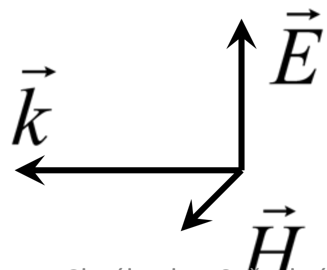
$$\vec{k} \times \vec{E_0} = \omega\mu\vec{H_0}$$

$$\vec{k} \times \vec{H_0} = -\omega\varepsilon\vec{E_0}$$

- $\varepsilon > 0, \mu > 0$ pak $\left(\vec{E}, \vec{H}, \vec{k}\right)$ je pravotočivá trojice vektorů :



- $\varepsilon < 0, \mu < 0$ pak $\left(\vec{E}, \vec{H}, \vec{k}\right)$ je levotočivá ***trojice vektorů***:



V.G.Veselago (v.veselago@relcom.ru) 1964

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

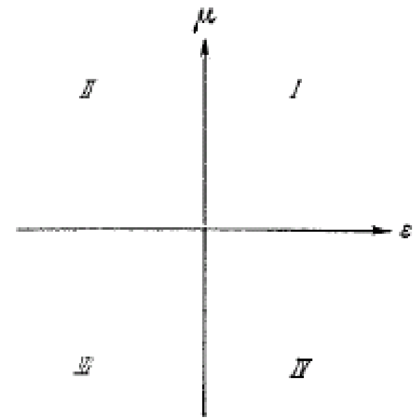
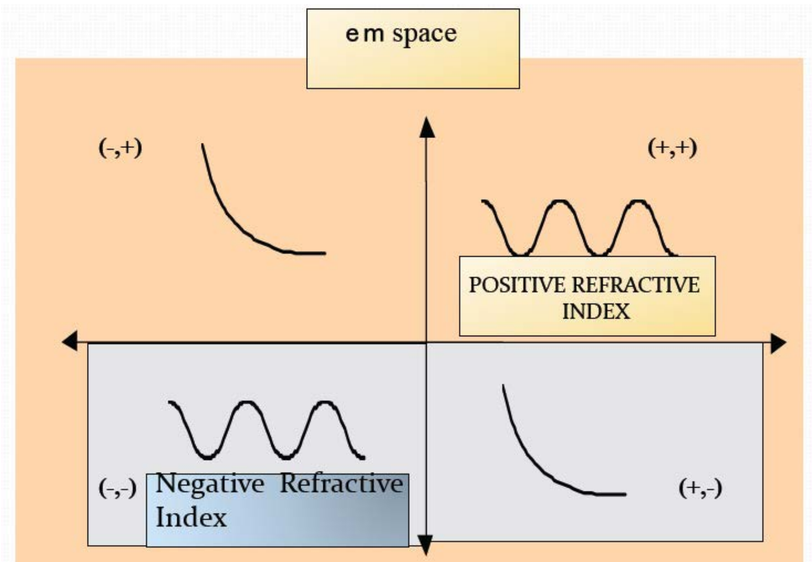
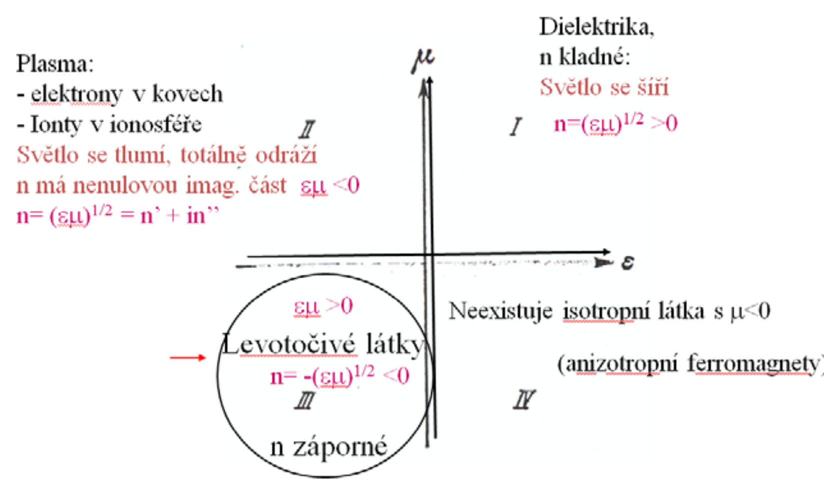


FIG. 7. $\epsilon - \mu$ diagram.



ε(ω) –μ(ω) diagram



Ale $\varepsilon<0$ a současně $\mu<0$? Neexistuje v přírodních materiálech

Ale toto omezení neplatí pro umělé materiály – tzv. METAMATERIÁLY

“Obrácení” Snellova zákona

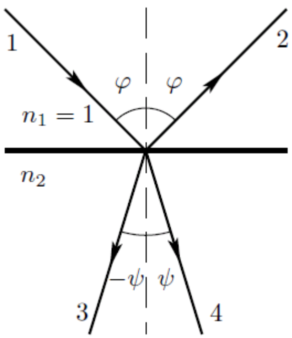
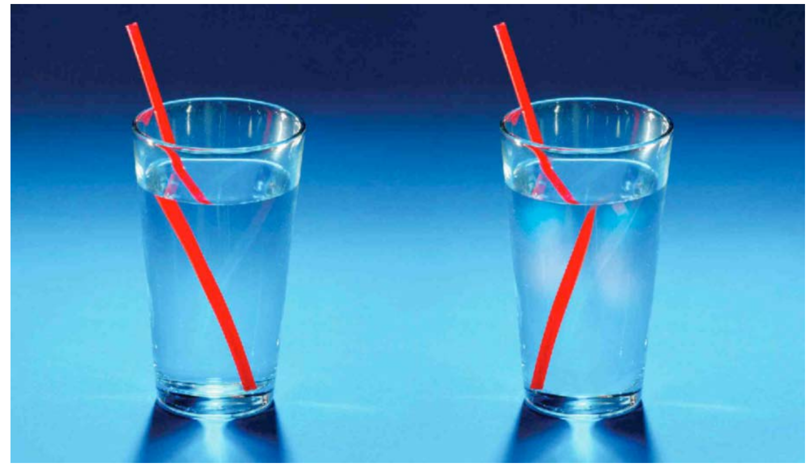


Рис. 1. Преломление света на границе двух сред. Путь 1–4 соответствует ходу падающего и преломлённого лучей для случая $n_2 > 0$, а путь 1–3 — для случая $n_2 < 0$



výpočet

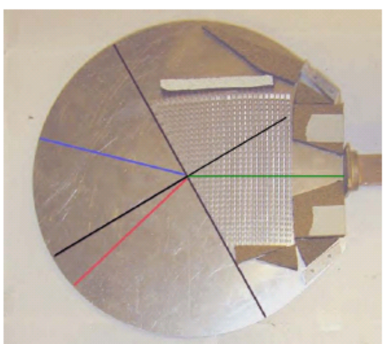


Fig. 11: Foto des Versuchsaufbaus des Shelby-Experimets

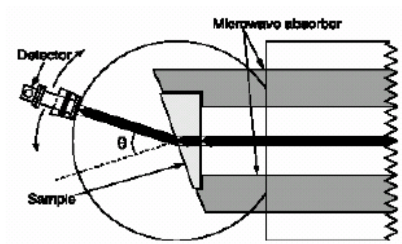


Fig. 12: Versuchsaufbau des Shelby-Experimets

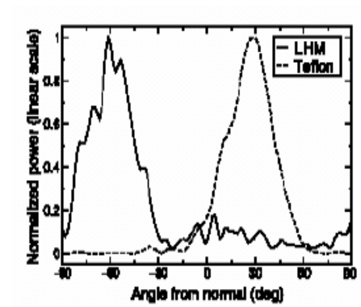


Fig. 13: transmittierte Leistung bei einer Frequenz von 10.5 GHz

experiment

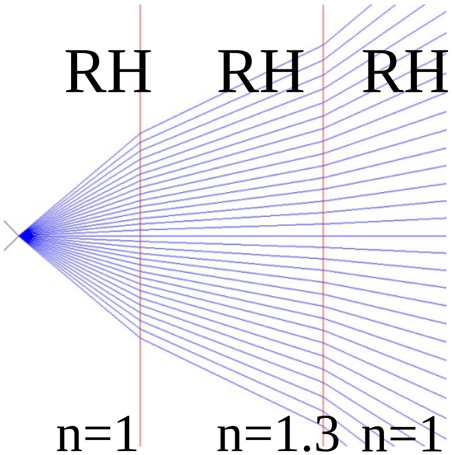
R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, S. Schultz, *Appl. Phys. Lett.* **78**, 489 (2001)
R. A. Shelby, D. R. Smith, S. Schultz, *Science* **292**, 77 (2001)

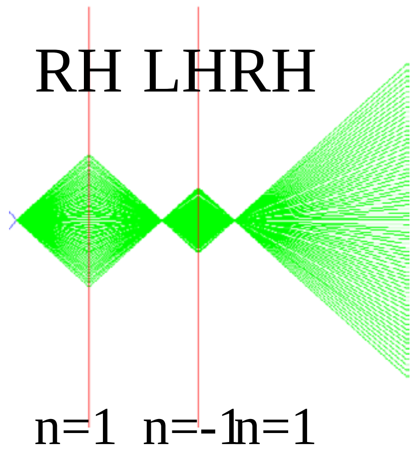
VOLUME 85, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 2000

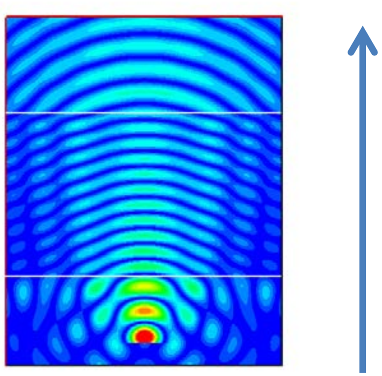
Negative Refraction Makes a Perfect Lens

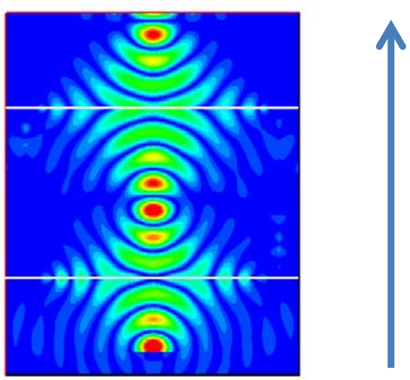
J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

Fokusace v „Left-Handed“ prostředí

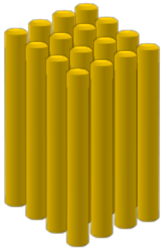




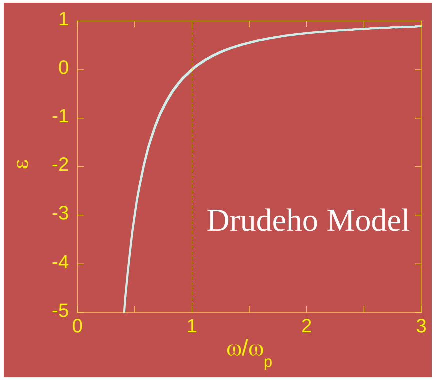




Negativní materiály



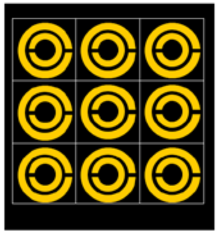
$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$



Elektrická odezva

Magnetická odezva vodičů: solenoidální proudy s časově proměnným magnetickým polem (vodivý prstýnek)

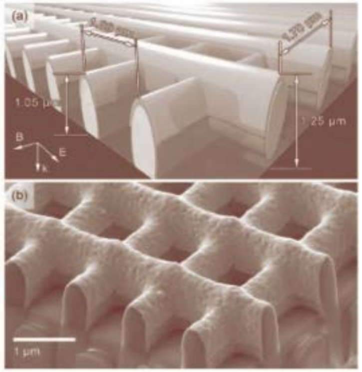
Mezery vedou k rezonancím, zesílení odezvy

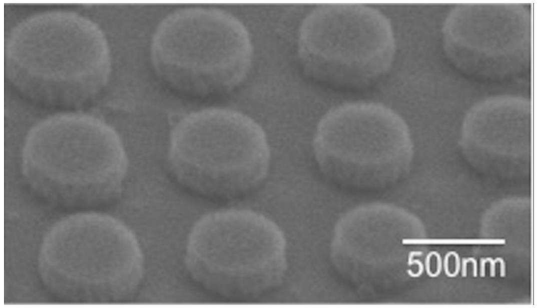


Magnetická odezva

D. R. Smith, W. J. Padilla, et al, Phys. Rev. Lett. 14, 234 (2000)

10.95 GHz





January 1, 2009 / Vol. 34, No. 1 / OPTICS LETTERS 19

Negative-index bianisotropic photonic metamaterial fabricated by direct laser writing and silver shadow evaporation

Michael S. Rill,[1,*] Christine E. Kriegler,[1] Michael Thiel,[1] Georg von Freymann,[1,2] Stefan Linden,[1,2] and Martin Wegener[1,2]

2D-PhC

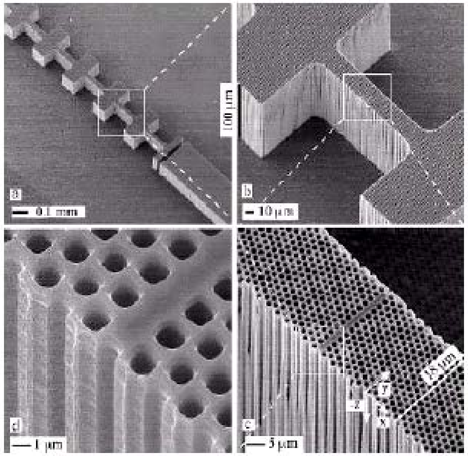


Fig. 18: Makroporöses Silizium; Bandlücke bei 3 - 4,5µm (nahes IR)

3D-PhC

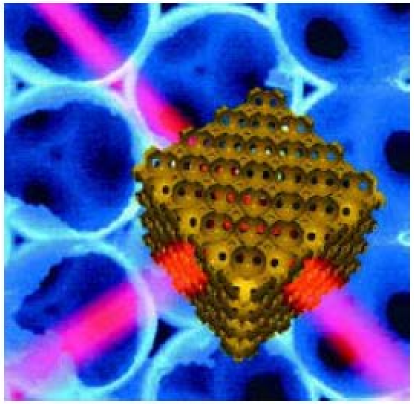
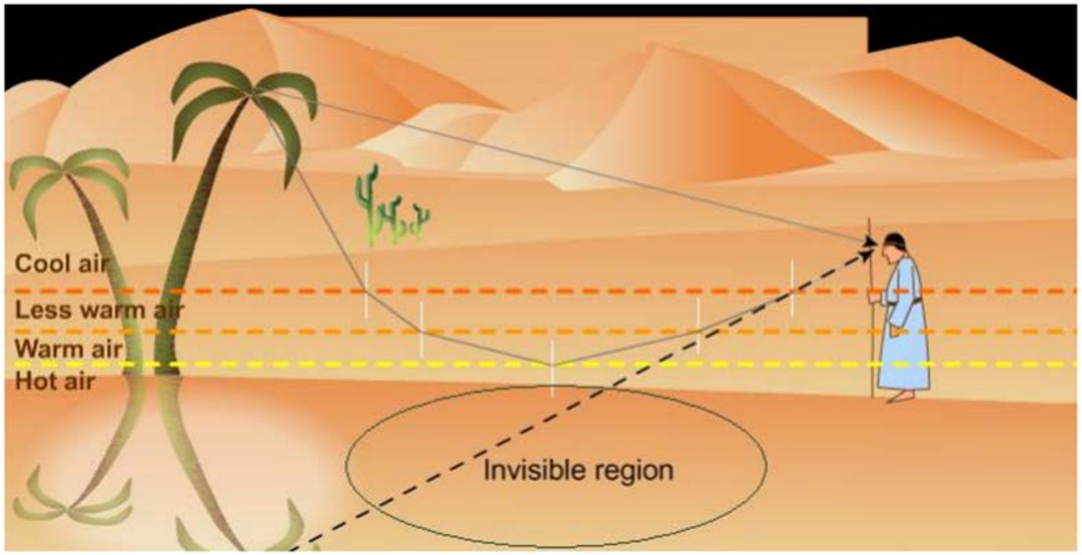


Fig. 19: sog. Invertierter Opal aus Silizium mit ‚leeren' kugelförmigen Zwischenräumen Bandlücke bei 1,4 – 1,5 µm

Fotonické krystaly

Cílená modifikace indexu lomu – změna šíření světla, zobrazování



Pendry et al., 2006

Nové metamateriály – široký interval hodnot indexu lomu

Nová optika – navrhování materiálů s cílenými průběhy indexu lomu

Plášť neviditelnosti

Plášť (*cloak*) je objekt vyrobený z metamateriálů, jehož funkcí je odklonit světelné paprsky, které by dopadly na předmět, vést je dále okolo předmětu a vrátit na původní trajektorii

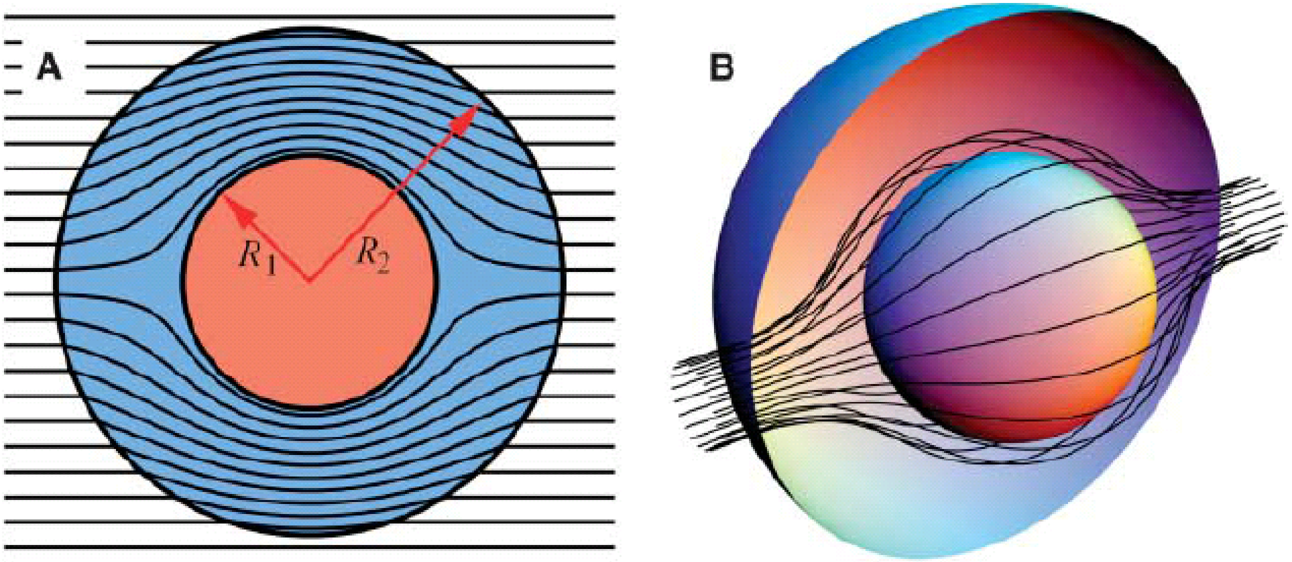


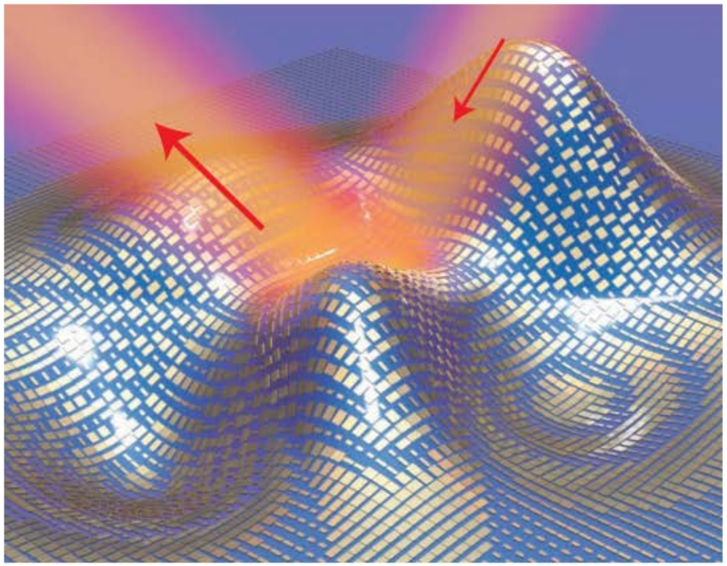
Fig. 2. A ray-tracing program has been used to calculate ray trajectories in the cloak, assuming that $R_2 \gg \lambda$. The rays essentially following the Poynting vector. (**A**) A two-dimensional (2D) cross section of rays striking our system, diverted within the annulus of cloaking material contained within $R_1 < r < R_2$ to emerge on the far side undeviated from their original course. (**B**) A 3D view of the same process.

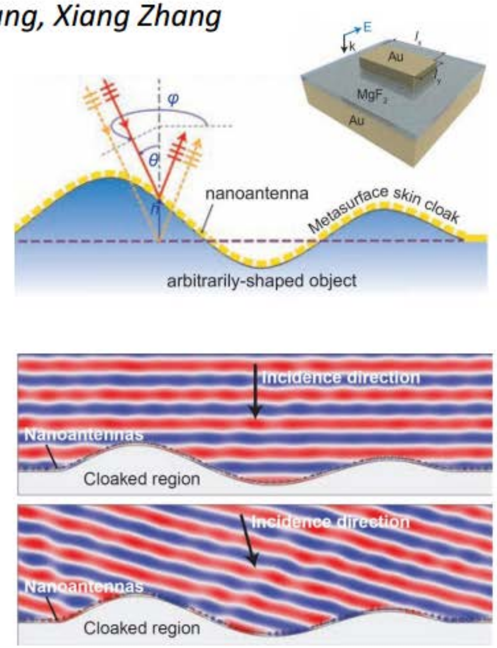
Pendry, Schurig and Smith, Science, (2006)

An ultrathin invisibility skin cloak for visible light

Sep. 18 2015 • Vol 349, Issue 6254

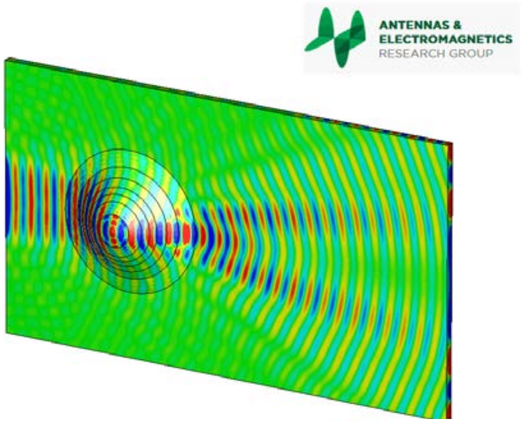
Xingjie Ni, Zi Jing Wong,* Michael Mrejen, Yuan Wang, Xiang Zhang*

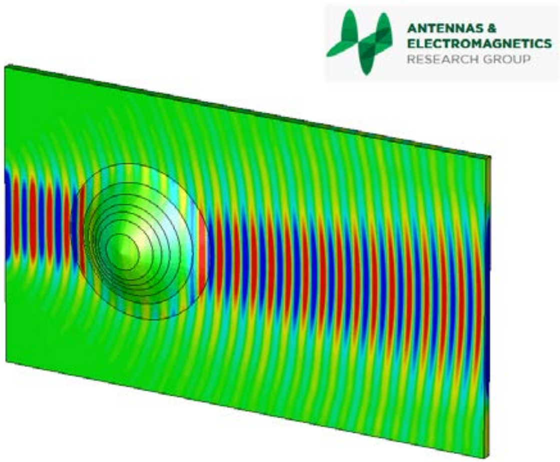




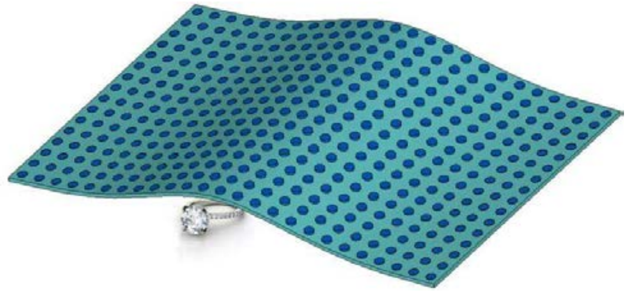
Tloušťka vrstvy 80 nm

Science





Queen Mary University
of London , 2016



An extremely thin cloaking device is designed using dielectric materials. The cloak is a thin Teflon sheet (light blue) embedded with many small, cylindrical ceramic particles (dark blue). Credit: Li-Yi Hsu/Jacobs School of Engineering/UC San Diego

PRL 102, 253902 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009

Illusion Optics: The Optical Transformation of an Object into Another Object

Yun Lai, Jack Ng, HuanYang Chen, DeZhuan Han, JunJun Xiao, Zhao-Qing Zhang,* and C. T. Chan†
Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
(Received 21 April 2009; revised manuscript received 26 May 2009; published 22 June 2009)

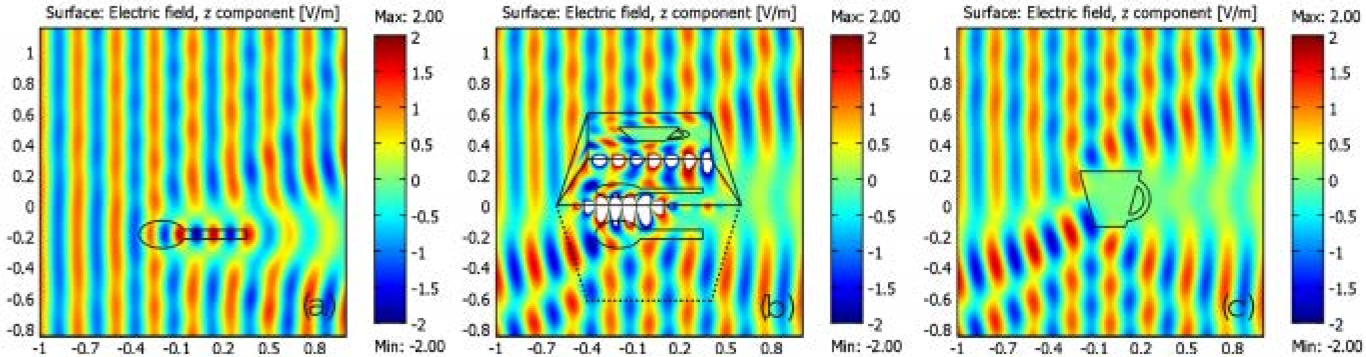


FIG. 2 (color online). A numerical demonstration of transforming the stereoscopic image of a dielectric spoon of $\varepsilon_o = 2$ (the object) into that of a metallic cup of $\varepsilon_i = -1$ (the illusion) through an illusion device, under an incident TE plane wave from the left. (a) The scattering pattern of the dielectric spoon. (b) The scattering pattern of the dielectric spoon is changed by the illusion device. Outside the virtual boundary, the scattering pattern becomes the same as that of the metallic cup, which is shown in (c).

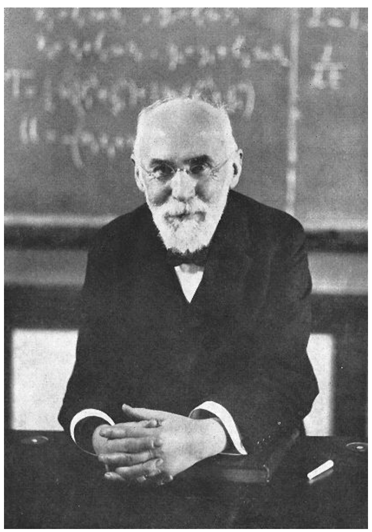
Laser
(s ultrakrátkými optickými pulsy)

LASER

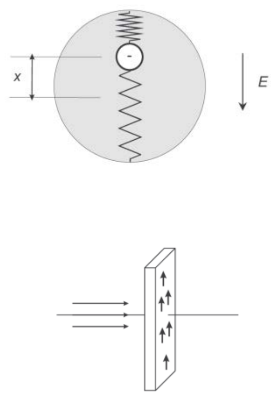
Light **A**mplification by **S**timulated **E**mission of **R**adiation

Zesílení světla stimulovanou emisí záření

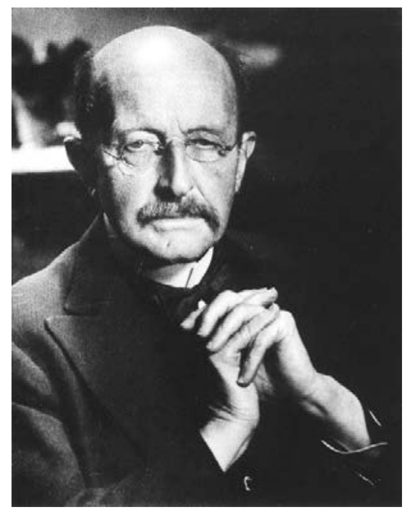
Interakce světla s látkami



H. A. Lorentz (1853 – 1928)



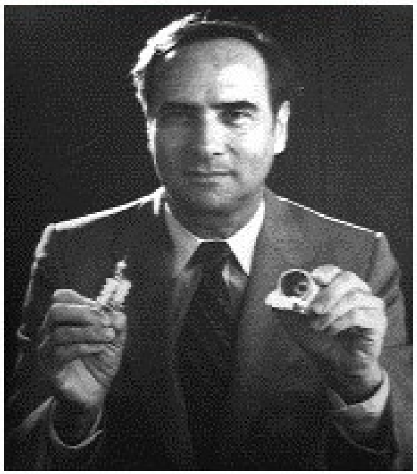
$E_{\text{ven}} = E_{\text{dovnitř}} + E_{\text{dipólků}}$

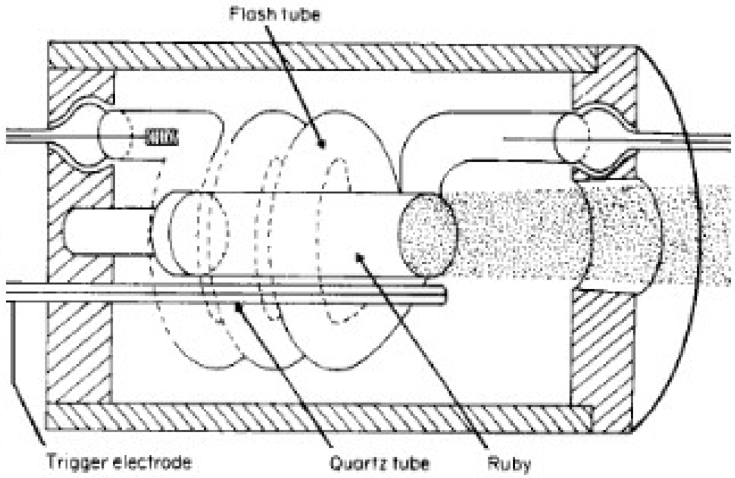


Max Planck (1858-1947)

A. Einstein (1879 – 1955)

A. Einstein: Zur Quantumtheorie der Strahlung, Phys. Z. **18**, 121 (1917)





Thomas Maiman, 1960 ....

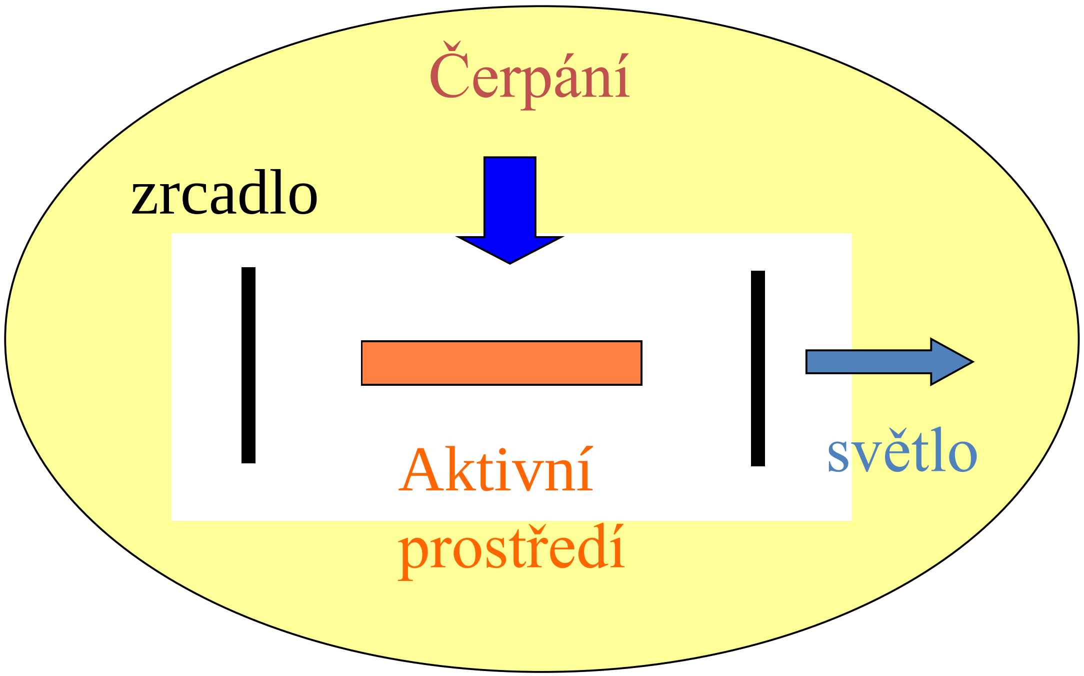
This man ignored the ridicule of his peers and easiliy succeeded in producing history's first visible light laser from this simple photographic coiled flashlamp and his ruby crystalline rod.

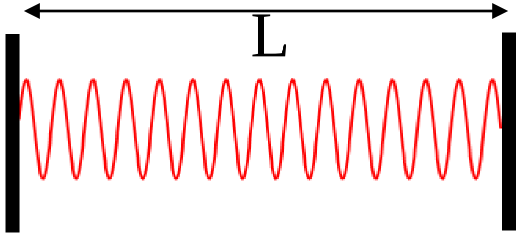
1974

Zavedení laserové čtečky čárových kódů

10-pack of Wrigley's chewing gum

LASER

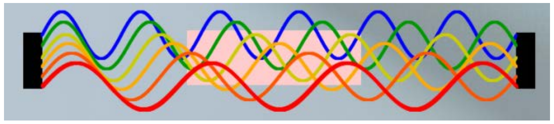




Přípustné vlny – mody
Dané okrajovou podmínkou na zrcadlech

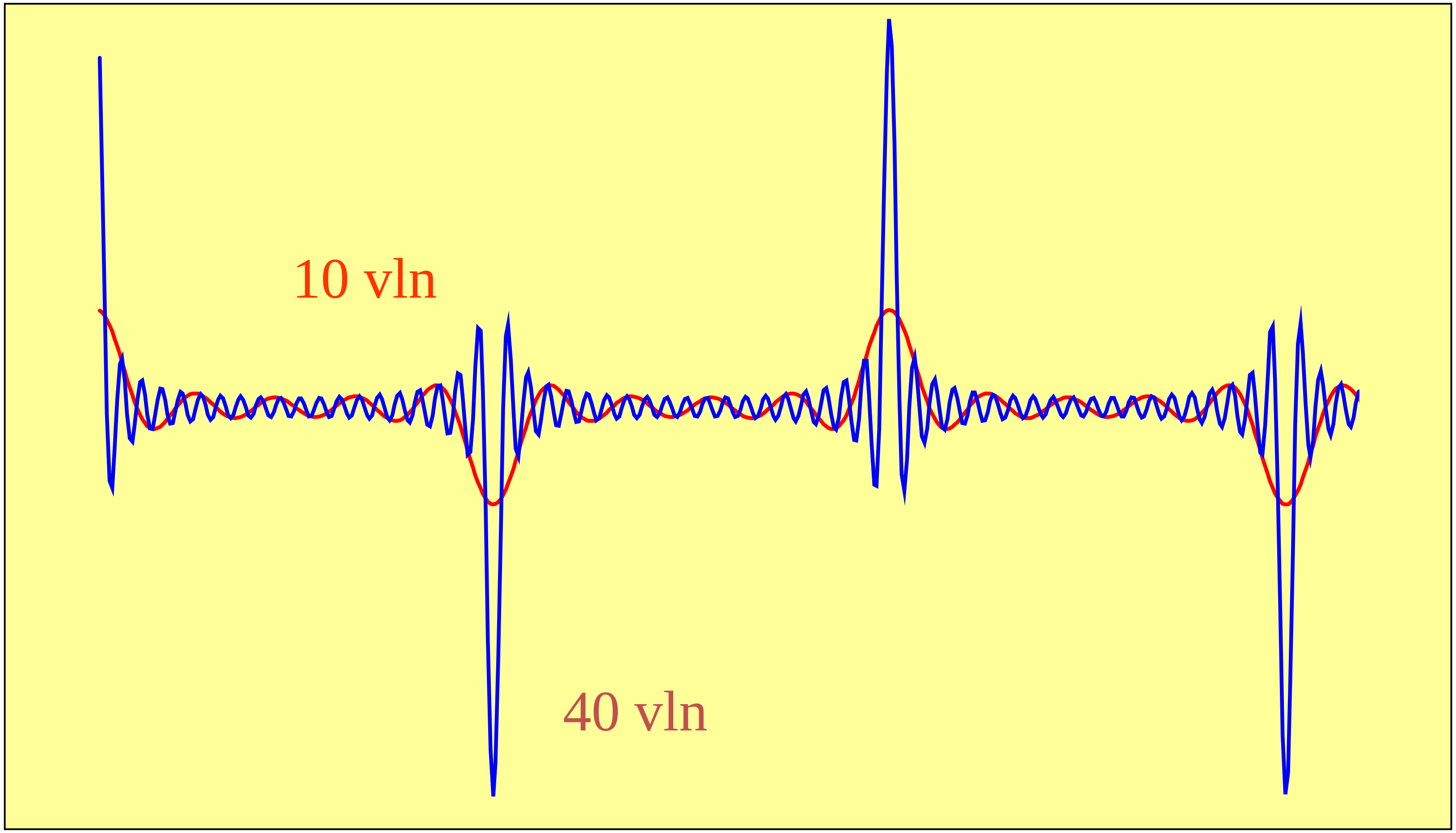
$$f_n = \frac{c}{\lambda} = n\frac{c}{2L}$$

$$L = n\frac{\lambda}{2}$$



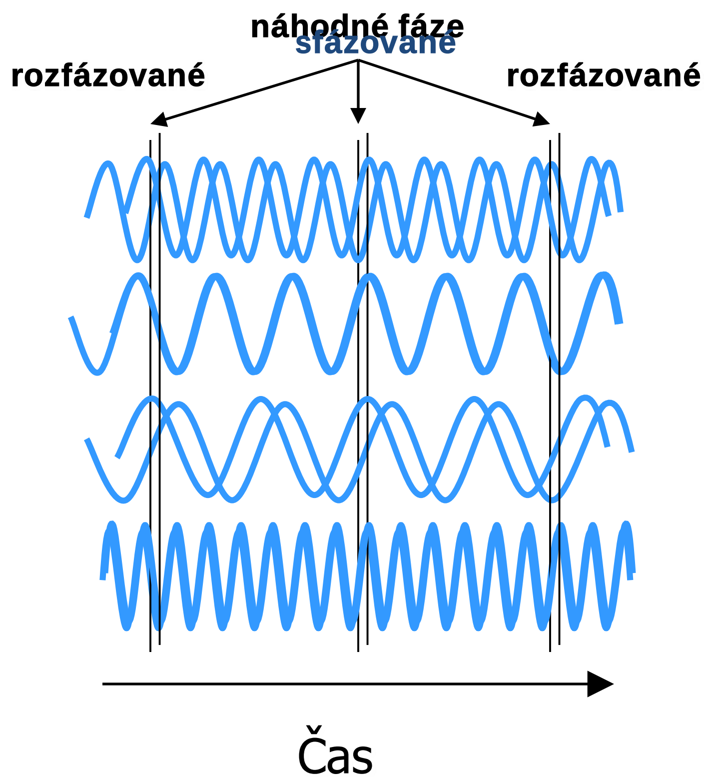
$$\Delta f = f_{n+1} - f_n = \frac{c}{2L} = \frac{1}{T_R}$$

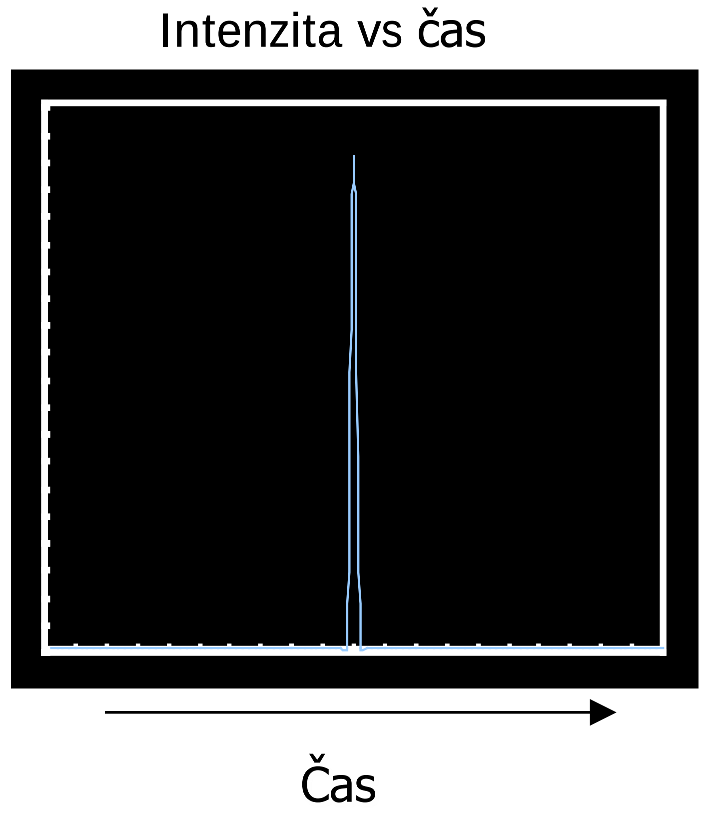
OBÁLKA



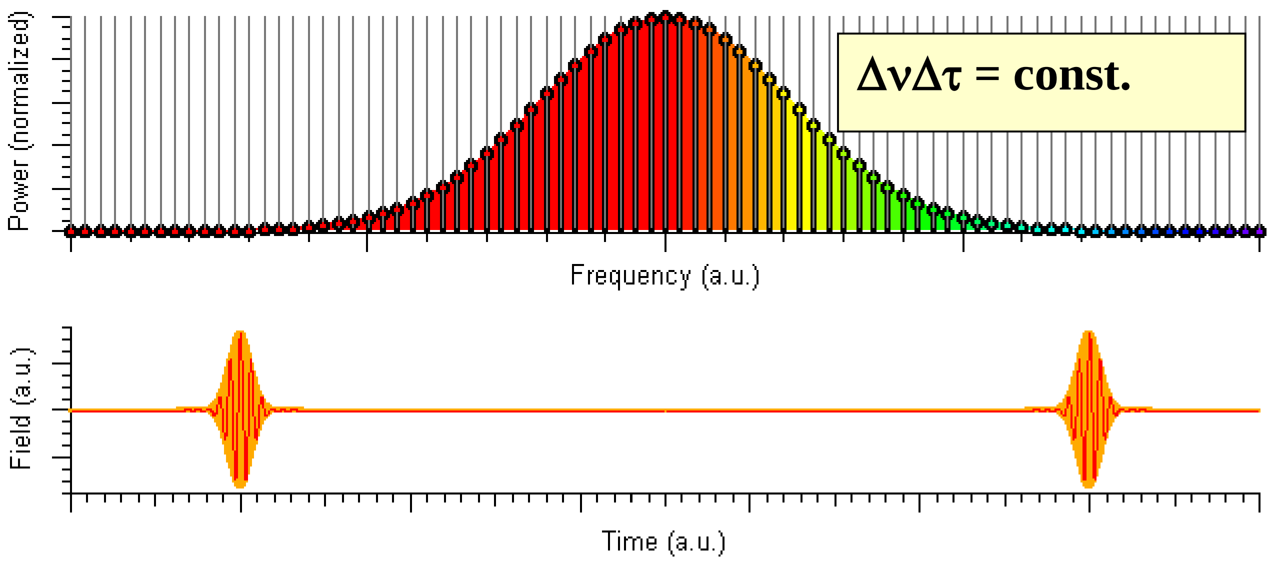
Synchornizované fáze pro všechny módy

Náhodné fáze módů

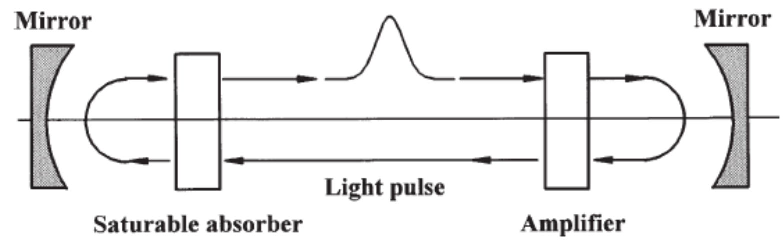




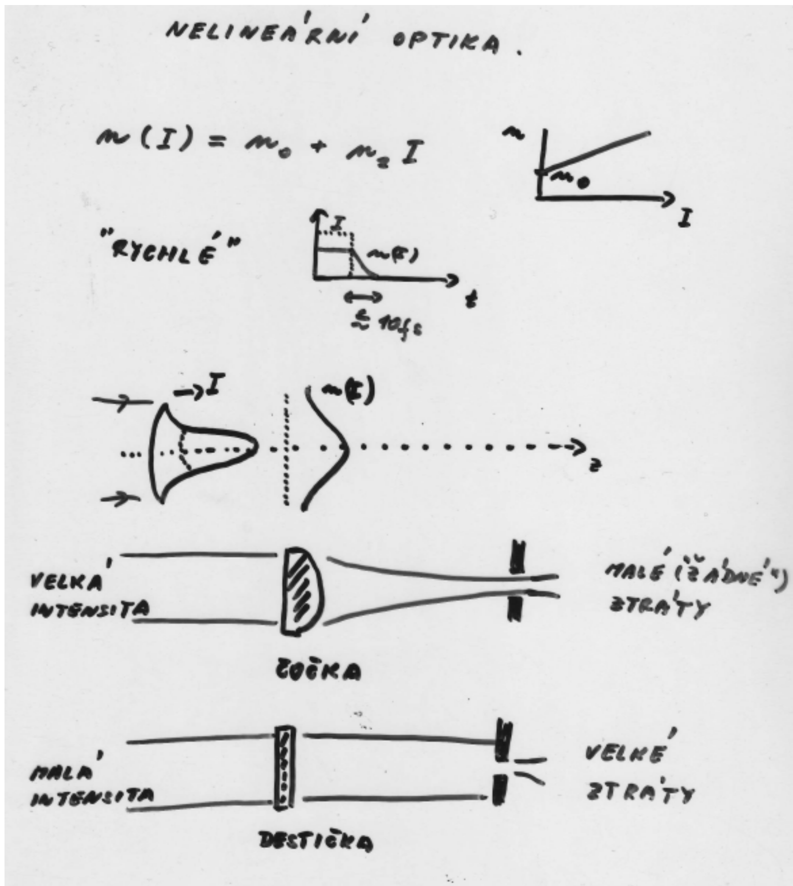
Time-width x spectral width

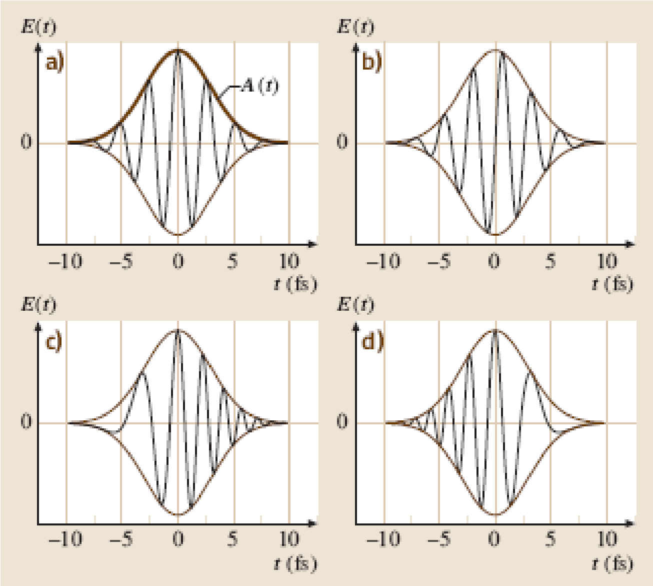


Pasivní módová synchronizace



Kerrovská synchronizace módů



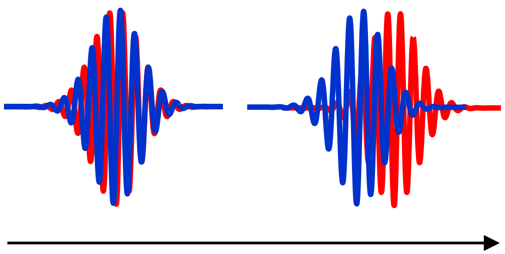


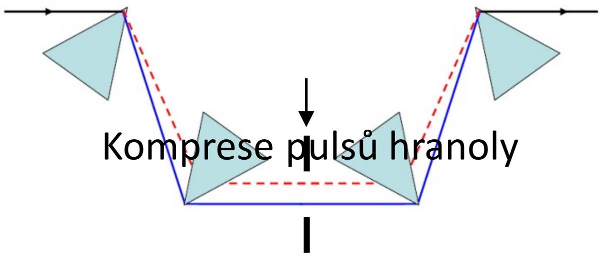
Optický puls

$$E(t) = A(t)\cos(\omega t + \varphi)$$

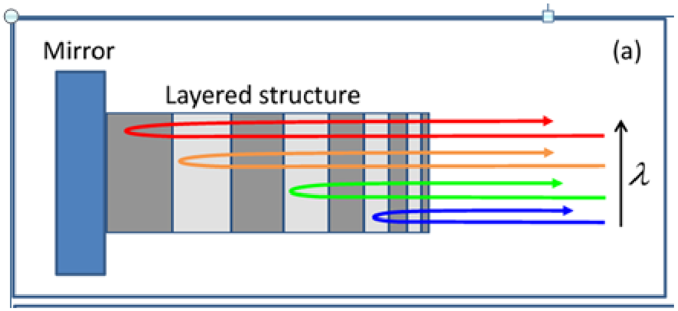
Pro femtosekundové pulsy další efekty: změny fáze při obězích v laseru

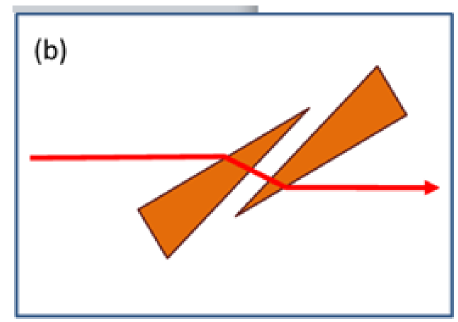
Nutná kompenzace





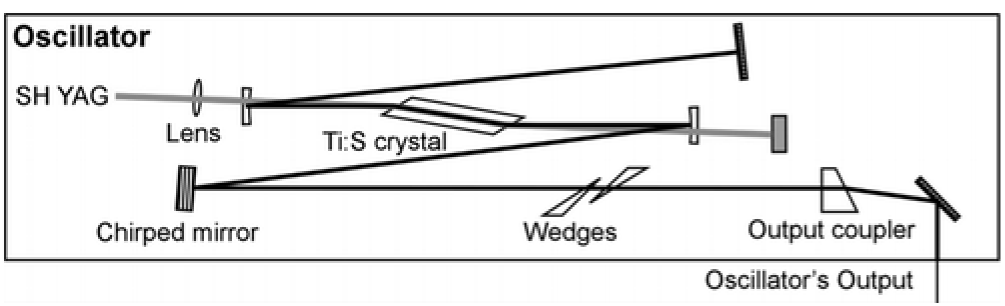
Komprese pulsů hranoly



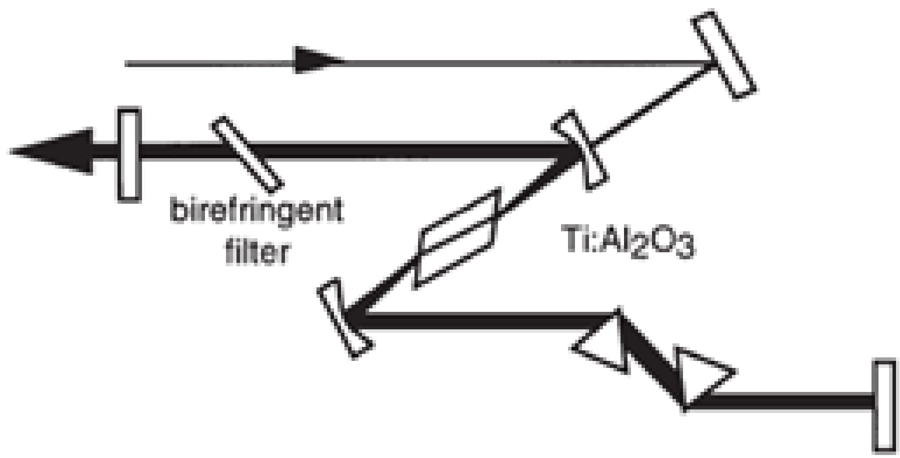


Tvarování (komprese) pulsů chirpovaným zrcadlem

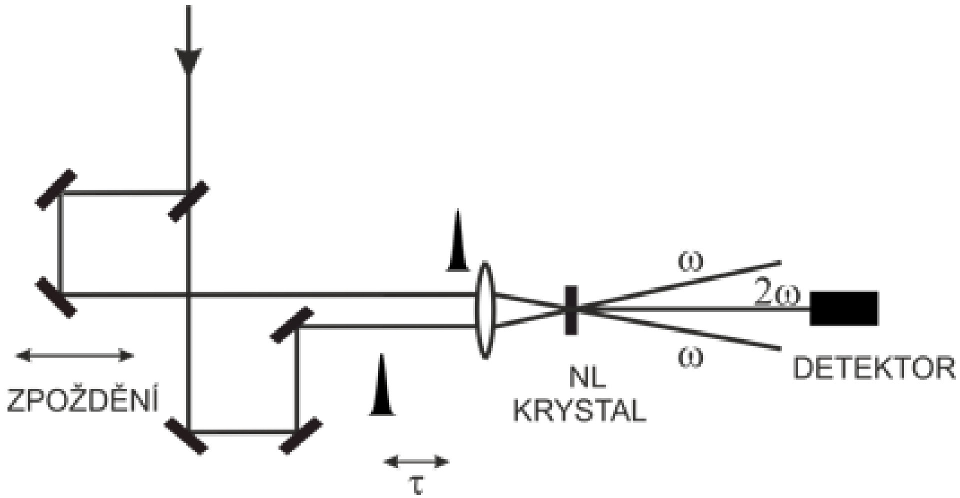
Tvarování pulsů chirpovaným zrcadlem



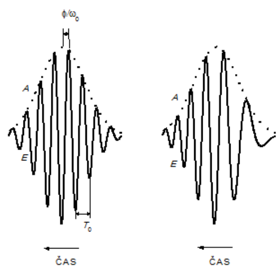
5 fs laser

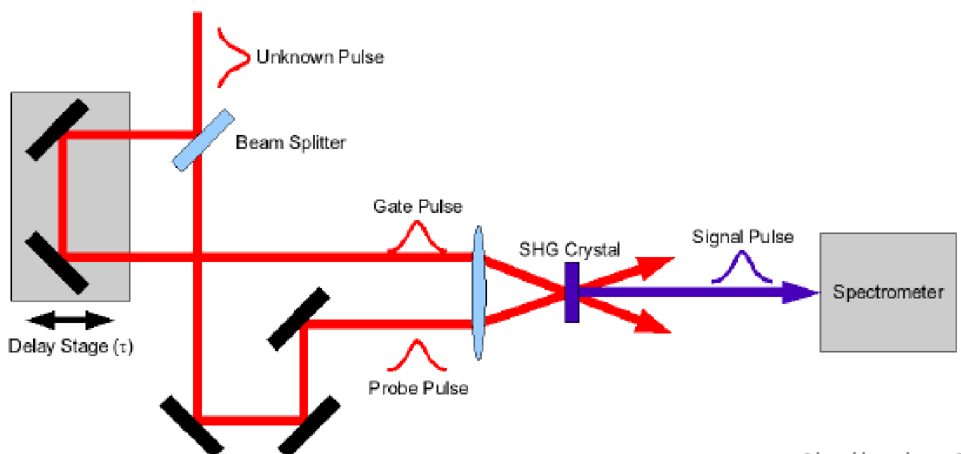


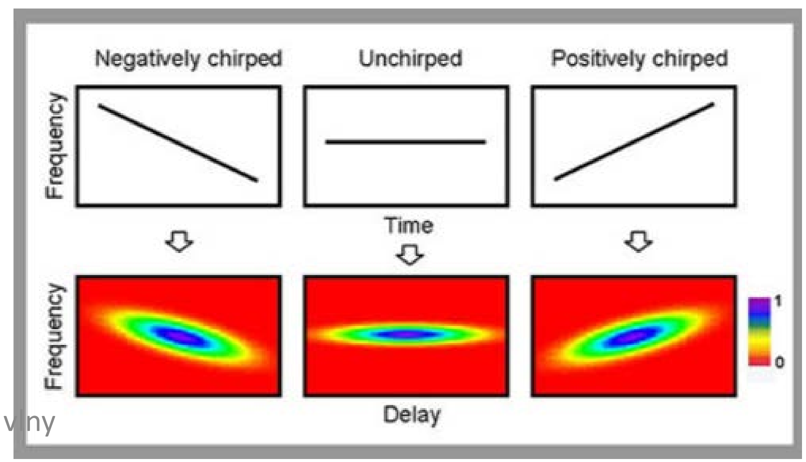
Femtosekundový laser – základní schéma



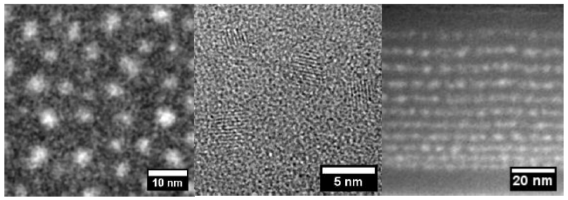
Obr. 4 Schéma korelačního měření časové délky světelných pulsů

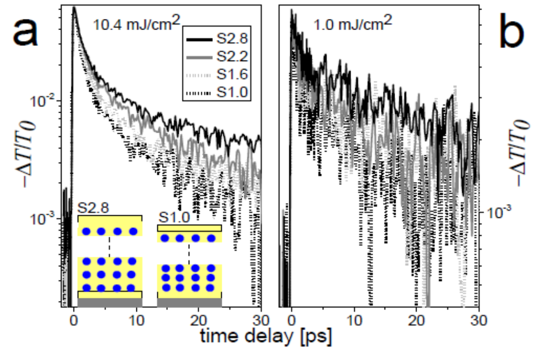


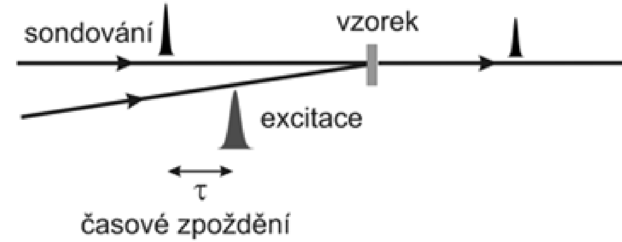




Ultrarychlá spektroskopie



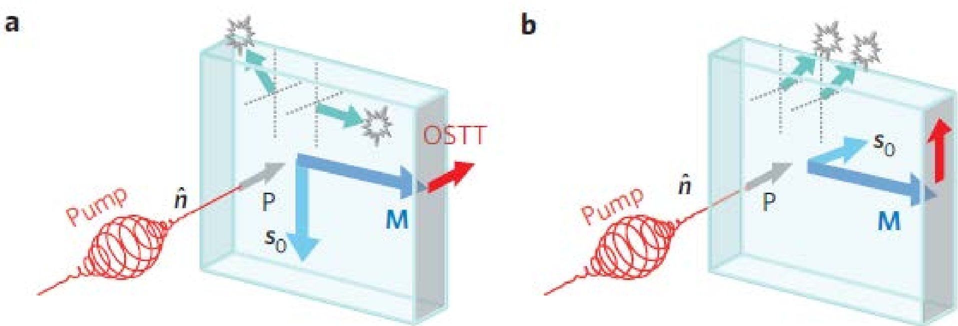




Metoda excitace a sondování

Nanokrystaly křemíku pro
fotovoltaiku (spolupráce s Freiburgem)

M. Kořínek, F. Trojánek, D. Hiller, S. Gutsch, M. Zacharias, C. Kübel, P. Malý: *Picosecond dynamics of photoexcited carriers in interacting silicon nanocrystals*, Appl. Surf. Sci. 377, 238 (2016).

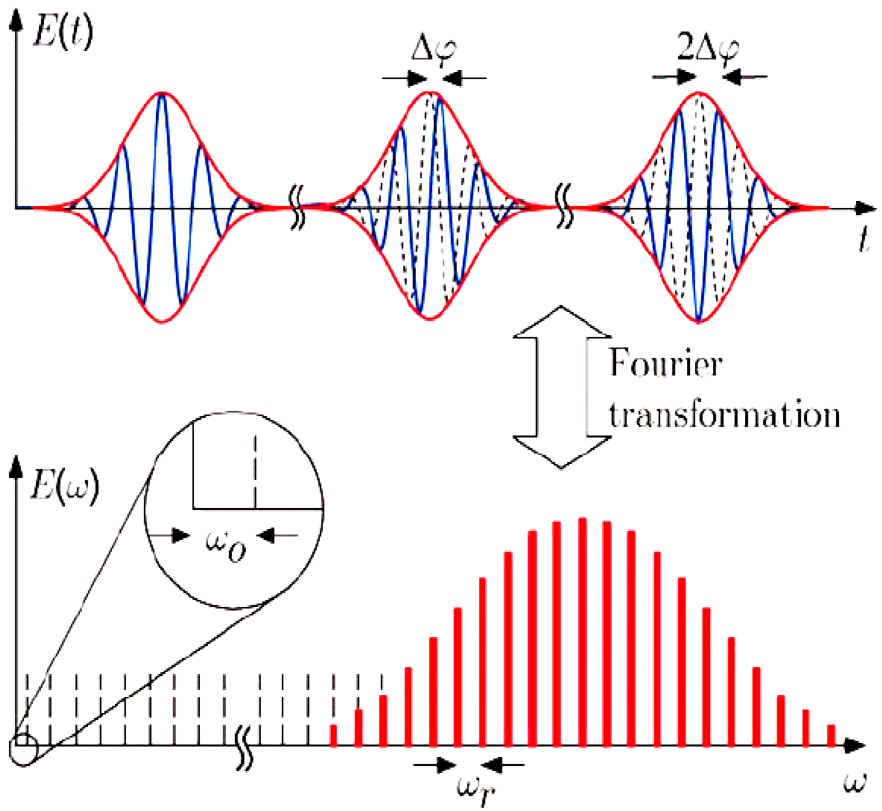


Opto-spintronika (spolupráce FzU AV ČR, Nottingham, Hitachi Cambridge)

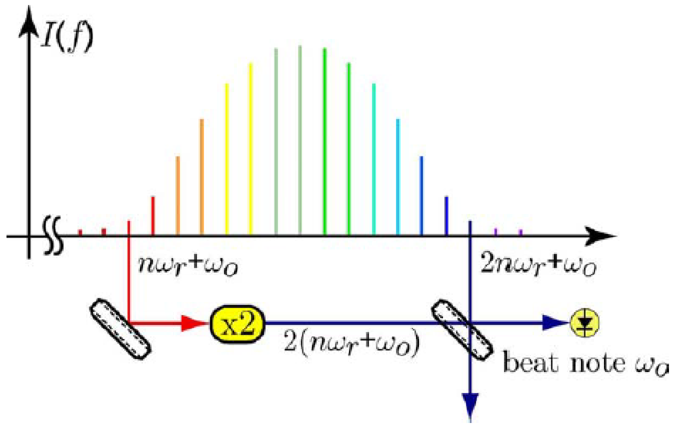
P. Němec, E. Rozkotová, N. Tesařová, F. Trojánek, E. De Ranieri, K. Olejník, J. Zemen, V. Novák, M. Cukr, P. Malý, T. Jungwirth, *Experimental observation of the optical spin transfer torque*, Nat. Phys. 8, 411-415 (2012).

Hřeben femtosekundových pulsů

Nobelova cena za fyziku 2005



Stabilizace fáze nosné vlny a obálky



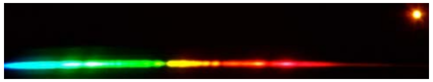
$$2 \cdot f_n - f_{2n} = 2(nf_r + f_o) - (2nf_r + f_o) = 2nf_r + 2f_o - 2nf_r - f_o = f_o$$

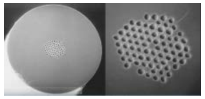
$$f_n = f_o + nf_r$$

Vysoké optické nelinearity

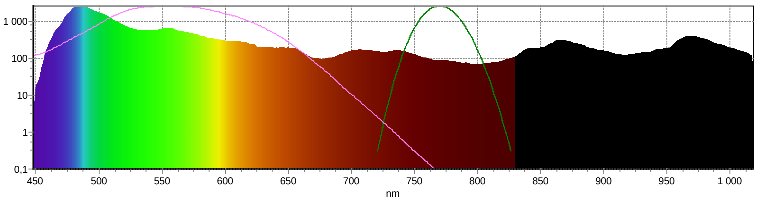
Fotonické vlákno

Generace femtosekundového kontinua



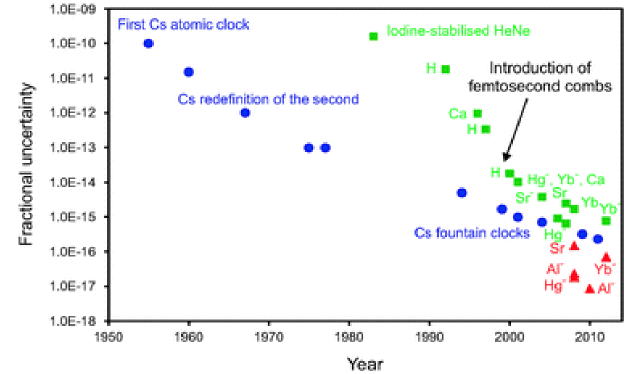


Zdvojování frekvence v nelineárním krystalu



Přesnost měření základní frekvence a 2. harmonické 2x 10^{-20}

Porovnání 2 hřebenů 10^{-20} relativní přesnost



Přesnost optických hodin lepší než atomových, během sekund …

Přesnost optických hodin v současnosti cca 1 s / dobu života Země

Synchronizace 2 optických hodin na 1000 km optickými vlákny

K. Predehl, G. Grosche, S.M.F. Raupach, S. Droste, O. Terra, J. Alnis, Th. Legero, T.W. Hänsch, Th. Udem, R. Holzwarth, and H. Schnatz
A 920 km Optical Fiber Link for Frequency Metrology at the 19th Decimal Place., *Science, 27 April 2012*

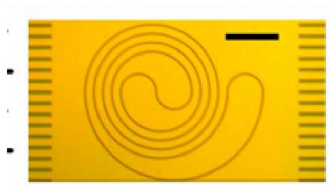
A broadband chip-scale optical frequency synthesizer at 2.7 × 10^{-16} relative uncertainty

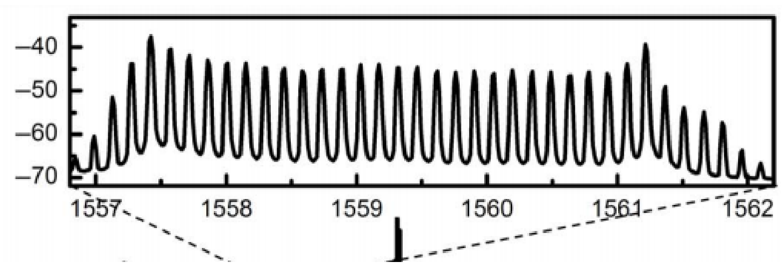
Shu-Wei Huang,[1]* Jinghui Yang,[1] Mingbin Yu,[2] Bart H. McGuyer,[3] Dim-Lee Kwong,[2] Tanya Zelevinsky,[3] Chee Wei Wong[1]*

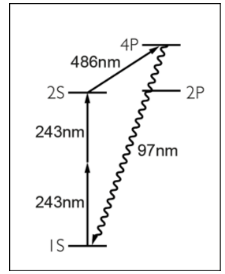
[1]Mesoscopic Optics and Quantum Electronics Labc
Angeles, CA 90095, USA. [2]Institute of Microelectro
ogy and Research (A*STAR), Singapore 117865, Si
Columbia University, New York, NY 10027, USA.

Huang *et al.* Sci. Adv. 2016;2:e1501489 22 April 2016

Scale bar, 250 µm.







Hydrogen 1S-2S frequency

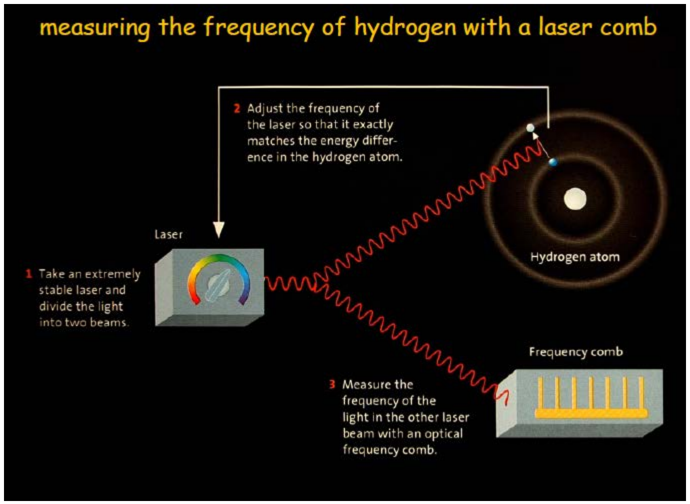
(F=1 to F'=1 hyperfine component)

Feb. 2003: f(1S-2S) = (2 466 061 102 474 851 ± 34) Hz
relative uncertainty: 1.4×10^{-14}

June 1999: f(1S-2S) = (2 466 061 102 474 870 ± 46) Hz
relative uncertainty: 1.9×10^{-14}

A difference of (-29 ± 57) Hz in 44 months equals a relative drift of the 1S-2S transition frequency of

$(3.2 \pm 6.3) \times 10^{-15}$ per year



T. Hansch, Nobel Lecture

PRL 102, 213002 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Measurement of the 2S Hyperfine Interval in Atomic Hydrogen

N. Kolachevsky,* A. Matveev,* J. Alnis, C. G. Parthey, S. G. Karshenboim,† and T. W. Hänsch
Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
(Received 3 February 2009; published 28 May 2009)

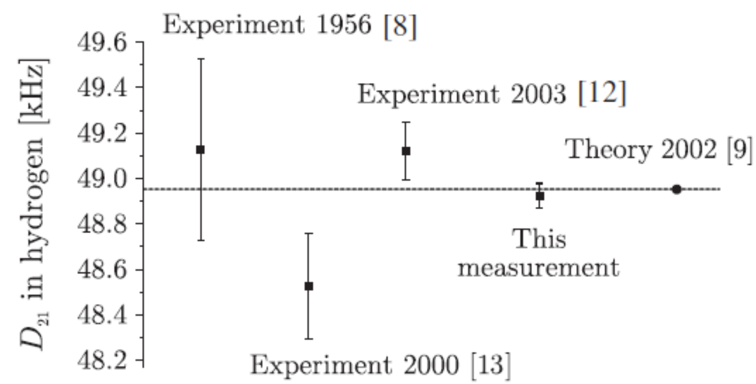
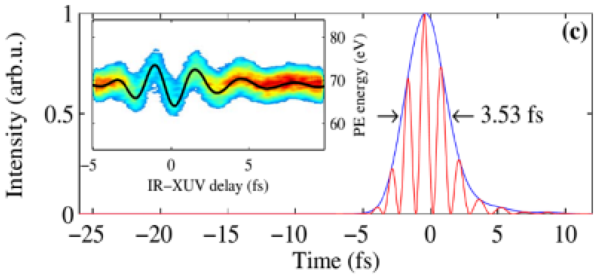


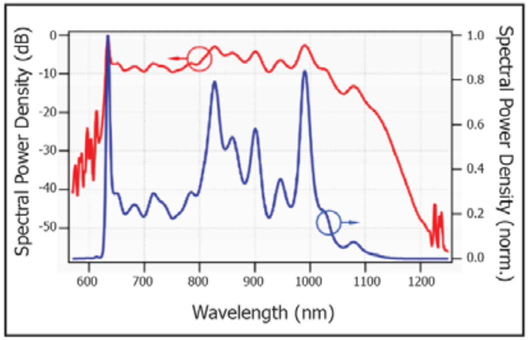
FIG. 4. Experimental and theoretical values for the $D_{21} = 8f_{HFS}(2S) - f_{HFS}(1S)$ difference in atomic hydrogen.

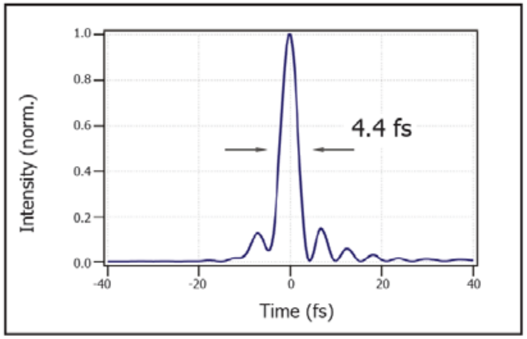
Laser s několika kmity elektrického pole



A pulse measurement by attosecond streaking confirms the pulse duration of 3.53 fs (1.5 cycles).

Okell, William A., Tobias Witting, Davide Fabris, Dane Austin, Maimouna Bocoum, Felix Frank, Aurelien Ricci, et al. Optics Letters 38, no. 19 (October 1, 2013): 3918–21.





Emise elektronů

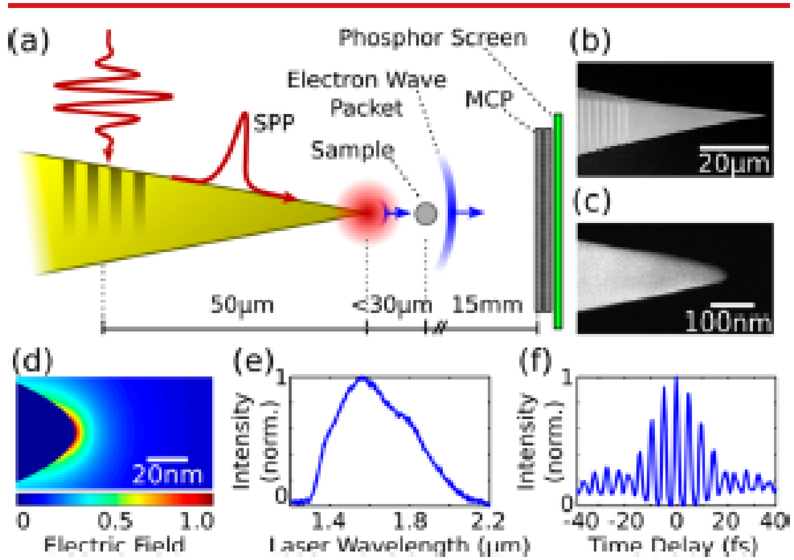


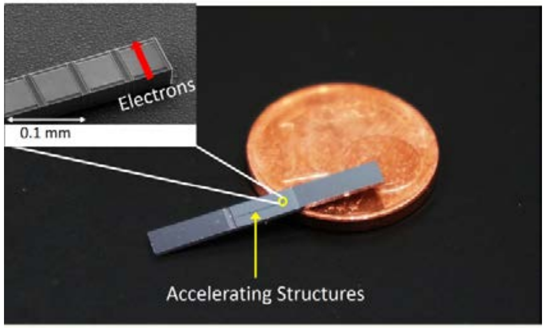
Figure 1. (a) Schematic of the setup for remotely driven electron emission. Few-cycle near-infrared light pulses are grating-coupled to a chemically etched gold taper. The launched SPP wavepacket propagates along the taper shaft and is nanofocused at the apex. The resulting strong field concentration leads to plasmon-induced electron emission. Electrons are detected in a point-projection setup using a microchannel plate equipped with a phosphor screen. (b) Scanning electron microscope image of a chemically etched gold taper. The grating coupler is fabricated by ion-beam milling. (c) Zoom of the apex region with a radius of curvature of 12 nm. (d) Simulated electric near-field distribution with a decay length of 8 nm. (e) Intensity spectrum and (f) interferometric autocorrelation function of the 16 fs

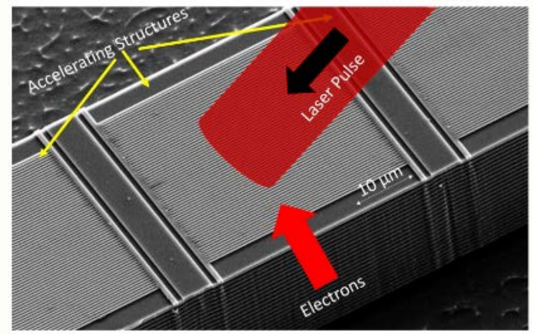
NANO LETTERS
Letter
pubs.acs.org/NanoLett

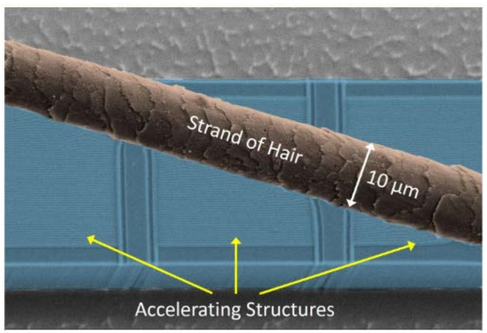
Ultrafast Electron Emission from a Sharp Metal Nanotaper Driven by Adiabatic Nanofocusing of Surface Plasmons

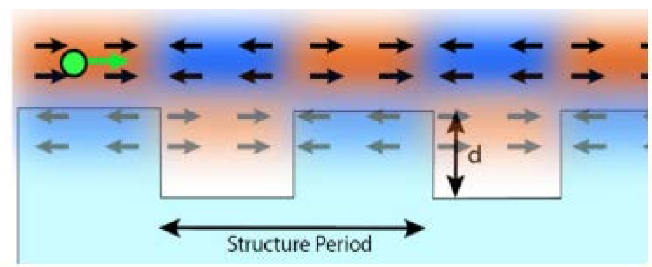
Jan Vogelsang,[†,‡] Jörg Robin,[†,‡] Benedek J. Nagy,[§,∥] Péter Dombi,[§] Daniel Rosenkranz,[†] Manuela Schiek,[†] Petra Groß,[*,†,‡] and Christoph Lienau[*,†,‡]

Urychlování elektronů







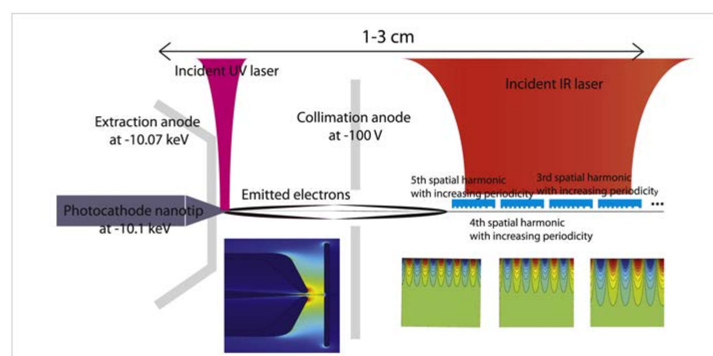


MeV electrons

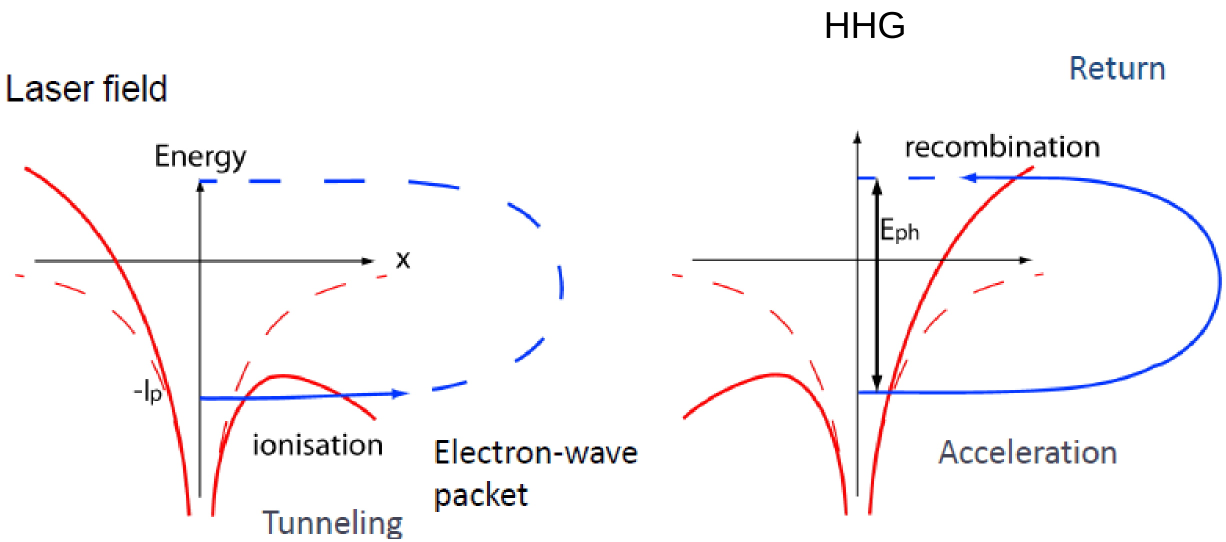
A miniaturized electron source based on dielectric laser accelerator operation at higher spatial harmonics and a nanotip photoemitter

Joshua McNeur[1], Martin Kozak[1], Dominik Ehberger[1,4], Norbert Schönenberger[1], Alexander Tafel[1], Ang Li[1] and Peter Hommelhoff[2,3]

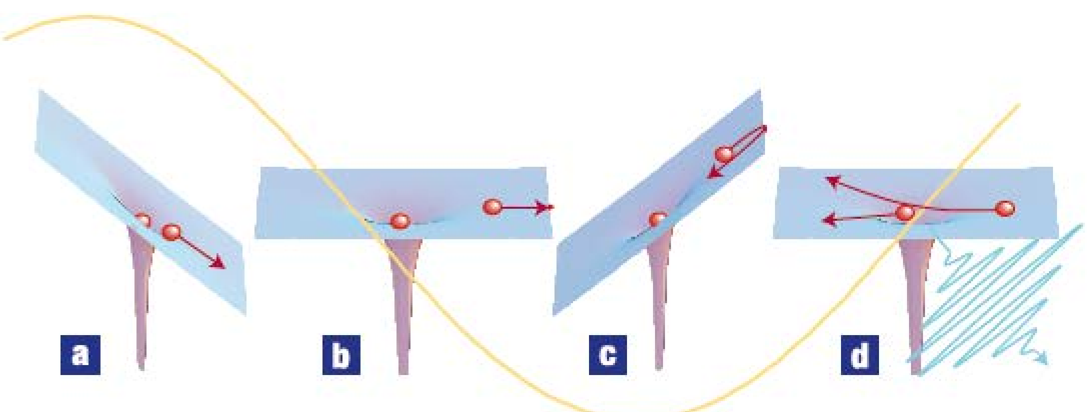
Published 21 January 2016 • © 2016 IOP Publishing Ltd
Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 49, Number 3



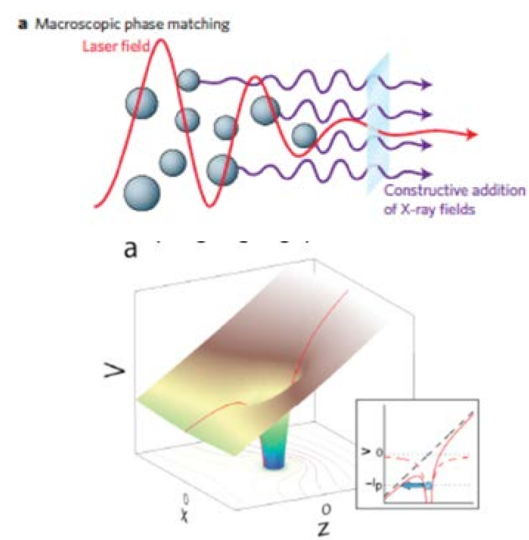
Generace attosekundových pulsů



P. Corkum, PRL, 1993

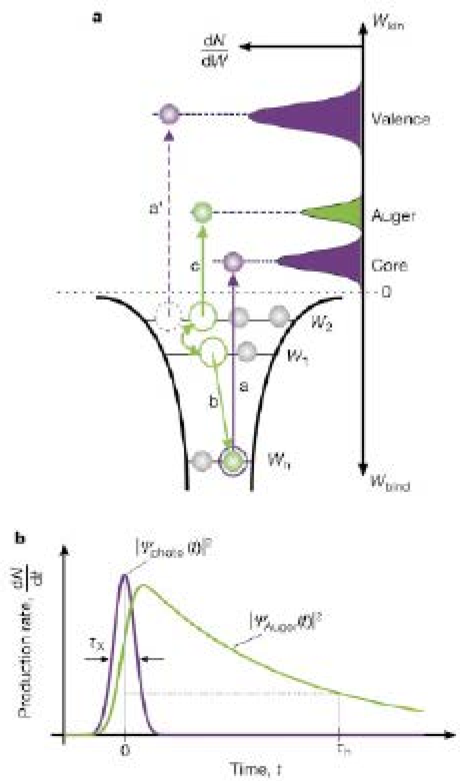


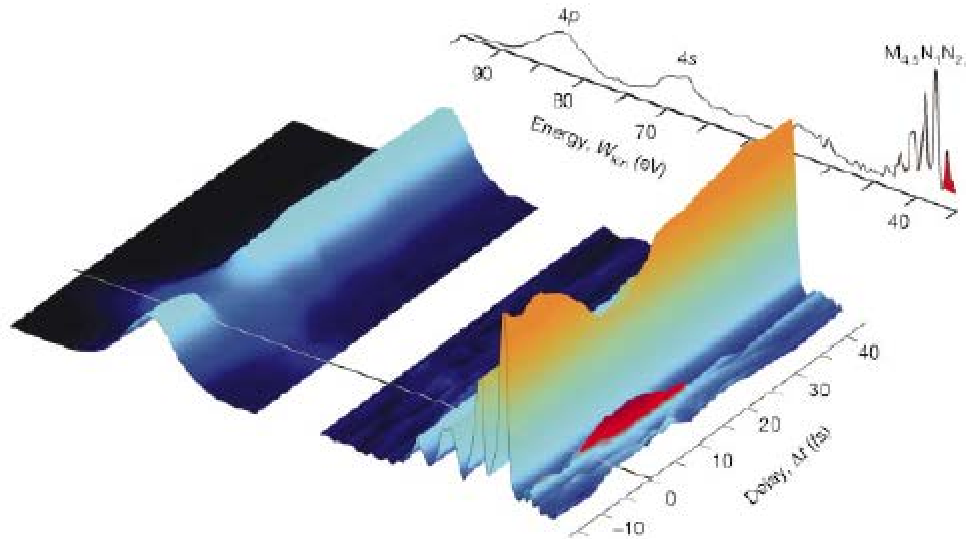
Phase matching



A. N. Pfeiffer *et al.*, *Nat. Phys.* **8**, 76 (2012)

Spektroskopie vnitřních stavů atomu





Time domain measurement of the M-shell vacancy lifetime in krypton: 7.9 fs

M. Drescher *et al.*, *Nature* **419**, 803 (2002)

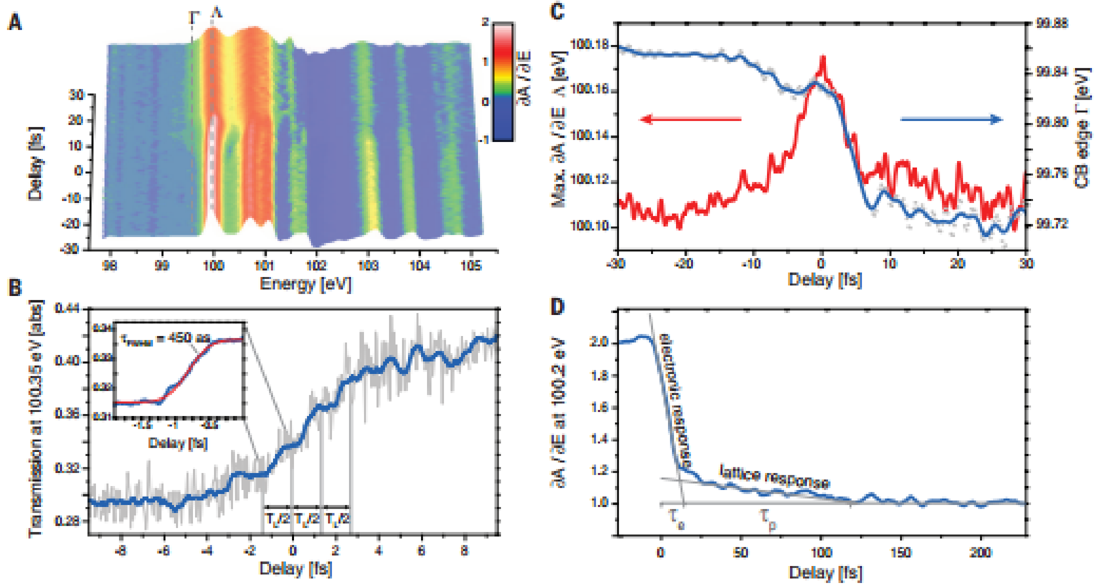


Fig. 2. Attosecond transient absorption spectroscopy of silicon. (A) The injection of electrons into conduction band states of silicon by a few-cycle near-infrared laser pump-pulse modifies the derivative of the XUV-absorbance $\partial A/\partial E$ plotted as a function of probe-photon energy E_{XUV} and time delay Δt between pump and probe pulse. The color scale represents the value of $\partial A/\partial E$. **(B)** A close-up of the temporal evolution of the XUV-transmission T (= 10^{-A}) at 100.35 eV reveals the increase of the signal amplitude in sharp steps synchronized with the laser electric field oscillations (also see Fig. 3B). The inset shows a fit to evaluate the step rise time. The blue line is a rolling average of the raw signal depicted in gray. **(C)** The position in energy of the first peak of the derivative [marked Λ in (A)] is plotted (red), along with the energy of the L-edge onset (marked Γ) evaluated at $\partial A/\partial E$ = 0.2 (blue). **(D)** tracks the amplitude of $\partial A/\partial E$ at 100.2 eV, the position of the maximum $\partial A/\partial E$ before excitation. The straight lines indicate the different time scales over which electronic (τ_e) and nuclear (τ_p) dynamics occur.

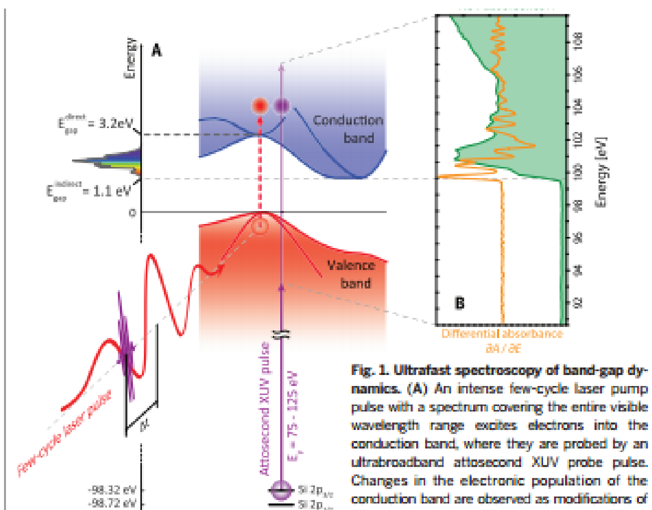


Fig. 1. Ultrafast spectroscopy of band-gap dynamics. (A) An intense few-cycle laser pump pulse with a spectrum covering the entire visible wavelength range excites electrons into the conduction band, where they are probed by an ultrabroadband attosecond XUV probe pulse. Changes in the electronic population of the conduction band are observed as modifications of the silicon L-edge absorbance A and its derivative $\partial A/\partial E$ **(B)**. By varying the time delay Δt between the two pulses, dynamic changes to the L-edge spectrum can be tracked and translated into the evolution of the conduction band population.

Attosecond band-gap dynamics in silicon

Martin Schultze[1,2,*,†], Krupa Ramasesha[1,*], C.D. Pemmaraju[3], S.A. Sato[4], D. Whitmore[1], A. Gandman[1], James S. Prell[1], L. J. Borja[1], D. Prendergast[3], K. Yabana[4,5], Daniel M. Neumark[1,6,†], Stephen R. Leone[1,6,7,†]

Science 12 Dec 2014:
Vol. 346, Issue 6215, pp. 1348-1352

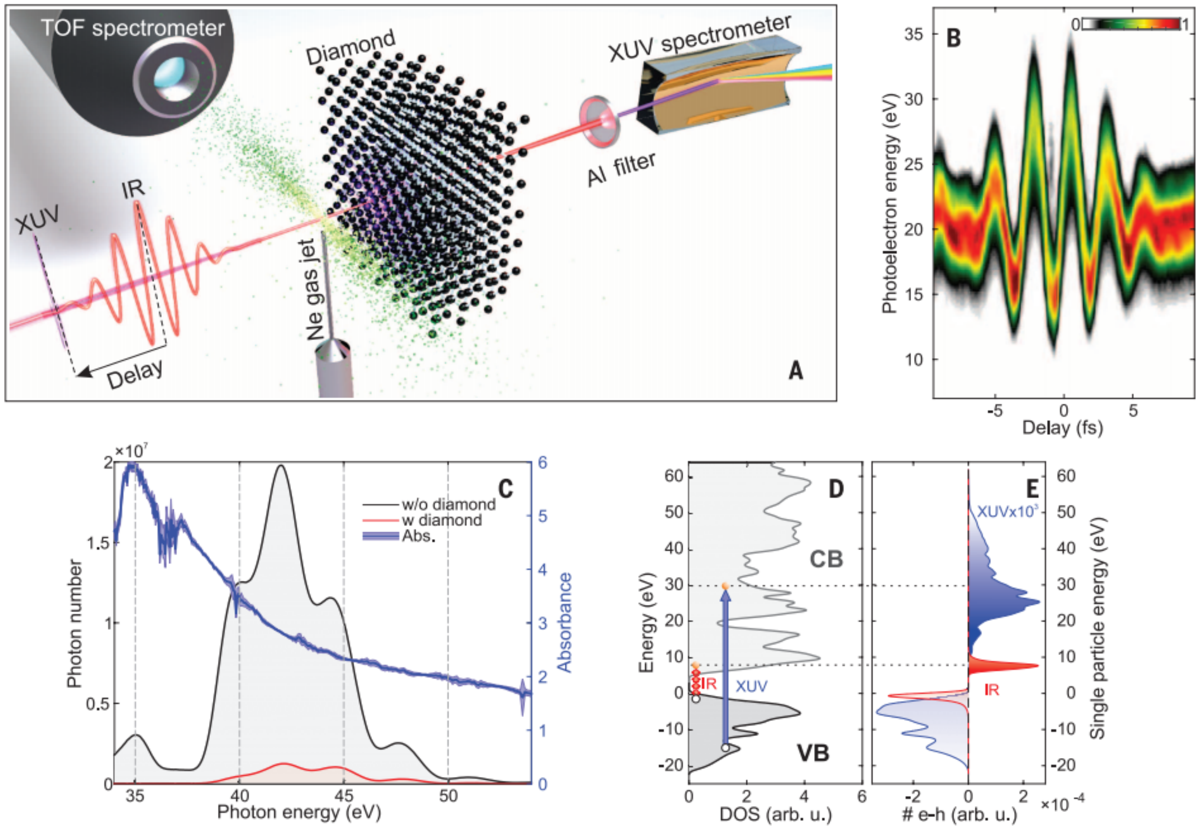


Fig. 1. Pulse and sample characterization. (**A**) Schematic of the experimental setup with the double-target for simultaneous detection of photons and electrons. (**B**) Example of a typical streaking trace used to characterize the single attosecond pulses (SAPs) and calibrate the pump-probe delay axis in a transient absorption measurement. (**C**) Spectrum of the SAP without (black line) and with (red line) transmission through a 50-nm polycrystalline diamond sample. The static absorbance measured with a broad harmonic spectrum (*27*) is shown in blue. The shaded light-blue area defines the statistical error bars assuming a Poisson distribution for the number of collected photons. (**D**) Density of states (DOS) of diamond calculated with density functional theory. The black and gray curves are the valence band (VB) and conduction band (CB), respectively. The zero of the energy axis coincides with top of the VB. (**E**) Number of electron-hole particles created by the XUV probe and the IR pump in blue and red, respectively.

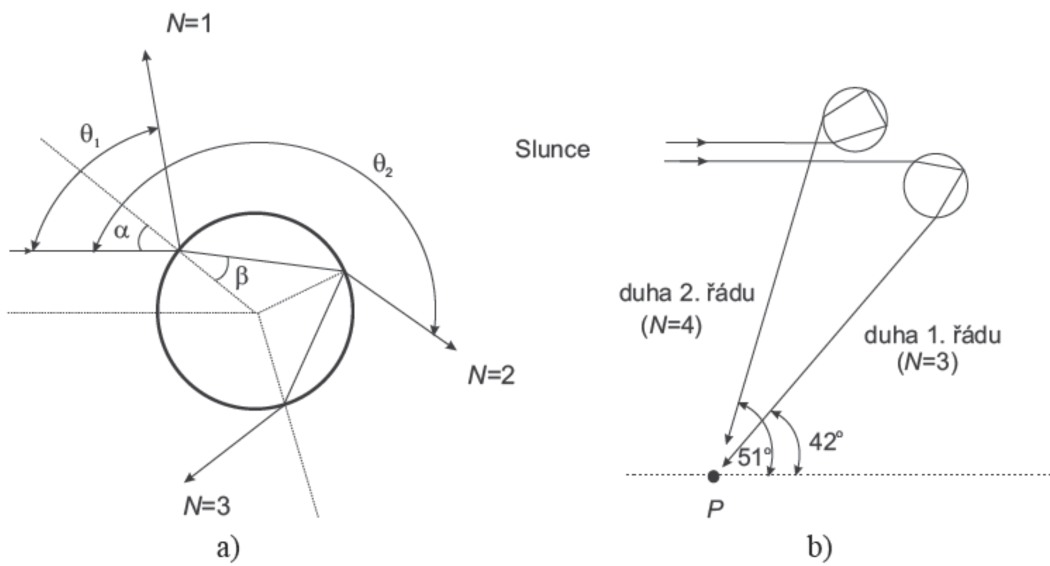
SCIENCE 26 AUGUST 2016 • VOL 353 ISSUE 6302

Attosecond dynamical Franz-Keldysh effect in polycrystalline diamond

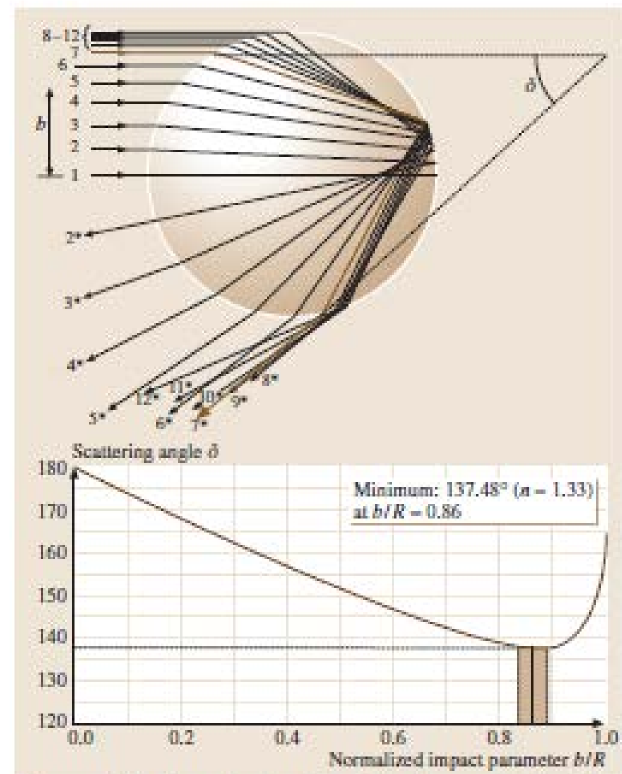
M. Lucchini,[1*] S. A. Sato,[2] A. Ludwig,[1] J. Herrmann,[1] M. Volkov,[1] L. Kasmi,[1]
Y. Shinohara,[3] K. Yabana,[2] L. Gallmann,[1,4] U. Keller[1]

Duha

Duha



Obr. 10.39 Vznik duhy: a) lom paprsku v kulové kapce, b) vznik duhy 1. a 2. řádu



$$\theta_N = 2\alpha + (N-1)(180^\circ - 2\beta).$$

$$\frac{d\theta_N}{d\alpha} = 0$$

$$\sin\alpha = n\sin\beta, \text{ tj. } \frac{d\beta}{d\alpha} = \frac{1}{n}\frac{\cos\alpha}{\cos\beta}$$

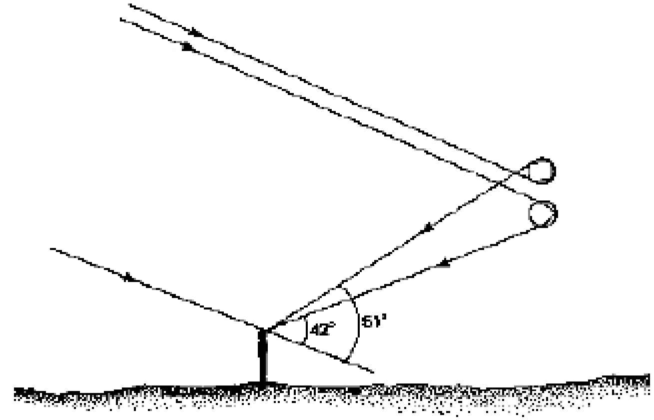
$$\cos\beta = (N-1)\frac{1}{n}\cos\alpha$$

$$\cos^2\alpha = \frac{n^2-1}{(N-1)^2-1}$$

Pro index lomu vody $n = 1{,}3324$

$\theta_3 = 318°$, $\theta_4 = 411°$, atd.

$(360° - \theta_{Nd})$, tj. 42° a sekundární dı hy –51°.



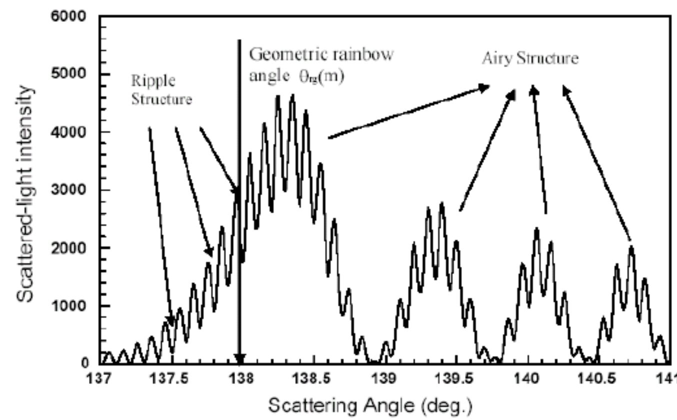


Figure 1-2 A first rainbow simulated by the Lorenz-Mie theory (m=*1.3324*, d=*600μm*, λ=*0.6328 μm*)

Děkuji za pozornost