3. Photonics

F3370

Repetition from the last lecture

- Optical imaging methods
  - What determines the Rayleigh criterion?
  - What is Laser Confocal Microscopy used for?
  - What is the purpose of the Dynamic light scattering?

- Electron imaging methods
  - What do SEM and TEM mean?
  - What is the typical resolution of SEM and TEM?
  - Describe different types of SEM imaging?

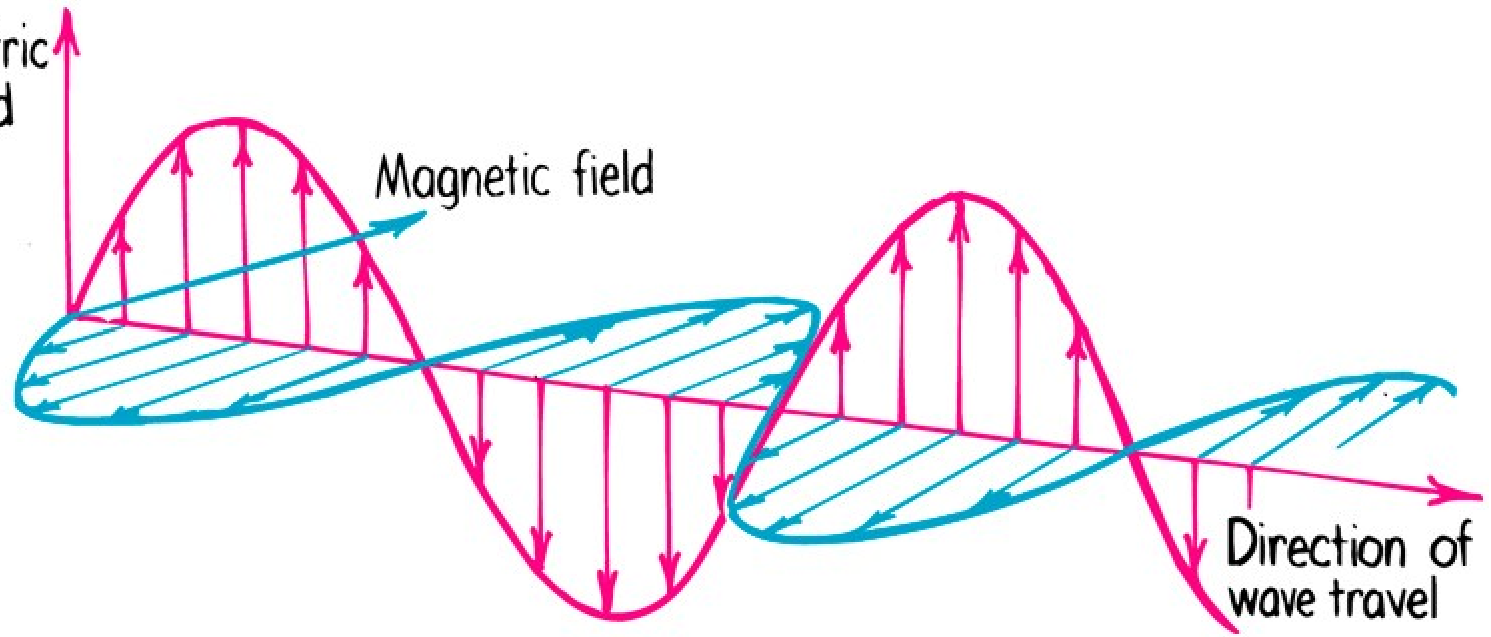
Repetition from the Last Lecture 2

- Probe force measurement
  - What do STM and AFM stand for?
  - What samples are suitable for STM?
  - What is the resolution of STM and AFM?

- Photon (spectroscopic) methods
  - What quantity is the XPS measurement based on?

- Ion-particle methods
  - The ratio of which quantities is measured in mass spectroscopy?

Light as an Electromagnetic Wave



- Light is an electromagnetic wave caused by the accelerated motion of an electric charge (typically an electron), and this electromagnetic wave can affect the motion of the electric charge in the medium through which it passes.
- The speed of light $c = 3 \cdot 10^8$ ms^{-1}

http://biggiephysicsquestionproject.weebly.com/background-science-what-is-light.html

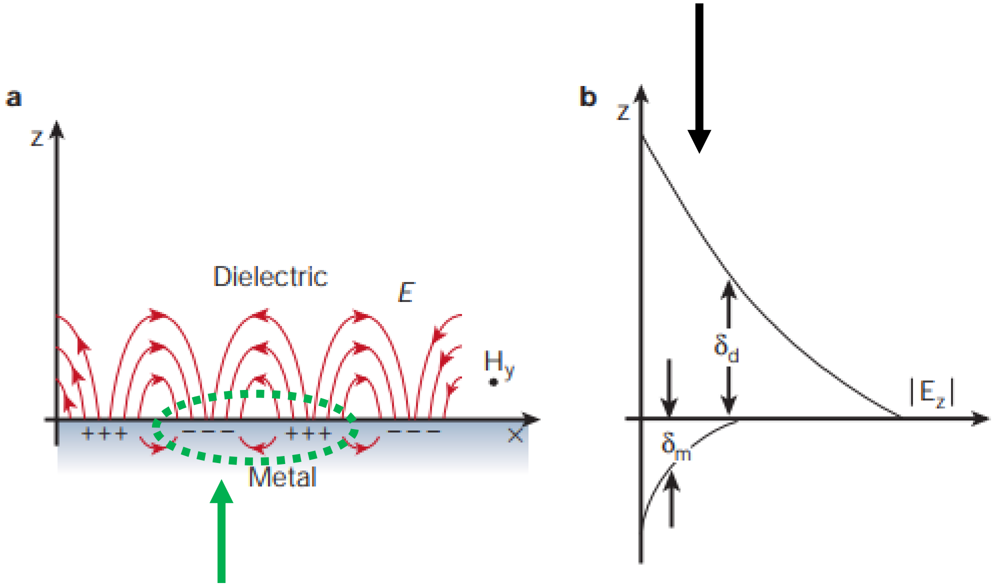
Light as a Photon

- In quantum mechanics, light is quantized and is transmitted by massless particles called photons
- The photon energy E = hν, where h is the Planck constant $6{,}6 \cdot 10^{-34}$ Js and ν is the frequency of the radiation (in Hz)
- Momentum of mass and massless particles :
  - Photon: λ = c/f = h/p
  - Electron: λ_{dB} = h/p = h/mv
- Photonics - describes the interaction of light and matter (containing charged particles) at the quantum level. Nanophotonics describes phenomena on structures below the diffraction limit of light (~ λ/2).

Plasmonics

- Surface plasmon (SP) - collective oscillation of 2D electron gas ("plasma") at the metal-dielectric interface
- SP is formed when the electrical intensity of the EM wave is perpendicular to the surface of the dielectric
- The intensity of the E field perpendicular to the surface of the dielectic in both directions is evanescent (exponentially damped) - the field is localized at the interface and does not propagate to the surroundings
- In a dielectric the penetration depth is ~ $\lambda/2$, in a metal it depends on the skin effect ~ 10 nm

There are no free electrons in the dielectric, the motion of SP is less damped than the motion of bulk P



Polariton – coupled oscillation between EM wave and electric dipoles in the condensed matter

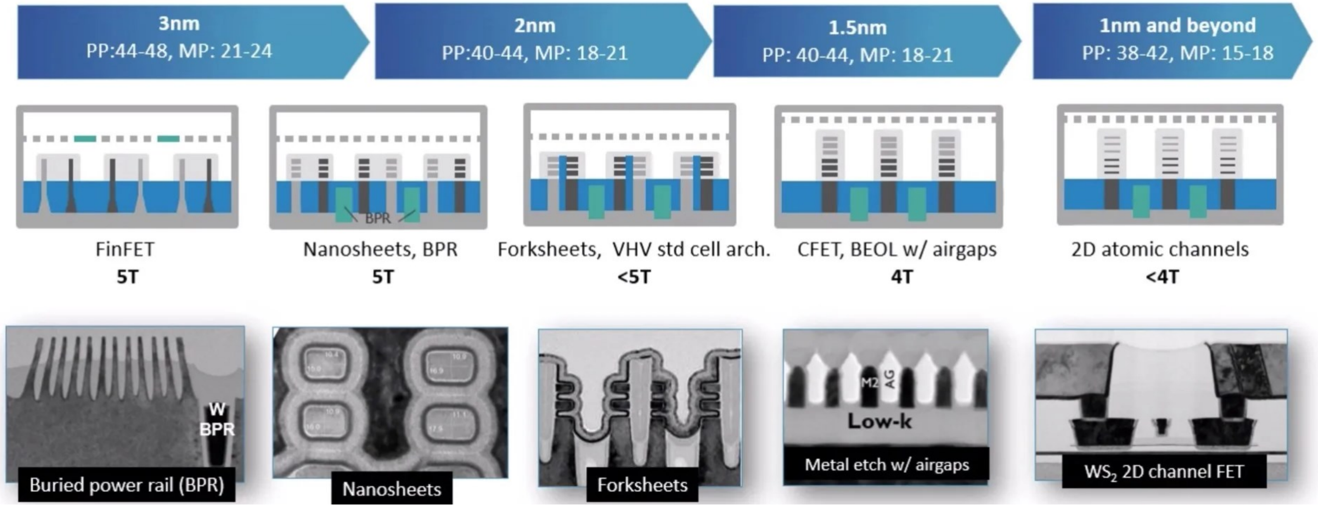
WL. Barnes, A. Dereux, TW. Ebbesen, Surface plasmon subwavelength optics, Nature 424, 2003

Use of the Surface Plasmon

- Using SP, we "glued" the light wave to the surface of the metal. The minimum dimensions of the metal structure are orders of magnitude smaller (~10 nm) than the wavelength of the radiation.
- The plasmon energy is transferred without the electrons having to physically travel through the path – less heat loss and faster signal transmission – applications in micro- and nano-electronics

Traditional Chips

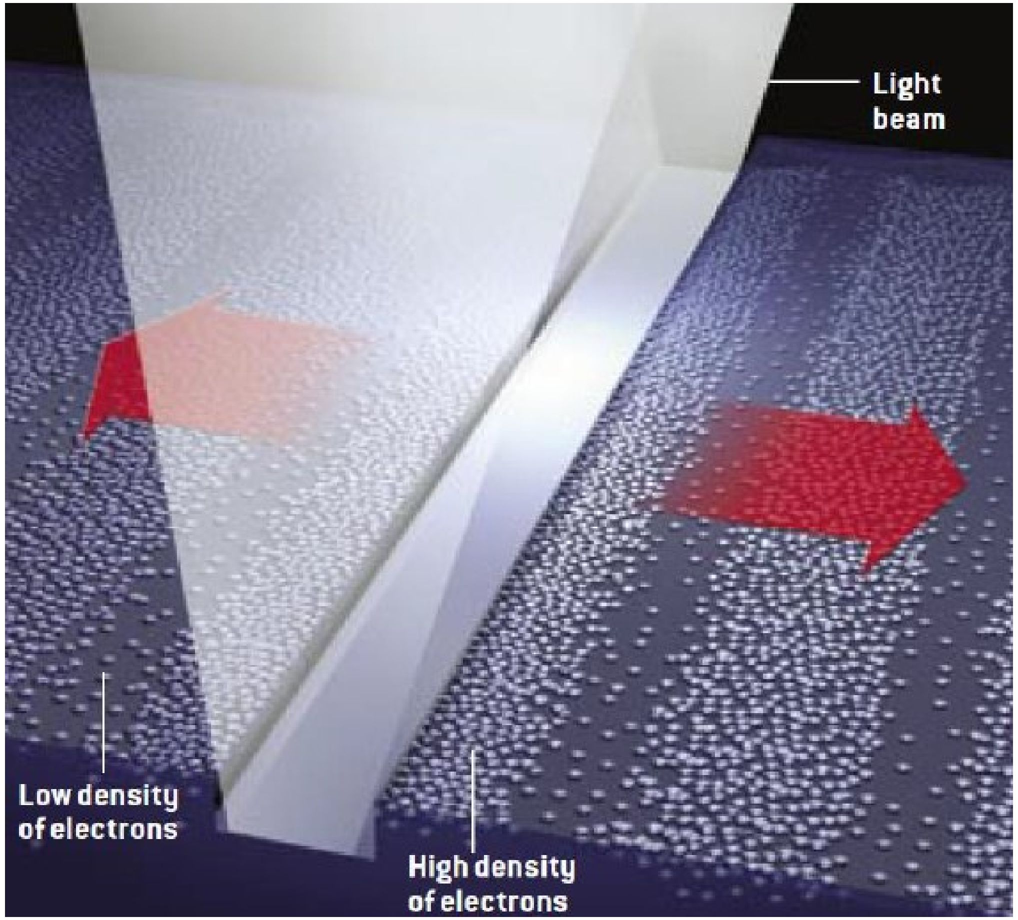
- Current computer chips have structures at the 10 nm level, and they are getting smaller
- It is not possible to significantly increase their frequency further - signal transmission on the order of centimetres by moving electrons in a metallic conductor is no longer sufficient, as very strong damping occurs above GHz
- Optical fibres allow THz transmission, but the dimensions of individual transistors are well below the diffraction limit of light (λ = 300 - 2000 nm)



https://semiengineering.com/imecs-plan-for-continued-scaling/

Plasmonic Chips

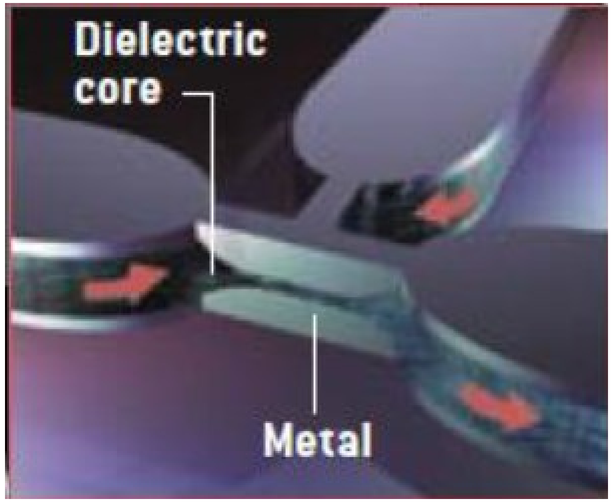
- Formation of SP for example by illuminating a narrow groove in a metalic surface.
- Plasmon can pass several cm in this way (sufficient for a computer processor)
- For real applications, it is necessary to reduce its area and guide it with plasmon waveguides.

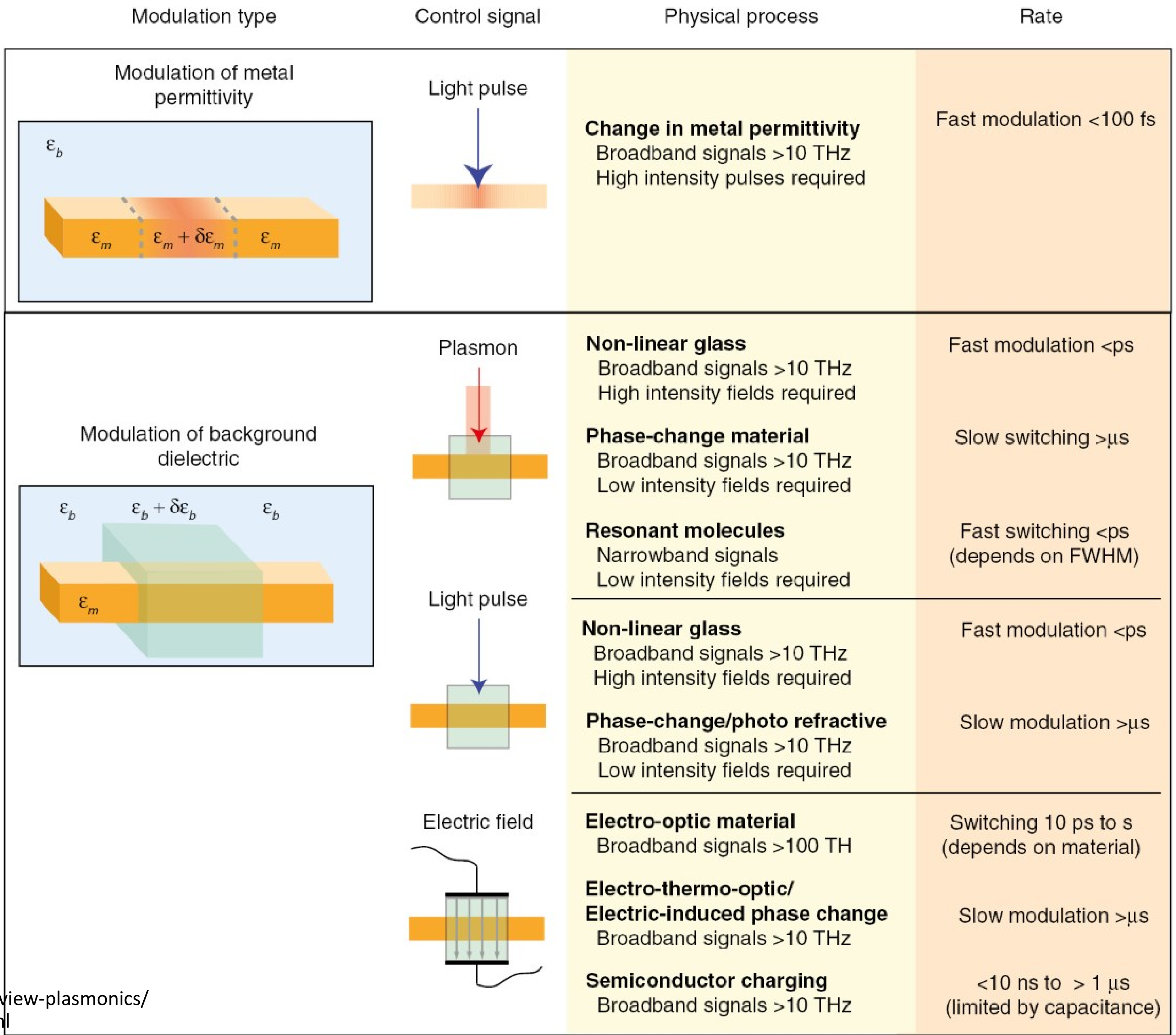


https://www.scientificamerican.com/article/the-promise-of-plasmonics-overview-plasmonics/

Plasmonic Waveguides

- The signal can be conducted and modulated in optical frequencies

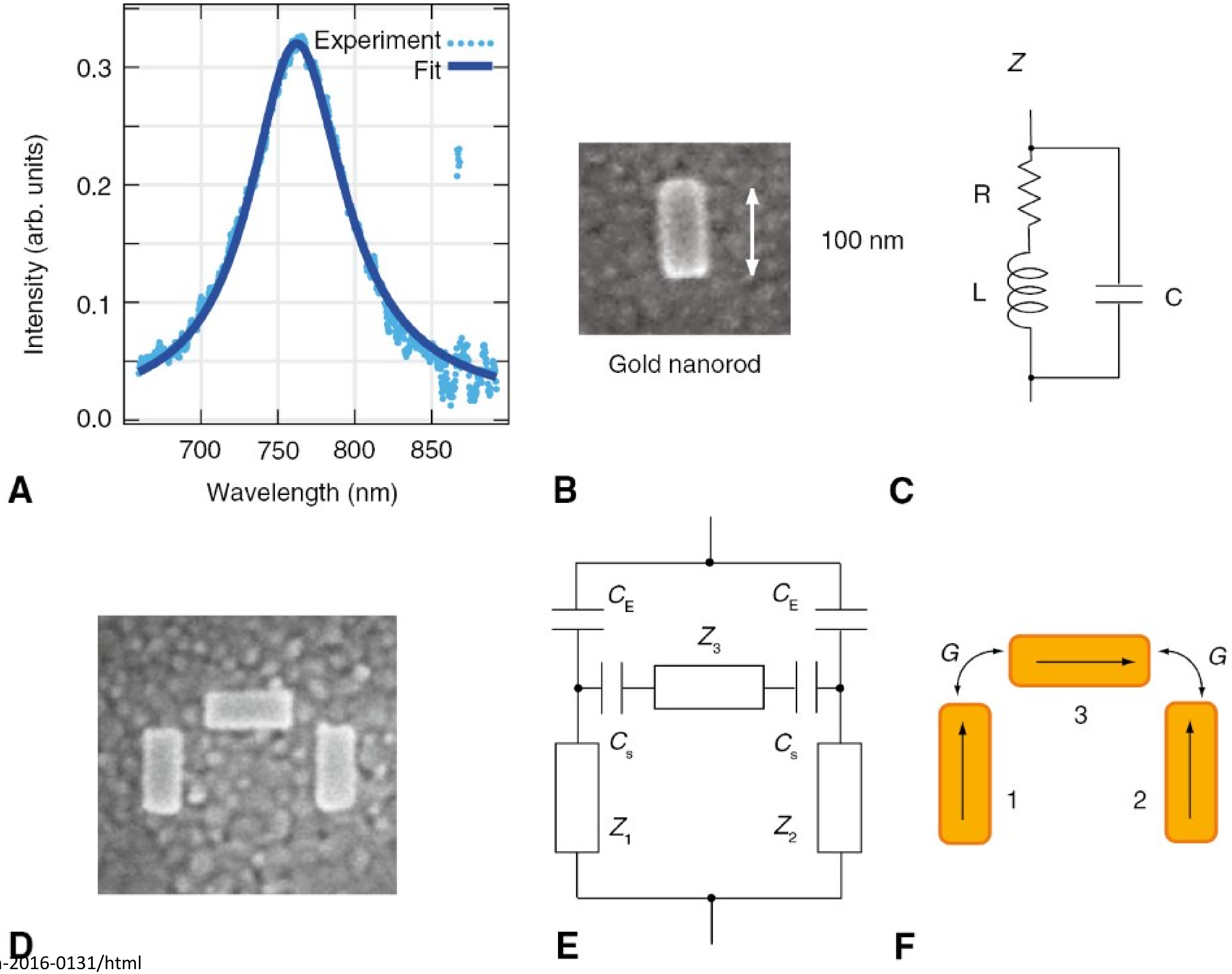




https://www.scientificamerican.com/article/the-promise-of-plasmonics-overview-plasmonics/
https://www.degruyter.com/document/doi/10.1515/nanoph-2016-0131/html

Plasmonic Electronics

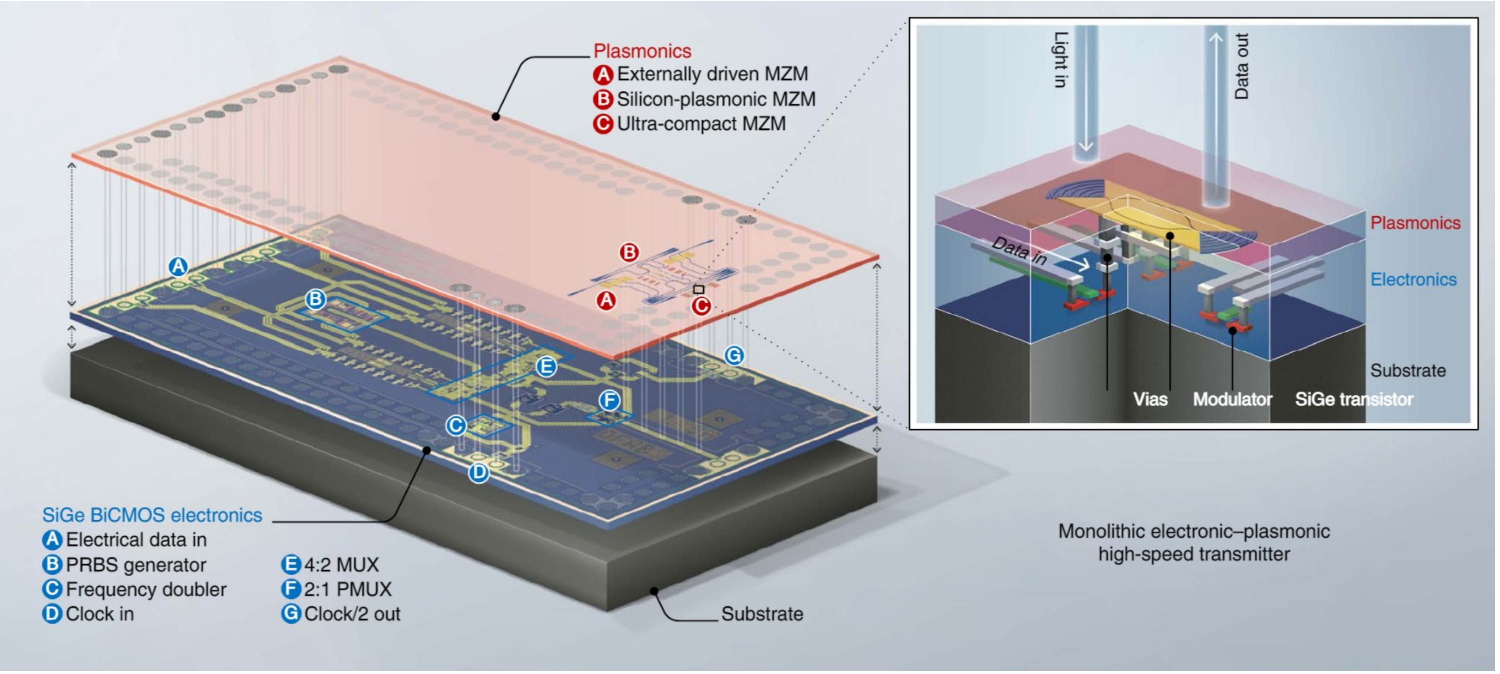
- Using plasmonics we can also replace other electrical components at optical frequencies



https://www.degruyter.com/document/doi/10.1515/nanoph-2016-0131/html

Real Plasmonic Chip

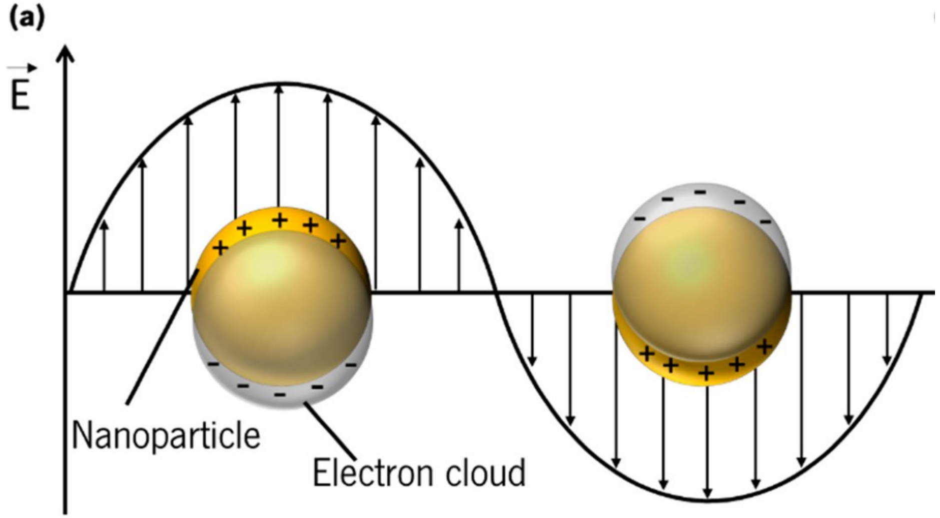
- First plasmonic chips operate at 100 GHz, 200 GHz is expected after optimizing



https://www.nature.com/articles/s41928-020-0417-9

Localised Surface Plasmons

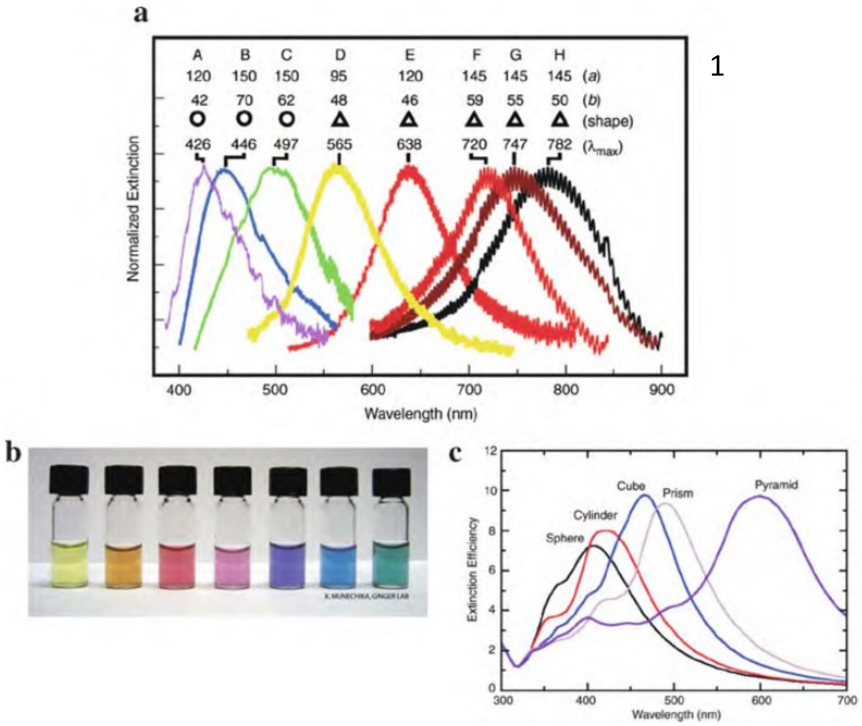
- LSPs are formed on the surface of metal nanoparticles. They don‘t propagate further. The induced dipole moment becomes a source of EM radiation with the same frequency as the incident wave, but in a different direction. Light scattering occurs - human eye perceives this as colour in the surroundings.



https://www.mdpi.com/2076-3417/11/12/5388/htm

LSP resonant frequency

- The resonant frequency depends on the size, shape and type of nanoparticles and the permittivity of the surrounding environment [2]



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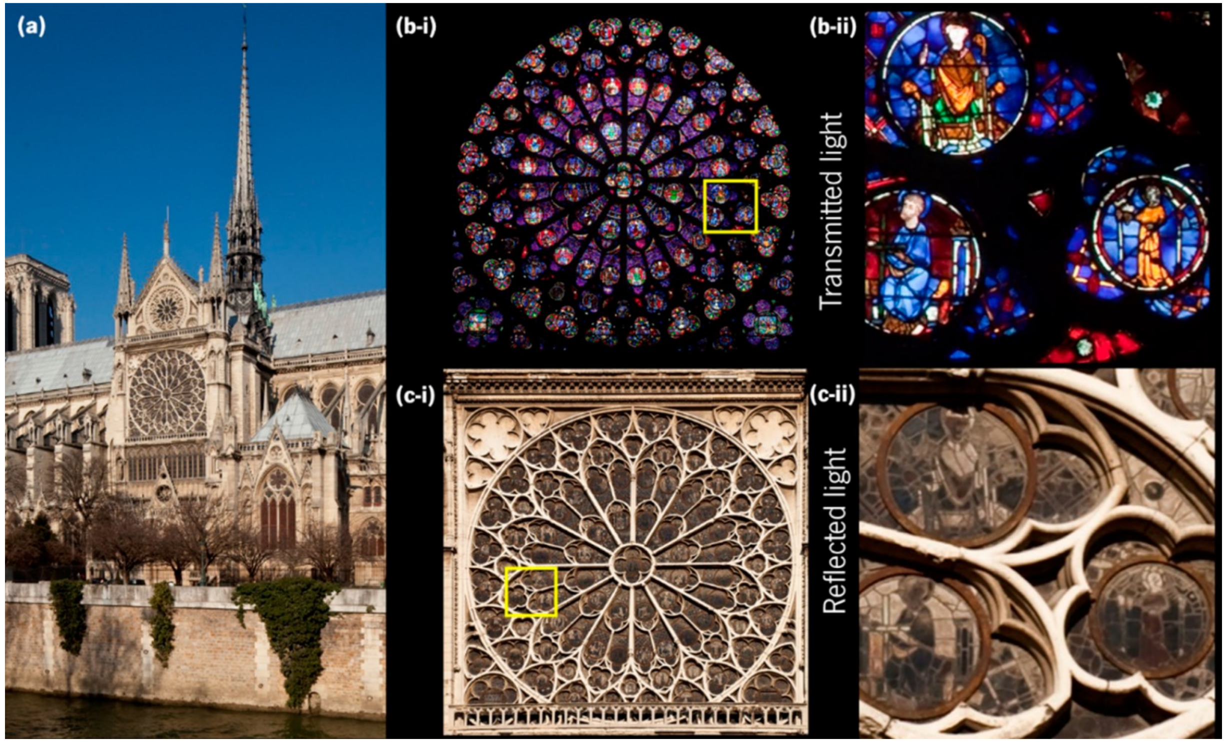
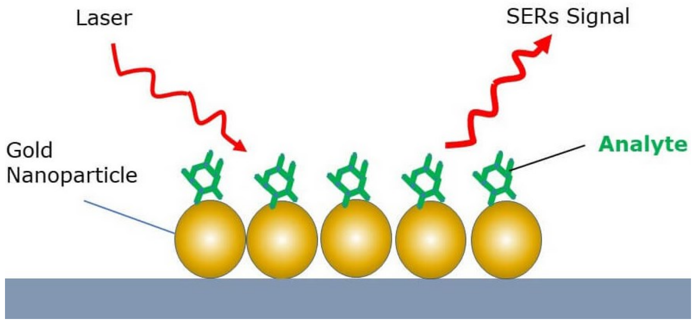


[1] H.E. Schaefer, Nanosciience: The Science of the Small in Physics, Engineering, Chemistry, Biology and Medicine, Springer, 2010

[2] https://www.mdpi.com/2076-3417/11/12/5388/htm

Other LSP Applications

- Surface enhanced Raman spectroscopy
  - Resonance with LSP significantly amplifies the signal of spectroscopic techniques
  - Up to 10^{10} signal enhancement after placing the analyte on a textured substrate or by excitation of the plasmon on a probe tip.



https://wasatchphotonics.com/applications/novel-sers-substrate/

- Cancer treatment
  - The use of gold or gold-coated nanoparticles. These are absorbed preferentially by a growing tumor. Thanks to LSP, the nanoparticles very efficiently convert EM radiation into heat and thus burn the tumor.
- Sensors
  - The resonance frequency is strongly dependent on the refractive index of the surrounding environment

Light transmission through apertures smaller than the wavelength of light

- If an aperture has r >> λ, the Huygens principle drscribes the light propagation
- If we have periodically arranged holes with r << λ, there is no diffraction, and moreover, more light passes through the holes than it should
    - Extraordinary transparency of perforated metal films – light incident on the holes produces an evanescent wave which is transmitted to the other side of the film. In addition, when this layer is metallic, it can interact with the surface plasmon and amplify the light

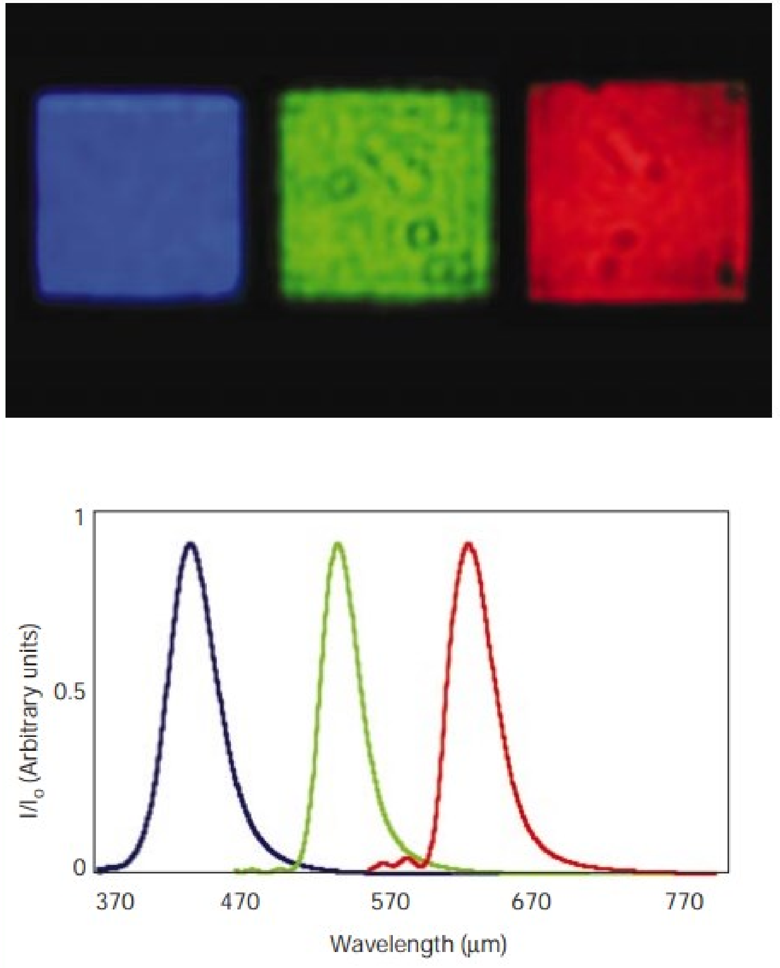
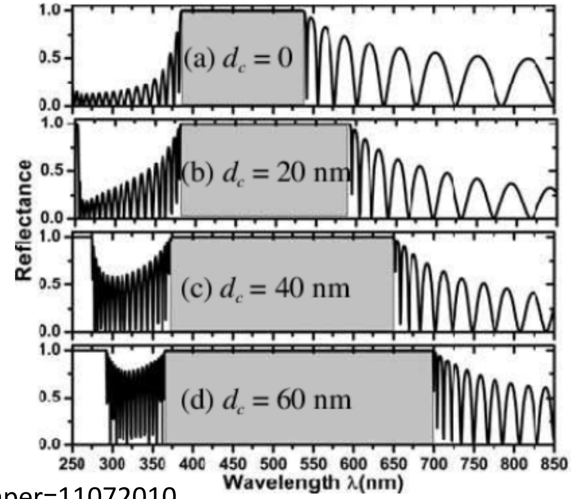


Figure 4 Normal incidence transmission for subwavelength holes. Normal incidence transmission images (top) and spectra (bottom) for three square arrays of subwavelength holes. For the blue, green and red arrays, the periods were 300, 450 and 550 nm, respectively, the hole diameters were 155, 180 and 225 nm and the peak transmission wavelengths 436, 538 and 627 nm. The arrays were made in a free standing 300 nm thick silver film (courtesy of A. Degiron, Université Louis Pasteur, France). Only the lowest

https://www.nature.com/articles/s41928-020-0417-9

Photonic Crystals

- In a photonic crystal, the refractive index changes periodically in 1, 2 or 3 directions. This makes the photon behave similarly to an electron in a crystal lattice – a forbidden band.



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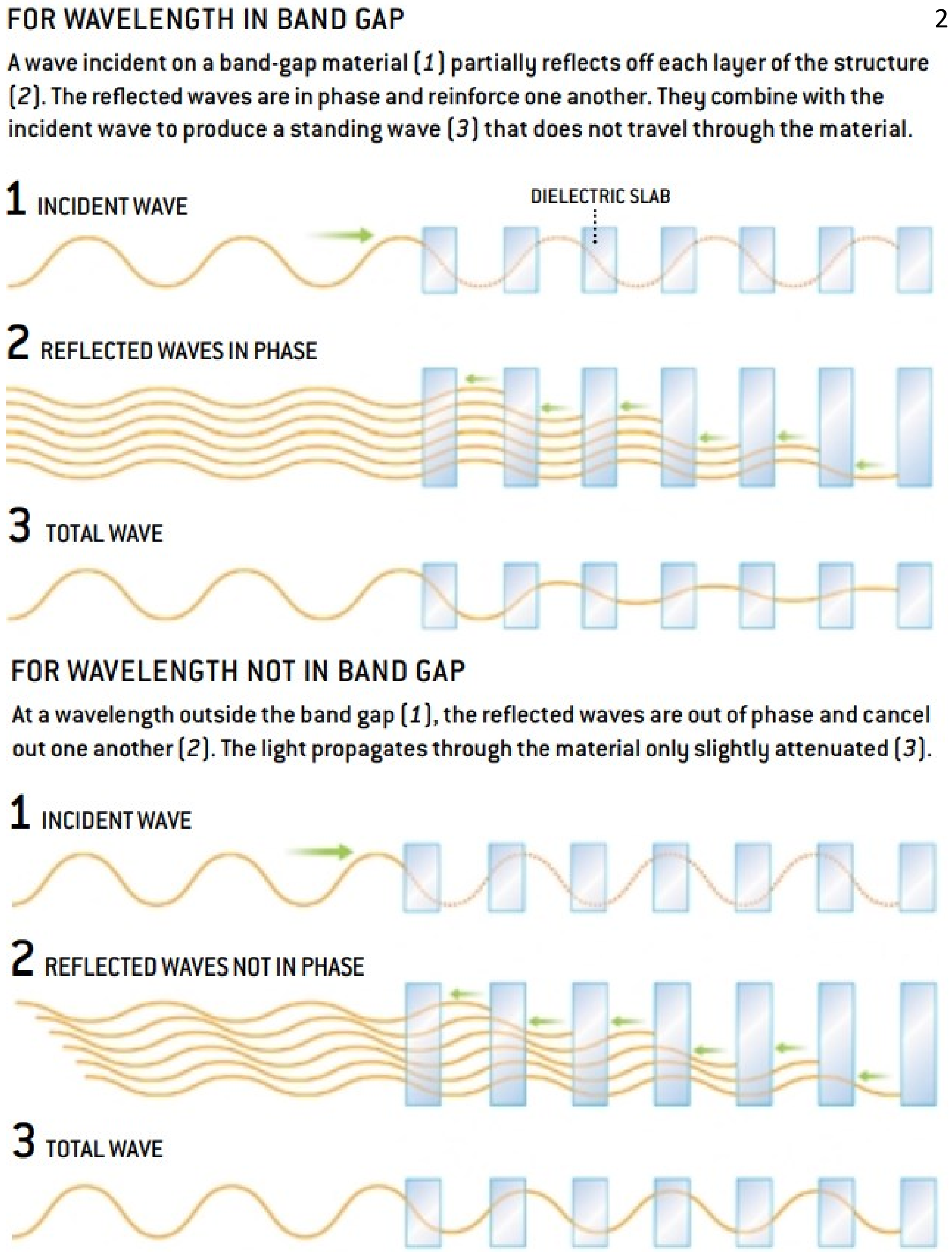


[2]

[1] http://www.jpier.org/PIER/pier.php?paper=11072010
[2] https://www.jstor.org/stable/26059459

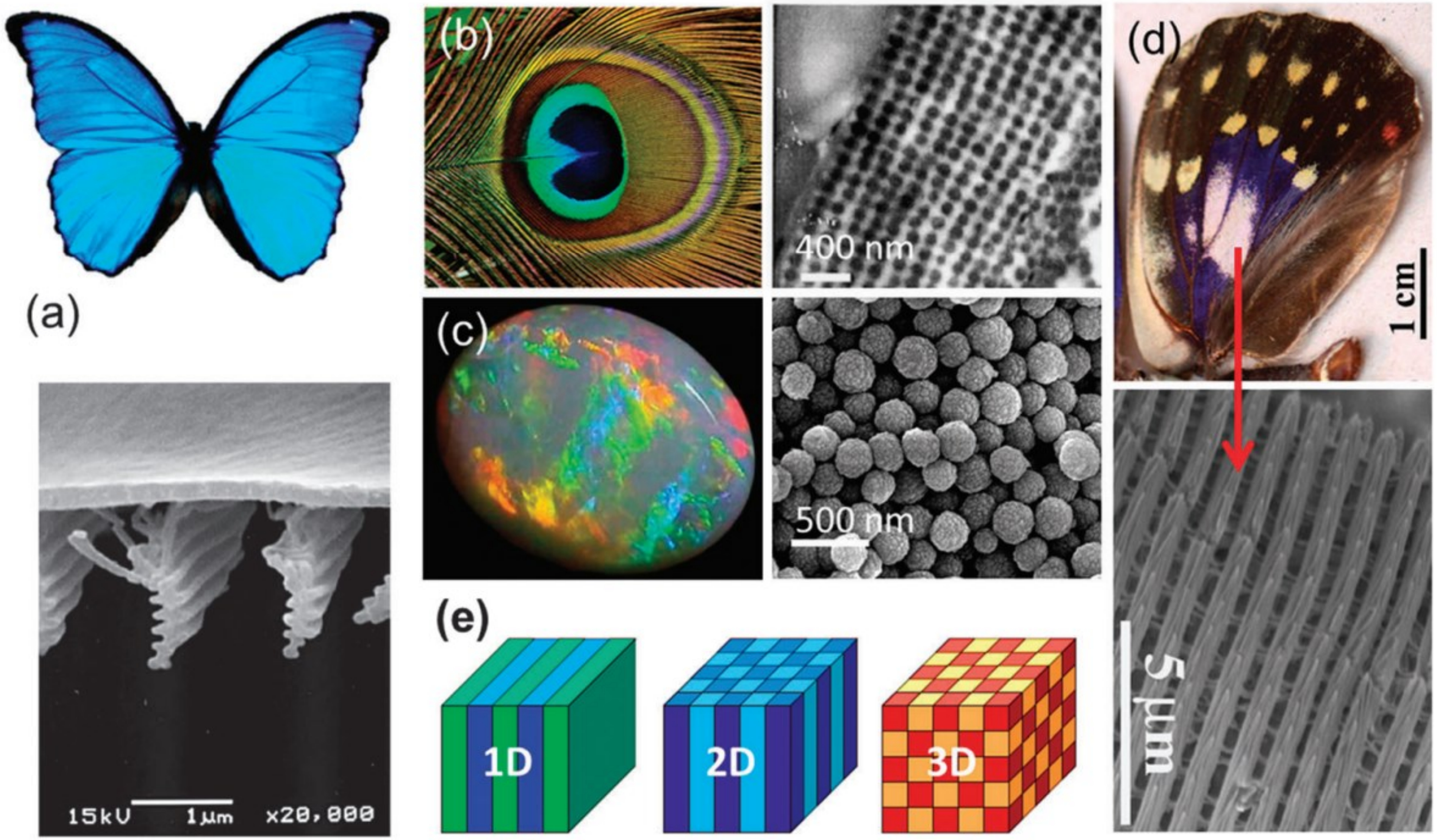
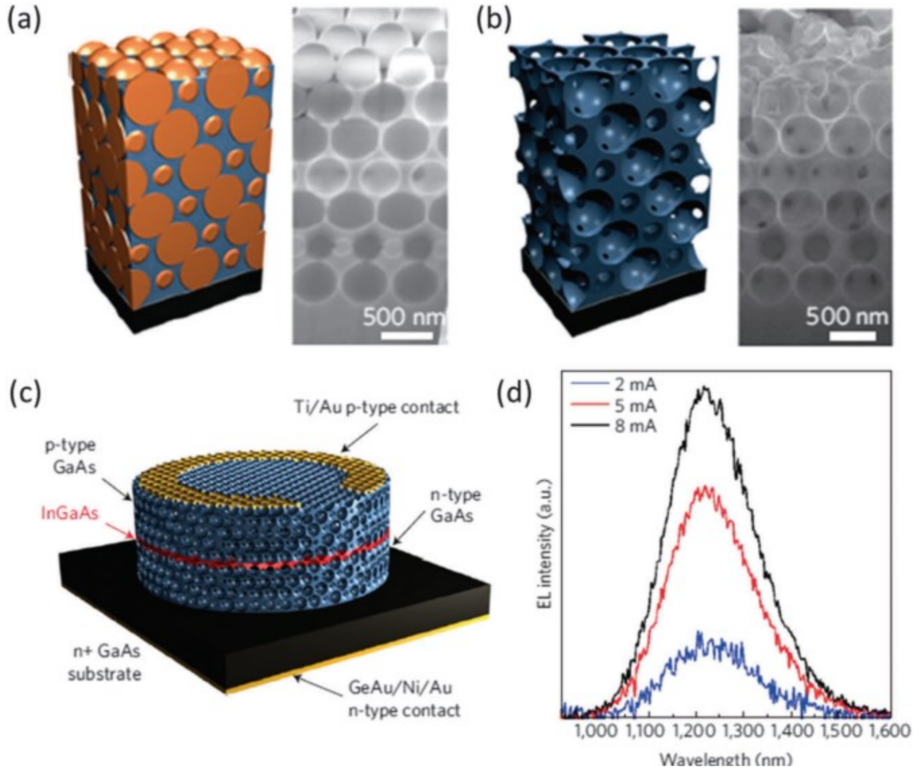


Fig. 1 Natural photonic crystals: (a) the blue iridescence and SEM image of the 1D structure of the Morpho butterfly.[14] Adapted with permission from ref. 14. Copyright 2004 The Royal Society. (b) Multi-coloured peacock feather (Image by Wikimedia Commons/CC BY-SA 3.0) and TEM image of transverse cross section of the 2D structure of the blue area of a wing.[11] Adapted with permission from ref. 11. Copyright 2002 Sci. press. (c) Natural opal gemstone and SEM image of the silica sphere structure within.[15] Adapted with permission from ref. 15. Copyright 2008 Mineralogical Society of America. (d) Wing of the male Sasakia Charonda butterfly and SEM image of the 3D structure of the white iridescent area.[12] Adapted with permission from ref. 12. Copyright 2010 The Japan Institute of Metals and Materials. (e) Schematic representation of 1D, 2D and 3D PhC structures, with different colours representative of different dielectric constants, indicating periodicity in one, two or three directions. Adapted from ref. 18. Copyright 2008 Princeton University Press.

https://pubs.rsc.org/en/content/articlelanding/2015/TC/C5TC01083G

Artificial Photonic Crystals

- Artificial photonic crystals for anti-reflective applications, lasers, energy storage,...



https://pubs.rsc.org/en/content/articlelanding/2015/TC/C5TC01083G

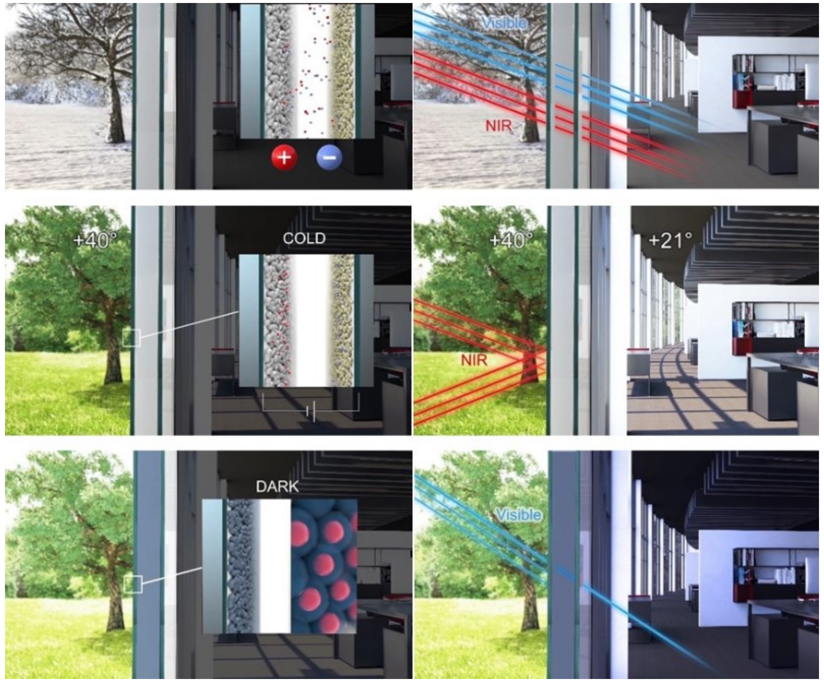
Quantum Dots and Photonics

- An excited electron in the QD may undergo several collisions before relaxing to the ground state and thus reduce its energy – the emitted photon will have a different color than the received one.
- Fluorescence tagging
- QDs have higher stability than conventional chemical dyes. Possibility to choose a specific chemical affinity

https://www.azolifesciences.com/news/20200219/Short-Wave-Infrared-Quantum-Dots-with-Compact-Sizes-as-Molecular-Probes-for-Fluorescence-Microscopy.aspx

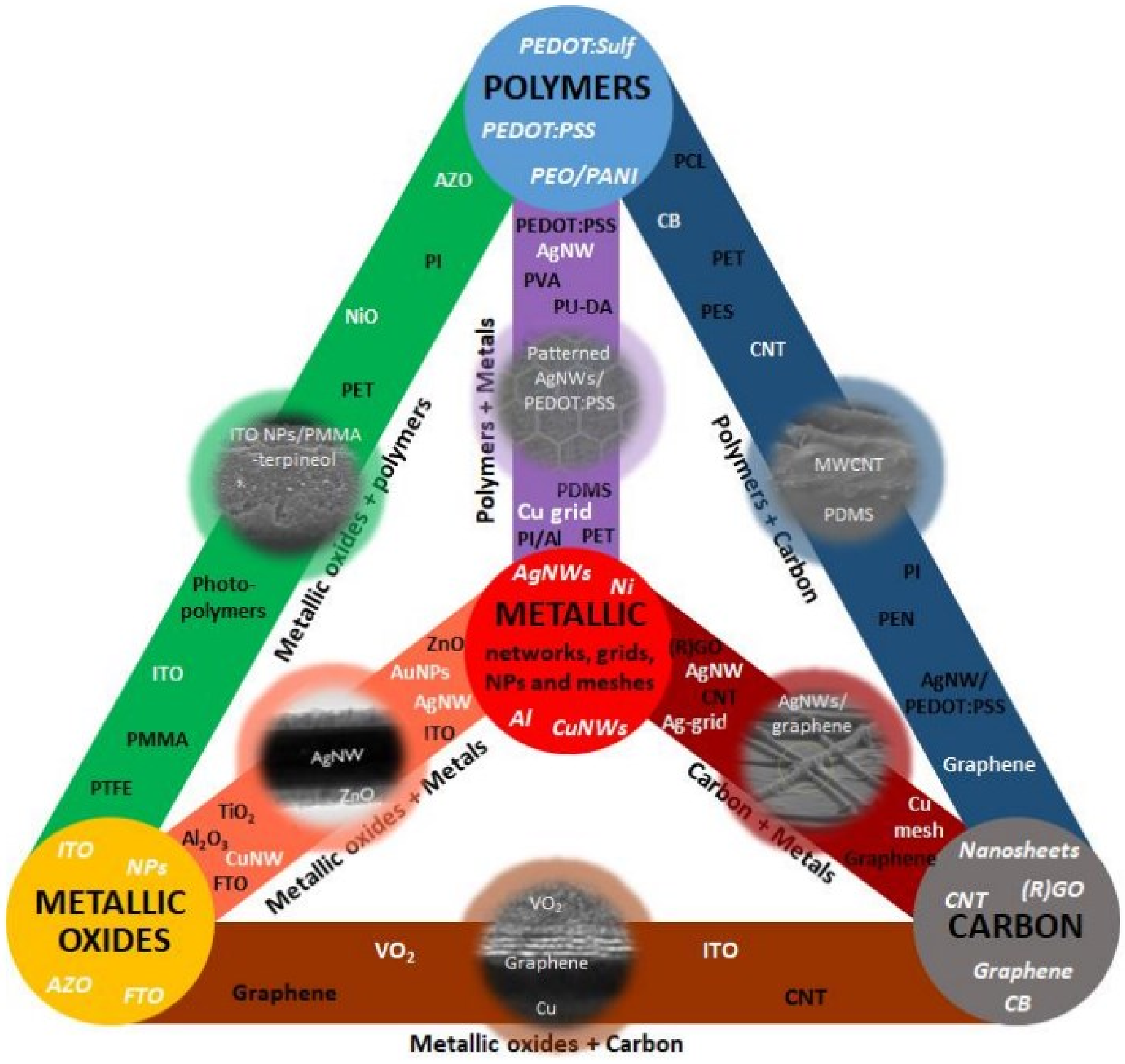
X-Chromic Materials

- Photochromic materials – change their optical properties depending on the illumination
- Thermochromic materials – change their optical properties depending on their temperature
- Electrochromic materials – change their optical properties depending on the applied voltage
- Mechanochromic materials – change their optical properties depending on the applied mechanical stress



https://www.earto.eu/rto-innovation/leitat-smart-windows-for-smart-buildings/

X-Chromic Nanomaterials



https://onlinelibrary.wiley.com/doi/abs/10.1002/adfm.201910225

Conclusion

- The wave-particle nature of light
- Plasmons
- Plasmonic chips and electronics
- Localised surface plasmon
- Photonic crystals
- X-chronic materials