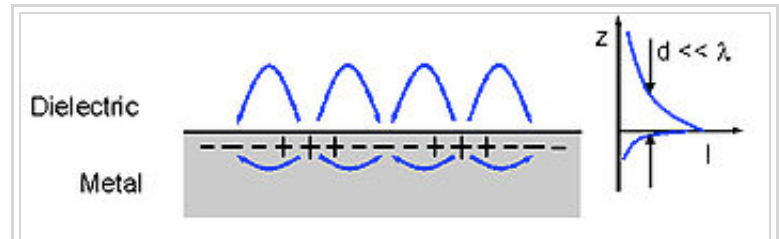# Evanescent Waves

Evanescent wave

From Wikipedia, the free encyclopedia

An **evanescent wave** is a nearfield standing wave
with an intensity that exhibits exponential decay
with distance from the boundary at which the wave
was formed. Evanescent waves are a general
property of wave-equations, and can in principle
occur in any context to which a wave-equation
applies. They are formed at the boundary between
two media with different wave motion properties,
and are most intense within one third of a
wavelength from the surface of formation. In
particular, evanescent waves can occur in the
contexts of optics and other forms of
electromagnetic radiation, acoustics, quantum
mechanics, and "waves on strings".[1][2]

Schematic representation of evanescent waves propagating
along a metal-dielectric interface. The charge density
oscillations, when associated with electromagnetic fields,
are called surface plasmon-polariton waves. The
exponential dependence of the electromagnetic field
intensity on the distance away from the interface is shown
on the right. These waves can be excited very efficiently
with light in the visible range of the electromagnetic
spectrum.

Contents

- 1 Evanescent wave applications
- 2 Total internal reflection of light
- 3 Evanescent-wave coupling
    - 3.1 Applications
- 4 See also
- 5 References
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Evanescent wave applications

In optics and acoustics, evanescent waves are formed when waves traveling in a medium undergo total internal
reflection at its boundary because they strike it at an angle greater than the so-called *critical angle*.[1][2] The
physical explanation for the existence of the evanescent wave is that the electric and magnetic fields (or
pressure gradients, in the case of acoustical waves) cannot be discontinuous at a boundary, as would be the
case if there were no evanescent wave field. In quantum mechanics, the physical explanation is exactly
analogous—the Schrödinger wave-function representing particle motion normal to the boundary cannot be
discontinuous at the boundary.

Electromagnetic evanescent waves have been used to exert optical radiation pressure on small particles in
order to trap them for experimentation, or to cool them to very low temperatures, and to illuminate very small
objects such as biological cells for microscopy (as in the total internal reflection fluorescence microscope). The

evanescent wave from an optical fiber can be used in a gas sensor, and evanescent waves figure in the infrared spectroscopy technique known as attenuated total reflectance.

In electrical engineering, evanescent waves are found in the nearfield region within one third of a wavelength of any radio antenna. During normal operation, an antenna emits electromagnetic fields into the surrounding nearfield region, and a portion of the field energy is reabsorbed, while the remainder is radiated as EM waves.

In quantum mechanics, the evanescent-wave solutions of the Schrödinger equation give rise to the phenomenon of wave-mechanical tunneling.

In microscopy, systems that capture the information contained in evanescent waves can be used to create super resolution images. Matter radiates both propagating and evanescent electromagnetic waves. Conventional optical systems capture only the information in the propagating waves and hence are subject to the diffraction limit. Systems that capture the information contained in evanescent waves, such as the superlens and near field scanning optical microscopy, can overcome the diffraction limit; however these systems are then limited by the system's ability to accurately capture the evanescent waves.[3] The limitation on their resolution is given by

$$k \propto \frac{1}{d} \ln \frac{1}{\delta},$$

where k is the maximum wave vector that can be resolved, d is the distance between the object and the sensor, and δ is a measure of the quality of the sensor.

More generally, practical applications of evanescent waves can be classified in the following way: (1) Those in which the energy associated with the wave is used to excite some other phenomenon within the region of space where the original traveling wave becomes evanescent (for example, as in the total internal reflection fluorescence microscope), (2) Those in which the evanescent wave "couples" two media in which traveling waves are allowed, and hence permits the transfer of energy or a particle between the media (depending on the wave equation in use), even though no traveling-wave solutions are allowed in the region of space between the two media. An example of this is so-called *wave-mechanical tunnelling*. This second type of application is known generally as *evanescent wave coupling*.

Total internal reflection of light

For example, consider total internal reflection in two dimensions, with the interface between the media lying on the x axis, the normal along y, and the polarization along z. One might naively expect that for angles leading to total internal reflection, the solution would consist of an incident wave and a reflected wave, with no transmitted wave at all, but there is no such solution that obeys Maxwell's equations. Maxwell's equations in a dielectric medium impose a boundary condition of continuity for the components of the fields $E_{//}$, $H_{//}$, D_y, and B_y. For the polarization considered in this example, the conditions on $E_{//}$ and B_y are satisfied if the reflected wave has the same amplitude as the incident one, because these components of the incident and reflected waves superimpose destructively.

Total internal reflection

Their H_x components, however, superimpose constructively, so there can be no solution without a non-vanishing transmitted wave. The transmitted wave cannot, however, be a sinusoidal wave, since it would then transport energy away from the boundary, but since the incident and reflected waves have equal energy, this would violate conservation of energy. We therefore conclude that the transmitted wave must be a non-vanishing solution to Maxwell's equations that is not a traveling wave, and the only such solutions in a dielectric are those that decay exponentially: evanescent waves.

Mathematically, evanescent waves can be characterized by a wave vector where one or more of the vector's components has an imaginary value. Because the vector has imaginary components, it may have a magnitude that is less than its real components. If the angle of incidence exceeds the critical angle, then the wave vector of the transmitted wave has the form

$$\mathbf{k} \;=\; k_y \hat{\mathbf{y}} + k_x \hat{\mathbf{x}} \;=\; i\alpha \hat{\mathbf{y}} + \beta \hat{\mathbf{x}},$$

which represents an evanescent wave because the y component is imaginary. (Here α and β are real and i represents the imaginary unit.)

For example, if the polarization is perpendicular to the plane of incidence, then the electric field of any of the waves (incident, reflected, or transmitted) can be expressed as

$$\mathbf{E}(\mathbf{r}, t) = \mathrm{Re}\left\{ E(\mathbf{r}) e^{i\omega t} \right\} \hat{\mathbf{z}}$$

where $\hat{\mathbf{z}}$ is the unit vector in the z direction.

Substituting the evanescent form of the wave vector **k** (as given above), we find for the transmitted wave:

$$E(\mathbf{r}) = E_o e^{-i(i\alpha y + \beta x)} = E_o e^{\alpha y - i\beta x}$$

where α is the *attenuation constant* and β is the *propagation constant*.

Top to bottom: representation of a refracted incident wave and an evanescent wave at an interface.

Evanescent-wave coupling

In optics, **evanescent-wave coupling** is a process by which electromagnetic waves are transmitted from one medium to another by means of the evanescent, exponentially decaying electromagnetic field.

Coupling is usually accomplished by placing two or more electromagnetic elements such as optical waveguides close together so that the evanescent field generated by one element does not decay much before it reaches the other element. With waveguides, if the receiving waveguide can support modes of the appropriate frequency, the evanescent field gives rise to propagating-wave modes, thereby connecting (or coupling) the wave from one waveguide to the next.
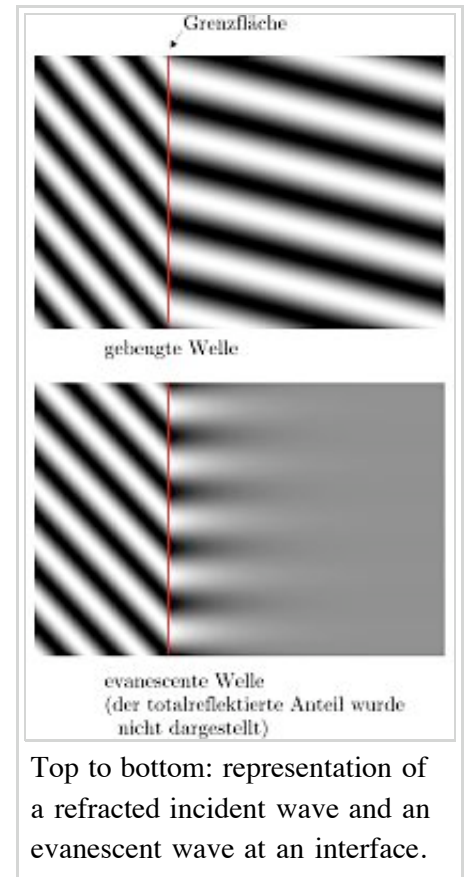
Evanescent-wave coupling is fundamentally identical to near field interaction in electromagnetic field theory. Depending on the impedance of the radiating source element, the evanescent wave is either predominantly electric (capacitive) or magnetic (inductive), unlike in the far field where these components of the wave eventually reach the ratio of the impedance of free space and the wave propagates radiatively. The evanescent wave coupling takes place in the non-radiative field near each medium and as such is always associated with matter, i.e. with the induced currents and charges within a partially reflecting surface. This coupling is directly analogous to the coupling between the primary and secondary coils of a transformer, or between the two plates of a capacitor. Mathematically, the process is the same as that of quantum tunneling, except with electromagnetic waves instead of quantum-mechanical wavefunctions.

Applications

- Evanescent wave coupling is commonly used in photonic and nanophotonic devices as waveguide sensors.
- Evanescent wave coupling is used to excite dielectric microsphere resonators among other things.
- A typical application is resonant energy transfer, useful, for instance, for charging electronic gadgets without wires. A particular implementation of this is WiTricity; the same idea is also used in some Tesla coils.
- Evanescent coupling, as near field interaction, is one of the concerns in electromagnetic compatibility.
- Evanescent wave coupling plays a major role in the theoretical explanation of extraordinary optical transmission.[4]

See also

- Coupling (electronics)
- Electromagnetic wave
- Quantum tunneling
- Resonant energy transfer
- Snell's law
- Total internal reflection
- Total internal reflection fluorescence microscope
- Waveguide

References

- Karalis, Aristeidis; J.D. Joannopoulos, Marin Soljačić (February 2007). *Efficient wireless non-radiative mid-range energy transfer*. arXiv:physics/0611063v2.
- "'Evanescent coupling' could power gadgets wirelessly", Celeste Biever, *NewScientist.com*, 15 November 2006 (http://www.newscientisttech.com/article/dn10575-evanescent-coupling-could-power-gadgets-wirelessly.html)
- Wireless energy could power consumer, industrial electronics (http://web.mit.edu/newsoffice/2006/wireless.html) - MIT press release

1. ^ *a b* Tineke Thio (2006). "A Bright Future for Subwavelength Light Sources". *American Scientist* (American Scientist) **94** (1): 40–47. doi:10.1511/2006.1.40 (http://dx.doi.org/10.1511%2F2006.1.40) .

2. ^ *a b* Marston, Philip L.; Matula, T.J. (May 2002). "Scattering of acoustic evanescent waves...". *Acoustical Society of America Journal (J. Acoust. Soc. Am.)* **111** (05): 2378. Bibcode 2002ASAJ..111.2378M (http://adsabs.harvard.edu/abs/2002ASAJ..111.2378M) .

3. ^ Neice, A., "Methods and Limitations of Subwavelength Imaging", Advances in Imaging and Electron Physics, Vol. 163, July 2010

4. ^ Z. Y. Fan, L. Zhan, X. Hu, and Y. X. Xia, "Critical process of extraordinary optical transmission through periodic subwavelength hole array: Hole-assisted evanescent-field coupling," Optics Communications 281, 5467-5471 (2008).

External links

- Evanescent waves (http://www.andrew.cmu.edu/user/dcprieve/Evanescent%20waves.htm)
- An animation from a product manufacturer that makes use of evanescent fields (http://www.farfieldgroup.shared.hosting.zen.co.uk/technology_dpi.asp)

Retrieved from "http://en.wikipedia.org/wiki/Evanescent_wave"
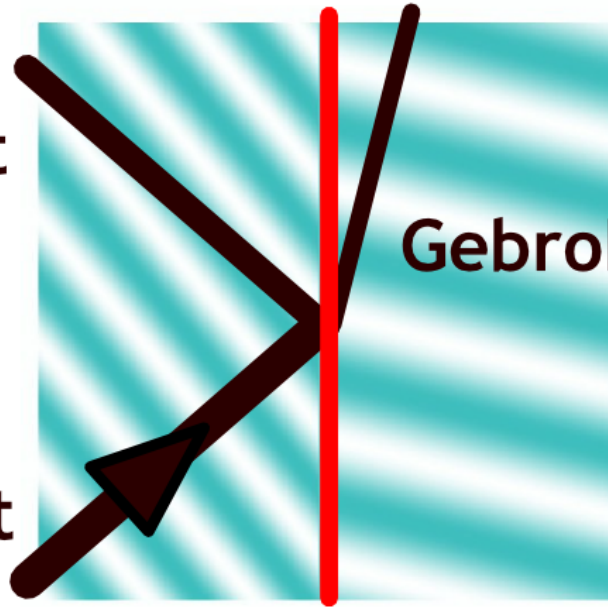Categories: Electrical engineering | Optics | Metamaterials | Materials science | Nanotechnology | Quantum mechanics

Incident
Light

Θ

ATR Crystal (n_0)

Substrate (n_1)

Air (n_2)

d_p

a

Z
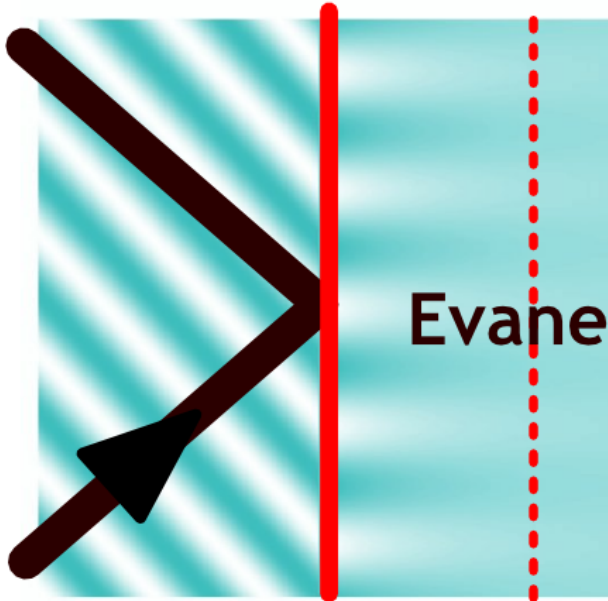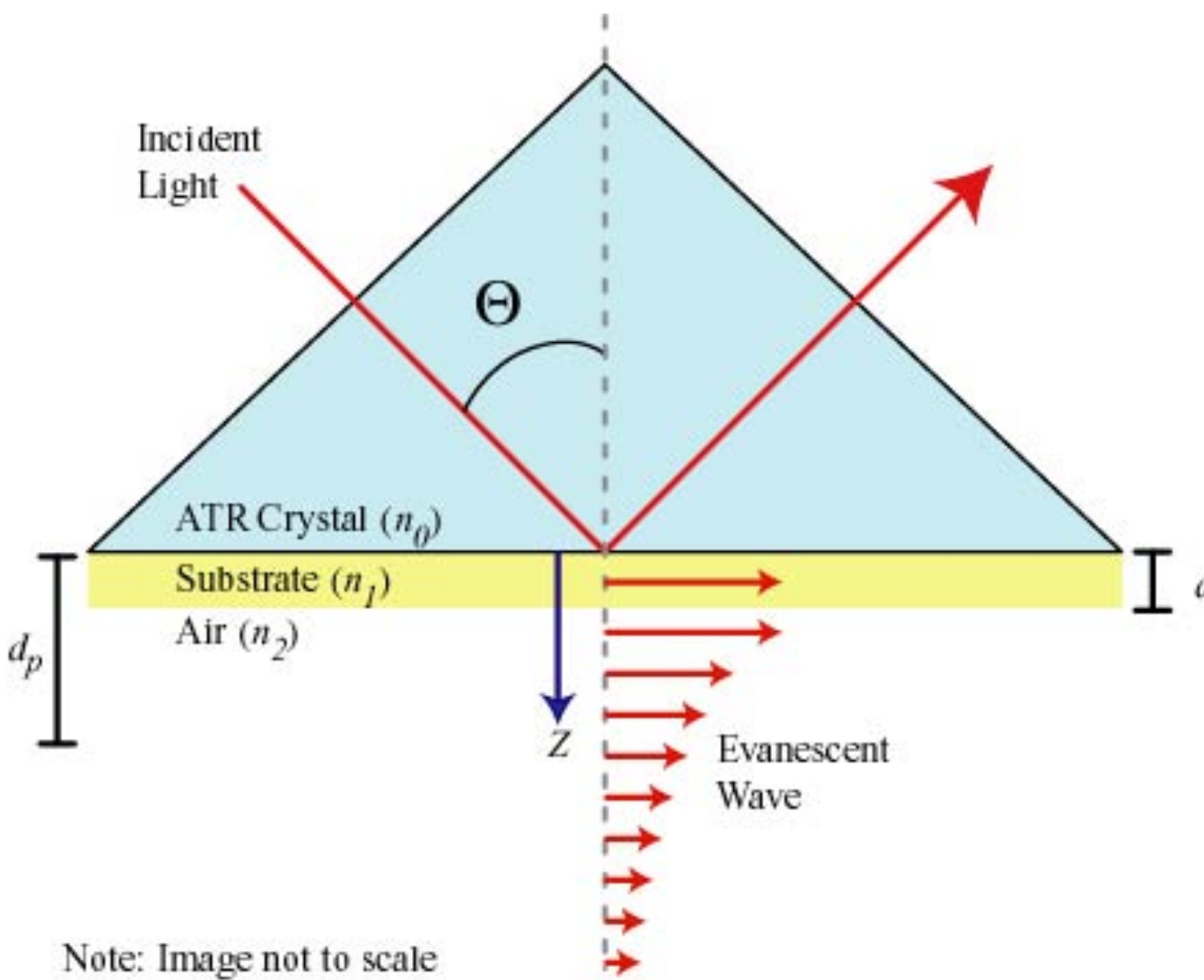
Evanescent
Wave

Note: Image not to scale
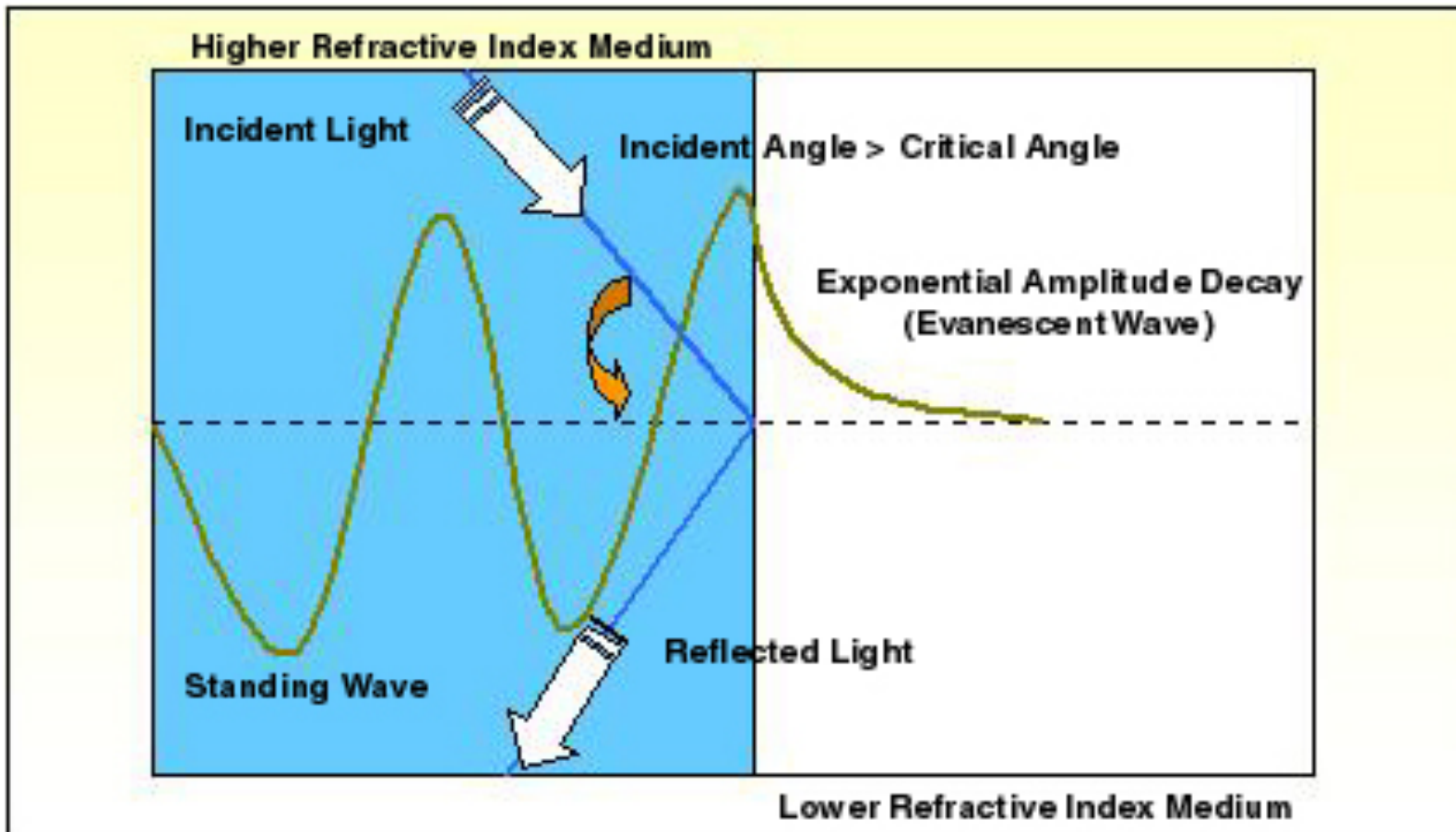
Evanescent Wave Generation

Grooves

Z (mm)

X (μm)
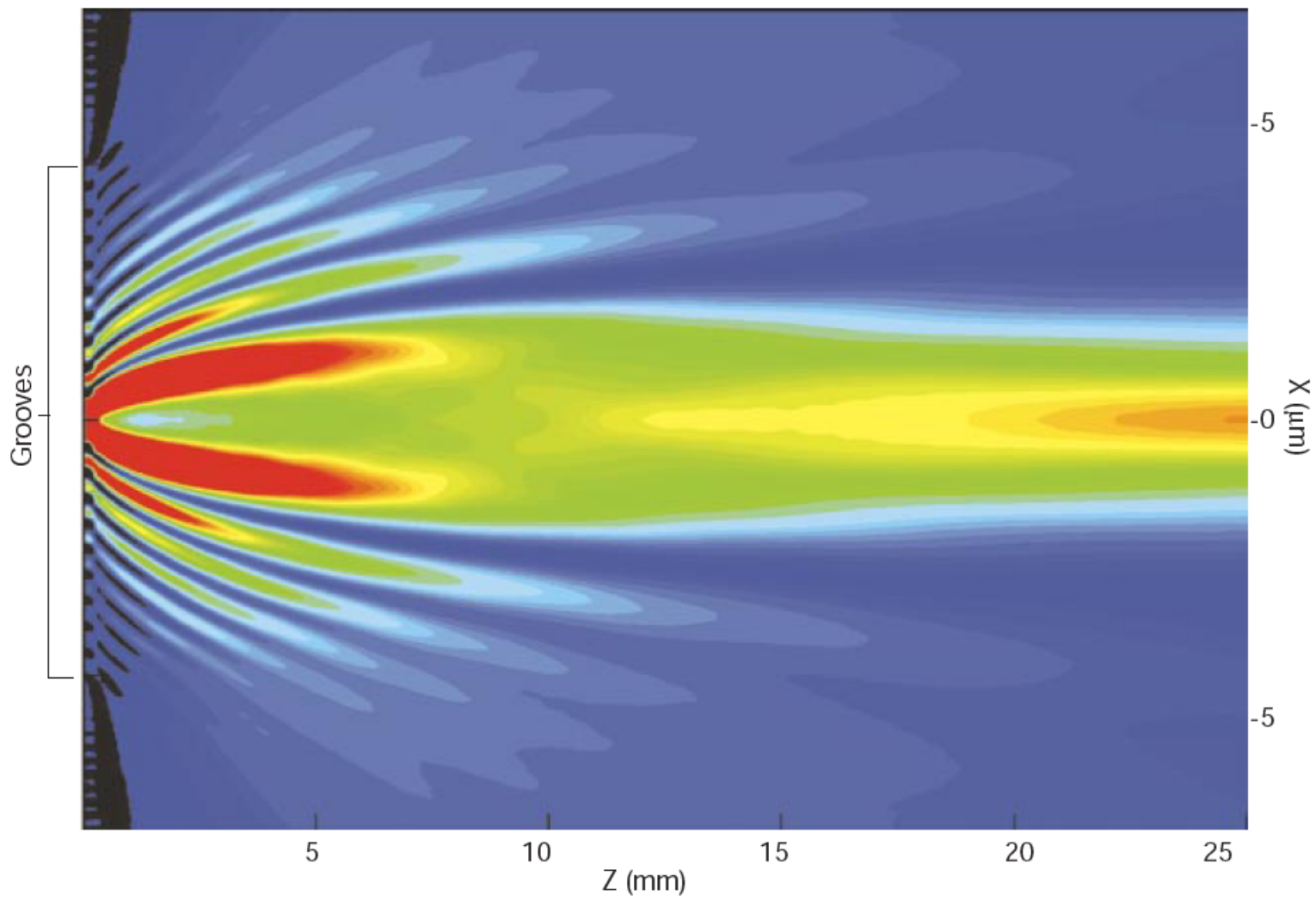
Total internal reflection fluorescence microscope

From Wikipedia, the free encyclopedia

A **total internal reflection fluorescence microscope** (**TIRFM**) is a type of microscope with which a thin region of a specimen, usually less than 200 nm, can be observed.

Contents

- 1 Background
- 2 Solution
- 3 References
- 4 External links

Background

In cell and molecular biology, a large number of molecular events in cellular surfaces such as cell adhesion, binding of cells by hormones, secretion of neurotransmitters, and membrane dynamics have been studied with conventional fluorescence microscopes. However, fluorophores that are bound to the specimen surface and those in the surrounding medium exist in an equilibrium state. When these molecules are excited and detected
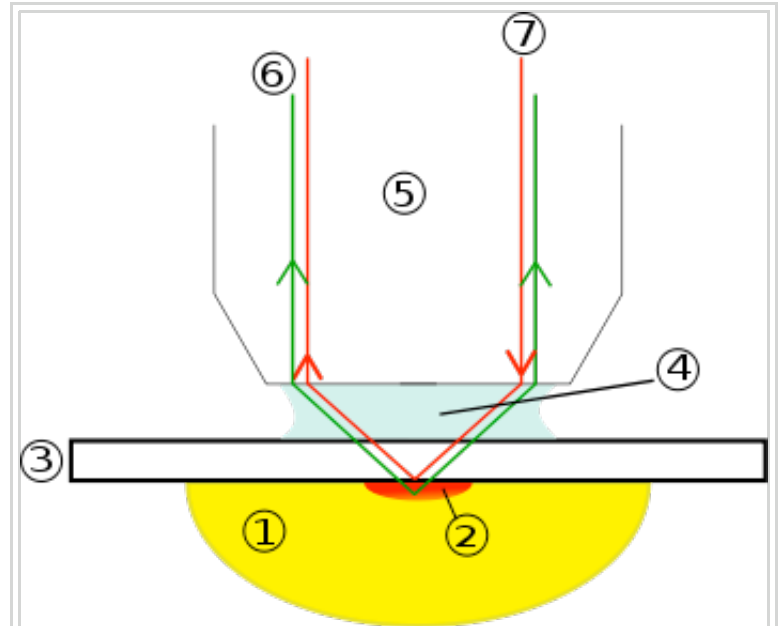
total internal reflection fluorescence microscope (TIRFM) diagram
1. Specimen
2. Evanescent wave range
3. Cover slip
4. Immersion oil
5. Objective
6. Emission beam (signal)
7. Excitation beam

with a conventional fluorescence microscope, the resulting fluorescence from those fluorophores bound to the surface is often overwhelmed by the background fluorescence due to the much larger population of non-bound molecules.

Solution

To solve this problem, TIRFM was developed by Daniel Axelrod at the University of Michigan, Ann Arbor in the early 1980s. A TIRFM uses an evanescent wave to selectively illuminate and excite fluorophores in a restricted region of the specimen immediately adjacent to the glass-water interface. The evanescent wave is generated only when the incident light is totally internally reflected at the glass-water interface. The evanescent electromagnetic field decays exponentially from the interface, and thus penetrates to a depth of only approximately 100 nm into the sample medium. Thus the TIRFM enables a selective visualization of surface regions such as the basal plasma membrane (which are about 7.5 nm thick) of cells as shown in the figure above. Note, however, that the region visualised is at least a few hundred nanometers wide, so the cytoplasmic zone immediately beneath the plasma membrane is necessarily visualised in addition to the plasma membrane during TIRF microscopy. The selective visualisation of the plasma membrane renders the features and events on the plasma membrane in living cells with high axial resolution.
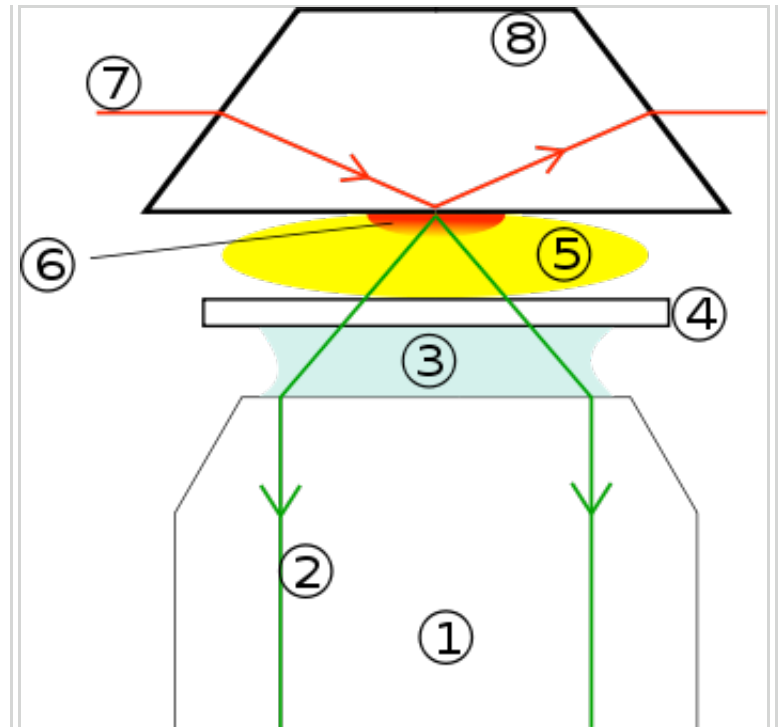

Total Internal Reflection Fluorescence Microscope trans-(TIRFM) diagram
1. Objective
2. Emission beam (signal)
3. Immersion oil
4. Cover slip
5. Specimen
6. Evanescent wave range
7. Excitation beam
8. Quartz prism

TIRF can also be used to observe the fluorescence of a single molecule,[1] making it an important tool of biophysics and quantitative biology.

References

1. ^ Andre et al. Cross-correlated tirf/afm reveals asymmetric distribution of forcegenerating heads along self-assembled, synthetic myosin filaments. Biophysical Journal, 96:1952–1960, 2009.

External links

- Interactive Fluorescence Dye and Filter Database (https://www.micro-shop.zeiss.com/?

s=2525647761b33&l=en&p=us&f=f) Carl Zeiss Interactive Fluorescence Dye and Filter Database.
- Biological imaging: The diffraction barrier broken (http://www.nature.com/nature/journal/v440/n7086/full/440879a.html) - Nature.com
- STED microscopy reveals that synaptotagmin remains clustered after synaptic vesicle exocytosis (http://www.nature.com/nature/journal/v440/n7086/full/nature04592.html) - Nature.com
- Cells come into focus: Glowing molecules can be distinguished one at a time (http://cmbi.bjmu.edu.cn/news/0608/49.htm) - cmbi.bjmu.edu.cn
- Superlenses bring the nanoworld into focus: Light microscopes beat the traditional resolution limits (http://www.bioedonline.org/news/news.cfm?art=2723) - Bioedonline.org
- cell^TIRF - Multicolor TIRF - Olympus (http://www.olympusamerica.com/TIRF) *commercial TIRF microscope systems*
- Leica Microsystems (http://www.Leica-Microsystems.com/TIRF) *commercial TIRF microscope systems*
- TIRF Microscopy: Introduction and Applications (http://www.microscopyu.com/articles/fluorescence/tirf/tirfintro.html) *TIRF Tutorial from Microscopy U*
- TIRF Microscopy: Overview (http://www.olympusmicro.com/primer/techniques/fluorescence/tirf/tirfhome.html) *TIRF Tutorial from Olympus Microscopy Resource Center*
- Olympus TIRFM Microscopes (http://www.microscopy.olympus.eu/microscopes/Life_Science_Microscopes_TIRFM.htm) *commercial TIRF microscope systems*
- Carl Zeiss Laser TIRF 3 (http://www.zeiss.de/c12567be0045acf1/Contents-Frame/649722ef8c671420c1256dd6004b7751) *commercial TIRF microscope systems*
- Lightguide- and prism-based TIRF microscopy (http://www.tirftechnologies.com/) *Commercial TIRF Microscopy, TIRF Spectroscopy, TIRF ElectroChemistry, and TIRF Dielectrophoresis systems*

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Categories: Cell imaging | Scientific techniques

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Total internal reflection

From Wikipedia, the free encyclopedia

Total internal reflection is an optical phenomenon that happens when a ray of light strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary, no light can pass through and all of the light is reflected. The critical angle is the angle of incidence above which the total internal reflection occur.

When light crosses a boundary between materials with different refractive indices, the light beam will be partially refracted at the boundary surface, and partially reflected. However, if the angle of incidence is greater (i.e. the ray is closer to being parallel to the boundary) than the critical angle – the angle of incidence at which light is refracted such that it travels along the boundary – then the light will stop crossing the boundary altogether and instead be totally reflected back internally. This can only occur where light travels from a medium with a higher [n_1=higher refractive index] to one with a lower refractive index [n_2=lower refractive index]. For example, it will occur when passing from glass to air, but not when passing from air to glass.
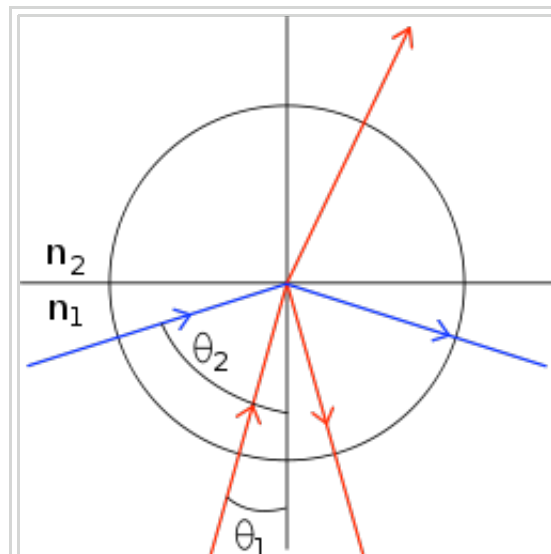
The larger the angle to the normal, the smaller is the fraction of light transmitted, until the angle when **total internal reflection** (blue line) occurs. (The color of the rays is to help distinguish the rays, and is not meant to indicate any color dependence.)

Contents

Optical description

Total internal reflections can be demonstrated using a semi-circular

glass block. A "ray box" shines a narrow beam of light (a "ray") onto the glass. The semi-circular shape ensures that a ray pointing towards the centre of the flat face will hit the curved surface at a right angle; this will prevent refraction at the air/glass boundary of the curved surface. At the glass/air boundary of the flat surface, what happens will depend on the angle. Where θ_c is the critical angle measurement which is caused by the **sun** or a **light source** (measured normal to the surface):

- If $\theta < \theta_c$, the ray will split. Some of the ray will reflect off the boundary, and some will refract as it passes through.
- If $\theta > \theta_c$, the entire ray reflects from the boundary. None passes through. This is called total internal reflection.

This physical property makes optical fibers useful and prismatic (what does this mean?) binoculars possible. It is also what gives diamonds their distinctive sparkle, as diamond has an extremely high refractive index.

Critical angle

Derivation of evanescent wave

An important side effect of total internal reflection is the propagation of an evanescent wave across the boundary surface. Essentially, even though the entire incident wave is reflected back into the originating medium, there is some penetration into the second medium at the boundary. The evanescent wave appears to travel along the boundary between the two materials, leading to the Goos-Hänchen shift.

If a plane wave, confined to the xz plane, is incident on a dielectric with an angle θ_I and wavevector $\mathbf{k_I}$ then a transmitted ray will be created with a corresponding angle of transmittance as shown in Fig. 1. The transmitted wavevector is given by:

$$\mathbf{k_T} = k_T \sin(\theta_T)\hat{x} + k_T \cos(\theta_T)\hat{z}$$
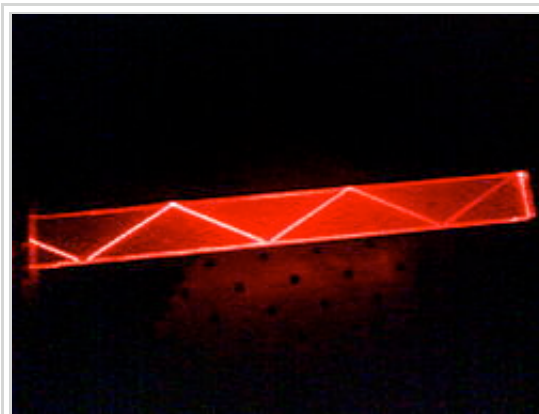
If $n_1 > n_2$, then $\sin(\theta_T) > 1$ since in the relation $\sin(\theta_T) = \dfrac{n_1}{n_2}\sin(\theta_I)$ obtained from Snell's law, $\dfrac{n_1}{n_2}\sin(\theta_I)$ is greater than one. As a result of this $\cos(\theta_T)$ becomes complex:
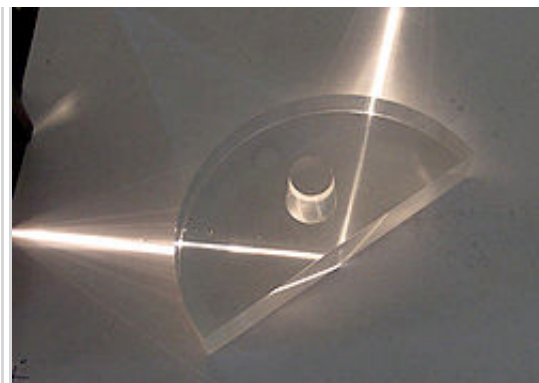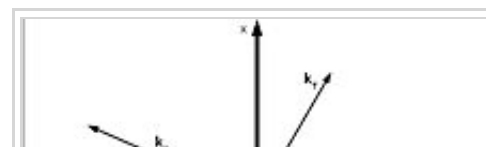

Total internal reflection
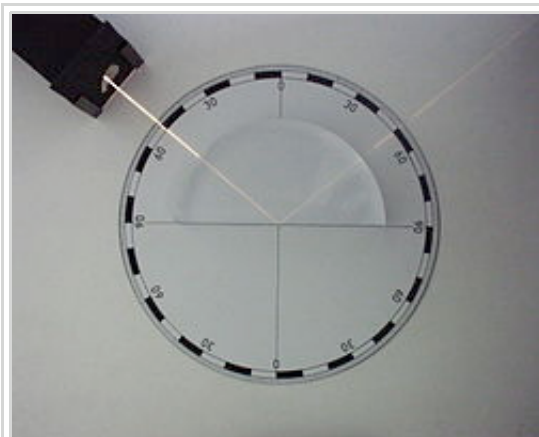
Total internal reflection on plexi–air surface

Total internal reflection in a block of PMMA

$$\cos(\theta_T) = \sqrt{1 - \sin^2(\theta_T)} = i\sqrt{\sin^2(\theta_T) - 1}$$

The electric field of the transmitted plane wave is given by
$\mathbf{E_T} = \mathbf{E_0}e^{i(\mathbf{k_T} \cdot \mathbf{r} - \omega t)}$ and so evaluating this further one obtains:

$$\mathbf{E_T} = \mathbf{E_0}e^{i(\mathbf{k_T} \cdot \mathbf{r} - \omega t)} = \mathbf{E_0}e^{i(xk_T \sin(\theta_T) + zk_T \cos(\theta_T) - \omega t)}$$

$$\mathbf{E_T} = \mathbf{E_0}e^{i(xk_T \sin(\theta_T) + zk_T i\sqrt{\sin^2(\theta_T) - 1} - \omega t)}$$

Fig. 1

Using the fact that $k_T = \dfrac{\omega n_2}{c}$ and Snell's law, one finally obtains:

$$\mathbf{E_T} = \mathbf{E_0}e^{-\kappa z}e^{i(kx - \omega t)}$$

where $\kappa = \dfrac{\omega}{c}\sqrt{(n_1 \sin(\theta_I))^2 - n_2^2}$ and $k = \dfrac{\omega n_1}{c}\sin(\theta_I)$

This wave in the optically less dense medium is known as the evanescent wave. Its characterized by its propagation in the x direction and its exponential attenuation in the z direction. Although there is field in the second medium, it can be shown that no energy flows across the boundary. The component of Poynting vector in the direction normal to the boundary is finite, but its time average vanishes. Whereas the other two components of Poynting vector (here x-component only), and their time averaged values are in general found to be finite.

Superluminal energy transport

The velocity of transfer energy of the transmitted electromagnetic field in the optically thinner medium can exceed the light speed c of vacuum.[1]

Frustrated total internal reflection

See also: attenuated total reflectance

Under "ordinary conditions" it is true that the creation of an evanescent wave does not affect the conservation of energy, i.e. the evanescent wave transmits zero net energy. However, if a third medium with a higher refractive index than the low-index second medium is placed within less than several wavelengths distance from the interface between the first medium and the second medium, the evanescent wave will be different from the one under "ordinary conditions" and it will pass energy across the second into the third medium. (See evanescent wave coupling.) This process is called "frustrated" total internal reflection (FTIR) and is very similar to quantum tunneling. The quantum tunneling model is mathematically analogous if one thinks of the electromagnetic field as being the wave function of the photon. The low index medium can be thought of as a potential barrier through which photons can tunnel.
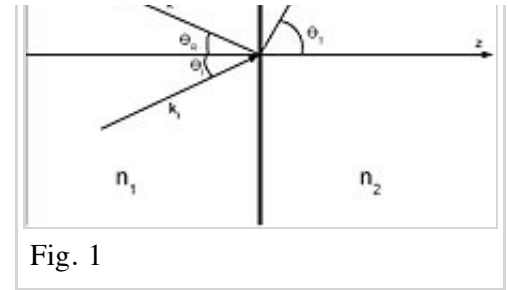
The transmission coefficient for FTIR is highly sensitive to the spacing between the high index media (the function is approximately exponential until the gap is almost closed), so this effect has often been used to modulate optical transmission and reflection with a large dynamic range. An example application of this principle is the multi-touch sensing technology for displays (http://www.cs.nyu.edu/~jhan/ftirsense/) as developed at the New York University's Media Research Lab.

Phase shift upon total internal reflection

A lesser-known aspect of total internal reflection is that the reflected light has an angle dependent phase shift between the reflected and incident light. Mathematically this means that the Fresnel reflection coefficient becomes a complex rather than a real number. This phase shift is polarization dependent and grows as the incidence angle deviates further from the critical angle toward grazing incidence.

The polarization dependent phase shift is long known and was used by Fresnel to design the Fresnel rhomb which allows to transform circular polarization to linear polarization and vice versa for a wide range of wavelengths (colors), in contrast to the quarter wave plate. The polarization dependent phase shift is also the reason why TE and TM guided modes have different dispersion relations.

Applications

- Optical fibers, which are used in endoscopes and telecommunications.
- Rain sensors to control automatic windscreen/windshield wipers.
- Another interesting application of total internal reflection is the spatial filtering of light.[2]
- Prismatic binoculars use the principle of total internal reflections to get a very clear image
- Some multi-touch screens use frustrated total internal reflection in combination with a camera and appropriate software to pick up multiple targets.
- Gonioscopy to view the anatomical angle formed between the eye's cornea and iris.
- Gait analysis instrument, CatWalk,[3] uses frustrated total internal reflection in combination with a high speed camera to capture and analyze footprints of laboratory rodents.
- Fingerprinting devices, which use frustrated total internal reflection in order to record an image of a person's fingerprint without the use of ink.
- Flashlights lenses.[4]

Examples in everyday life

Total internal reflection can be observed while swimming, if one opens one's eyes just under the water's surface. If the water is calm, its surface appears mirror-like.

One can demonstrate total internal reflection by filling a sink or bath with water, taking a glass tumbler, and placing it upside-down over the plug hole (with the tumbler completely filled with water). While water remains both in the upturned tumbler and in the sink surrounding it, the plug hole and plug are visible since the angle of refraction between

glass and water is not greater than the critical angle. If the drain is
opened and the tumbler is kept in position over the hole, the water in
the tumbler drains out leaving the glass filled with air, and this then acts
as the plug. Viewing this from above, the tumbler now appears
mirrored because light reflects off the air/glass interface.

Total internal reflection of the green
turtle can be seen at the air-water
boundary.

Another very common example of total internal reflection is a critically cut diamond. This is what gives it
maximum sparkle.

See also

- Evanescent wave
- Fresnel equations
- Goos-Hänchen effect
- Perfect mirror
- Refraction
- Refractive index
- Snell's window
- Total internal reflection fluorescence microscope

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External links

- FTIR Touch Sensing (http://cs.nyu.edu/~jhan/ftirsense/index.html)
- Multi-Touch Interaction Research (http://cs.nyu.edu/~jhan/ftirtouch/index.html)
- Georgia State University (http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/totint.html)
- Total Internal Reflection (http://demonstrations.wolfram.com/TotalInternalReflection/) by Michael Schreiber, Wolfram Demonstrations Project
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Categories: Physical optics | Geometrical optics | Glass physics

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Surface Plasmons

Surface plasmon resonance

From Wikipedia, the free encyclopedia

The excitation of surface plasmons by light is denoted as a **surface plasmon resonance** (SPR) for planar surfaces or **localized surface plasmon resonance** (LSPR) for nanometer-sized metallic structures.

This phenomenon is the basis of many standard tools for measuring adsorption of material onto planar metal (typically gold and silver) surfaces or onto the surface of metal nanoparticles. It is the fundamentals behind many color based biosensor applications and different lab-on-a-chip sensors.

Contents

Explanation

Surface plasmons, also known as surface plasmon polaritons, are surface electromagnetic waves that propagate in a direction parallel to the metal/dielectric (or metal/vacuum) interface. Since the wave is on the boundary of the metal and the external medium (air or water for example), these oscillations are very sensitive to any change of this boundary, such as the adsorption of molecules to the metal surface.

To describe the existence and properties of surface plasmons, one can choose from various models (quantum theory, Drude model, etc.). The simplest way to approach the problem is to treat each material as a homogeneous continuum, described by a frequency-dependent relative permittivity between the external medium and the surface. This quantity, hereafter referred to as the materials' "dielectric constant," is complex-valued. In order for the terms which describe the electronic surface plasmons to exist, the real part of the dielectric constant of the metal must be negative and its magnitude must be greater than that of the dielectric. This condition is met in the IR-visible wavelength region for air/metal and water/metal interfaces (where the real dielectric constant of a metal is negative and that of air or water is positive).

Localized surface plasmon polaritons (LSPRs) are collective electron charge oscillations in metallic nanoparticles that are excited by light. They exhibit enhanced near-field amplitude at the resonance wavelength. This field is highly localized at the nanoparticle and decays rapidly away from the nanoparticle/dieletric interface into the dielectric background, though far-field scattering by the particle is also enhanced by the resonance. Light intensity enhancement is a very important aspect of LSPRs and localization means the LSPR has very high spatial resolution (subwavelength), limited only by the size of nanoparticles. Because of the enhanced field amplitude, effects that depend on the amplitude such as magneto-optical effect are also enhanced by LSPRs.[1][2]

Realisation

In order to excite surface plasmons in a resonant manner, one can use an electron or light beam (visible and infrared are typical). The incoming beam has to match its impulse to that of the plasmon. In the case of p-polarized light (polarization occurs parallel to the plane of incidence), this is possible by passing the light through a block of glass to increase the wavenumber (and the impulse), and achieve the resonance at a given wavelength and angle. S-polarized (polarization occurs perpendicular to the plane of incidence) light cannot excite electronic surface plasmons. Electronic and magnetic surface plasmons obey the following dispersion relation:

Otto configuration

$$K(\omega) = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2\mu_1\mu_2}{\varepsilon_1\mu_1 + \varepsilon_2\mu_2}}$$

where ε stands for the dielectric constant, and μ for the magnetic permeability of the materials (1: the glass block, 2: the metal film).

Typical metals that support surface plasmons are silver and gold, but metals such as copper, titanium or chromium are also known to be applicable.

Kretschmann configuration

Using light to excite SP waves, there are two constructions which are well known. In the Otto setup, the light is shone on the wall of a glass block, typically a prism, and totally reflected. A thin metal (for example gold) film is positioned close enough, that the evanescent waves can interact with the plasma waves on the surface and excite the plasmons.

In the Kretschmann configuration, the metal film is evaporated onto the glass block. The light is again illuminating from the glass, and an evanescent wave penetrates through the metal film. The plasmons are excited at the outer side of the film. This configuration is used in most practical applications.

SPR emission
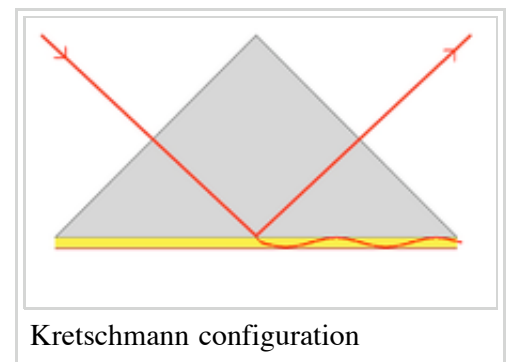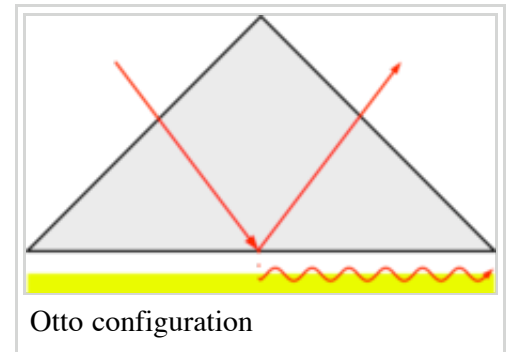
When the surface plasmon wave hits a local particle or irregularity—like on a rough surface—, part of the energy can be re-emitted as light. This emitted light can be detected *behind* the metal film in various directions.

Applications

Surface plasmons have been used to enhance the surface sensitivity of several spectroscopic measurements including fluorescence, Raman scattering, and second harmonic generation. However, in their simplest form, SPR reflectivity measurements can be used to detect molecular adsorption, such as polymers, DNA or proteins, etc. Technically, it is common, that the angle of the reflection minimum (absorption maximum) is measured. This angle changes in the order of 0.1° during thin (about nm thickness) film adsorption. (See also the Examples.) In other cases the changes in the absorption wavelength is followed.[3] The mechanism of detection is based on that the adsorbing molecules cause changes in the local index of refraction, changing the resonance conditions of the surface plasmon waves.

If the surface is patterned with different biopolymers, using adequate optics and imaging sensors (i.e. a camera), the technique can be extended to surface plasmon resonance imaging (SPRI). This method provides a high contrast of the images based on the adsorbed amount of molecules, somewhat similar to Brewster angle microscopy (this latter is most commonly used together with a Langmuir-Blodgett trough).

For nanoparticles, localized surface plasmon oscillations can give rise to the intense colors of suspensions or sols containing the nanoparticles. Nanoparticles or nanowires of noble metals exhibit strong absorption bands in the ultraviolet-visible light regime that are not present in the bulk metal. This extraordinary absorption increase has been exploited to increase light absorption in photovoltaic cells by depositing metal nanoparticles on the cell surface.[4] The energy (color) of this absorption differs when the light is polarized along or perpendicular to the nanowire.[5] Shifts in this resonance due to changes in the local index of refraction upon adsorption to the nanoparticles can also be used to detect biopolymers such as DNA or proteins. Related complementary techniques include plasmon waveguide resonance, QCM, extraordinary optical transmission, and Dual Polarisation Interferometry

Data interpretation

The most common data interpretation is based on the Fresnel formulas, which treat the formed thin films as infinite, continuous dielectric layers. This interpretation may result multiple possible refractive index and thickness values. However, usually only one solution is within the reasonable data range.

Metal particle plasmons are usually modeled using the Mie scattering theory.

In many cases no detailed models are applied, but the sensors are calibrated for the specific application, and used with interpolation within the calibration curve.

Examples

Layer-by-layer self-assembly

One of the first common applications of surface plasmon resonance spectroscopy was the measurement of the thickness (and refractive index) of adsorbed self-assembled nanofilms on gold substrates. The resonance curves shift to higher angles as the thickness of the adsorbed film increases. This example is a 'static SPR' measurement.

When higher speed observation is desired, one can select an angle right below the resonance point (the angle of minimum reflectance), and measure the reflectivity changes at that point. This is the so called 'dynamic SPR' measurement. The interpretation of the data assumes, that the structure of the film does not change significantly during the measurement.

SPR curves measured during the adsorption of a polyelectrolyte and then a clay mineral self-assembled film onto a thin (ca. 38 nanometers) gold sensor.
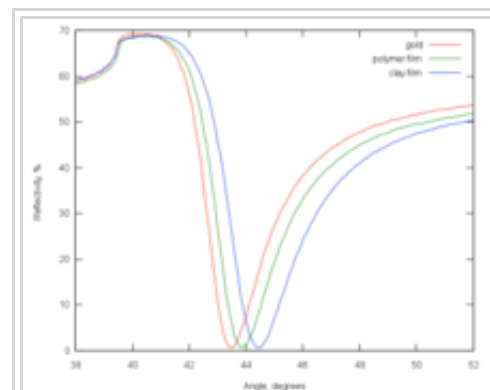
Binding constant determination

When the affinity of two ligands has to be determined, the binding constant must be determined. It is the equilibrium value for the product quotient. This value can also be found using the dynamical SPR parameters and, as in any chemical reaction, it is the association rate divided by the dissociation rate.

For this, a so-called bait ligand is immobilized on the dextran surface of the SPR crystal. Through a microflow system, a solution with the prey analyte is injected over the bait layer. As the prey analyte binds the bait ligand, an increase in SPR signal (expressed in response units, RU) is observed. After desired association time, a solution without the prey analyte (usually the buffer) is injected on the microfluidics that dissociates the bound complex between bait ligand and prey analyte. Now as the prey analyte dissociates from the bait ligand, a decrease in SPR signal (expressed in response units, RU) is observed. From these association ('on rate', k_a) and dissociation rates ('off rate', k_d), the equilibrium dissociation constant ('binding constant', K_D) can be calculated.

Association and dissociation signal
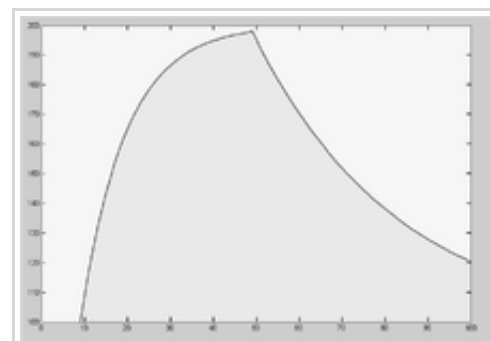

Example of output from Biacore

The actual SPR signal can be explained by the electromagnetic 'coupling' of the incident light with the surface plasmon of the gold layer. This plasmon can be influenced by the layer just a few nanometer across the gold-solution interface i.e. the bait protein and possibly the prey protein. Binding makes the reflection angle change;
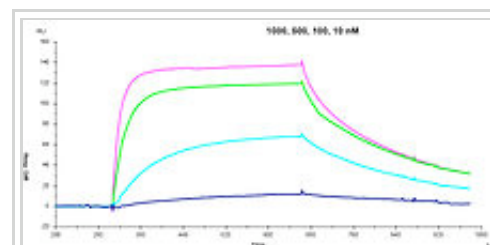
$$K_D = \frac{k_d}{k_a}$$

Magnetic plasmon resonance

Recently, there has been an interest in magnetic surface plasmons. These require materials with large negative magnetic permeability, a property that has only recently been made available with the construction of metamaterials.

See also

- Waves in plasmas
- plasmon
- Plasma oscillation
- Spinplasmonics
- Hydrogen sensor
- Nano-optics
- Biosensor
- Dual Polarization Interferometry

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Further reading

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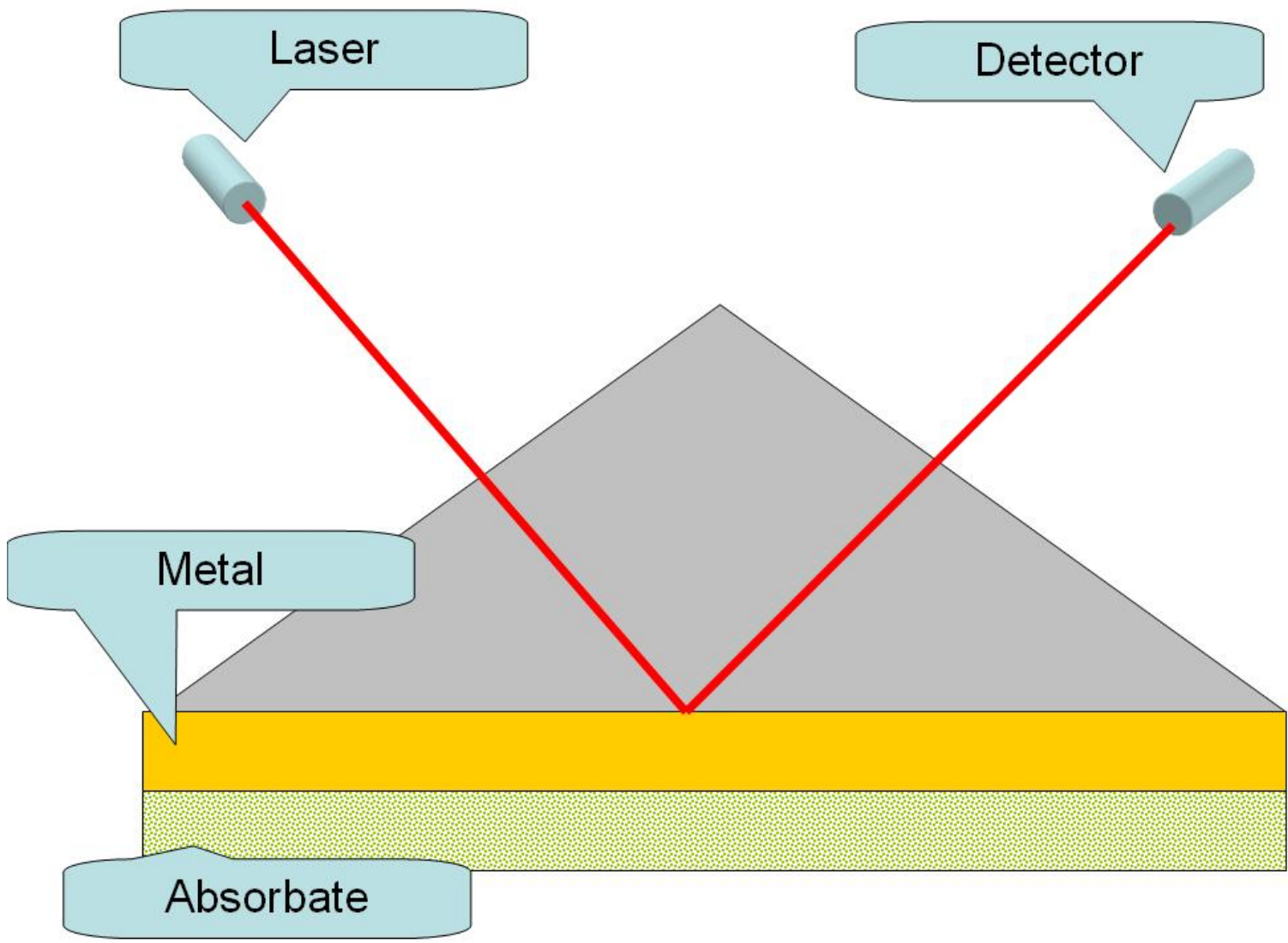# External links

- The affinity and valence of an antibody can be determined by equilibrium dialysis (ncbi.nlm.nih.gov) (http://www.ncbi.nlm.nih.gov/books/bv.fcgi?rid=imm.figgrp.2463)

Intensity of reflected light (%)

A B

Angle (φ)

Incident wave

45°

Glass

Silver

Air

Depth of wave into material

$\delta_{air} > \delta_{silver}$

EM field strength

Figure 3: Excitation process

Flow of sample
with analyte ▲

Bound ligand **Y**

Gold 50 nm

Glass

Analyte molecule

Probe molecule

Gold-coated chip

Polarizer

Bandpass filter

White light

CCD camera

Processed image showing
analyte binding

a

z

Dielectric

E

H_y

+ + + − − − + + + − − − ×

Metal

b

z

δ_d

δ_m

$|E_z|$

c

ω

$\omega = ck$

ω

k_o k_{SP}

k_x
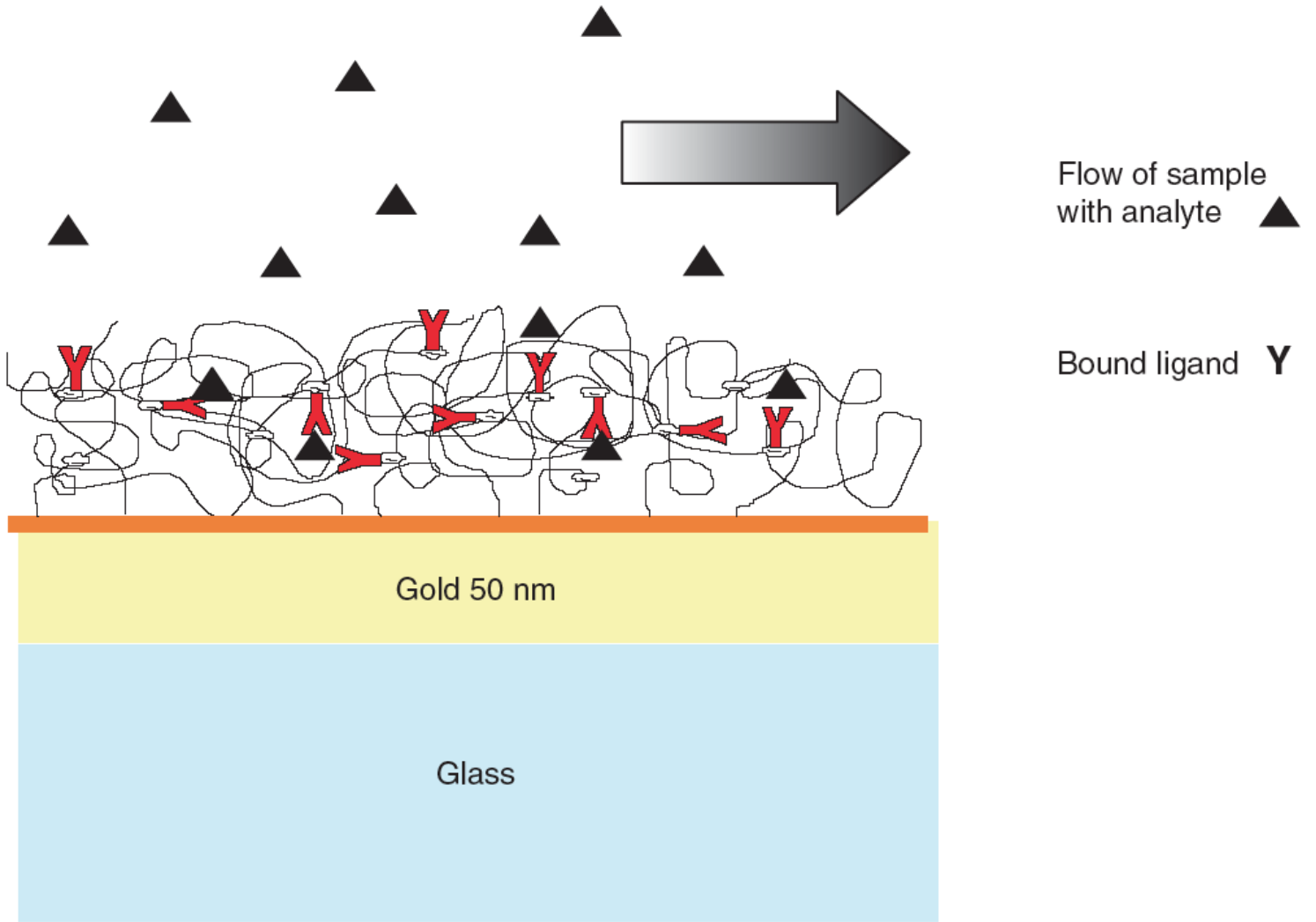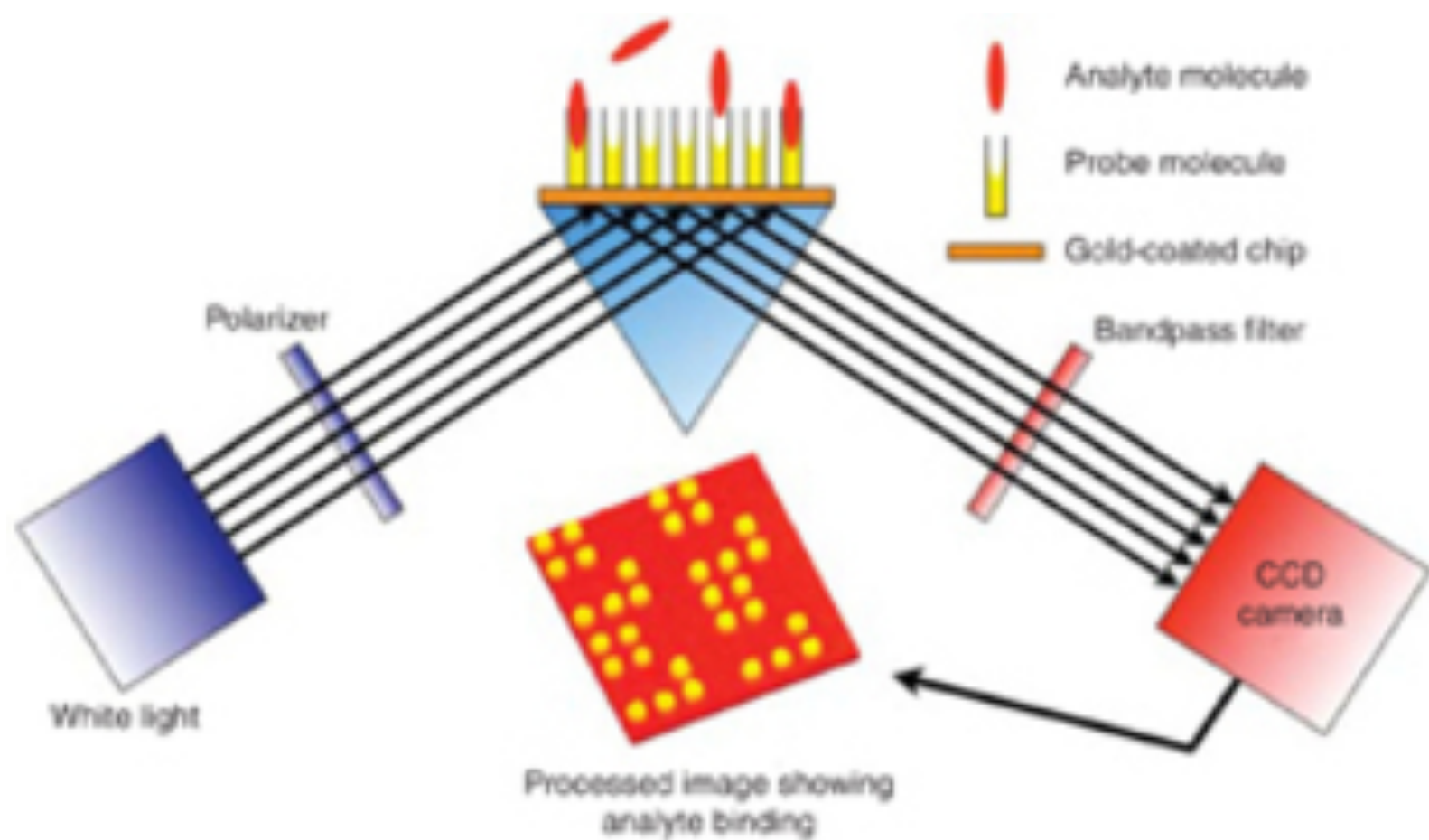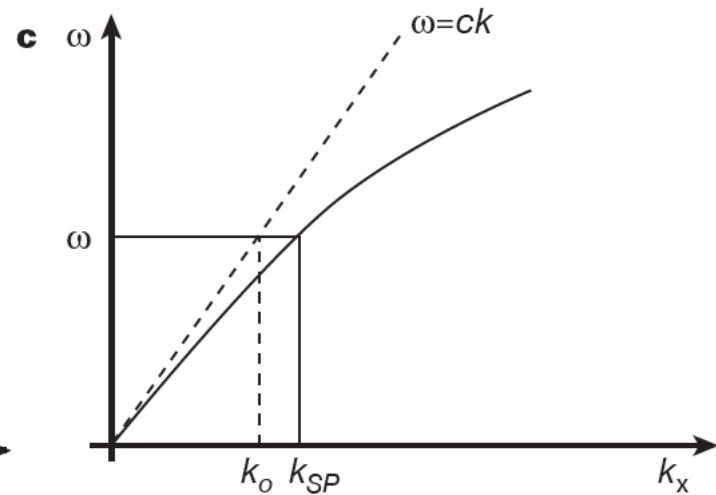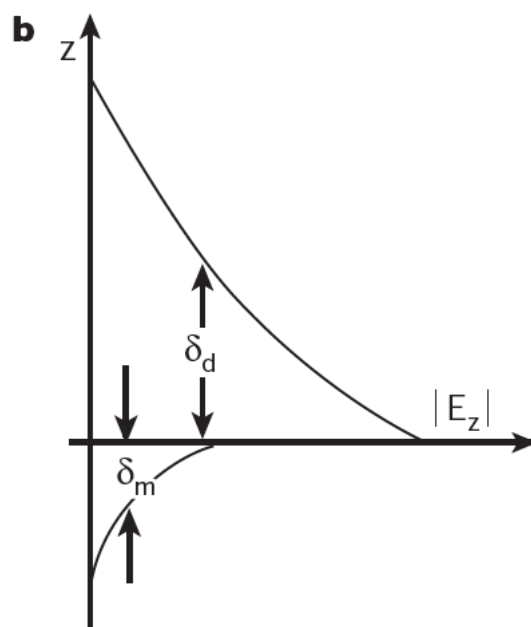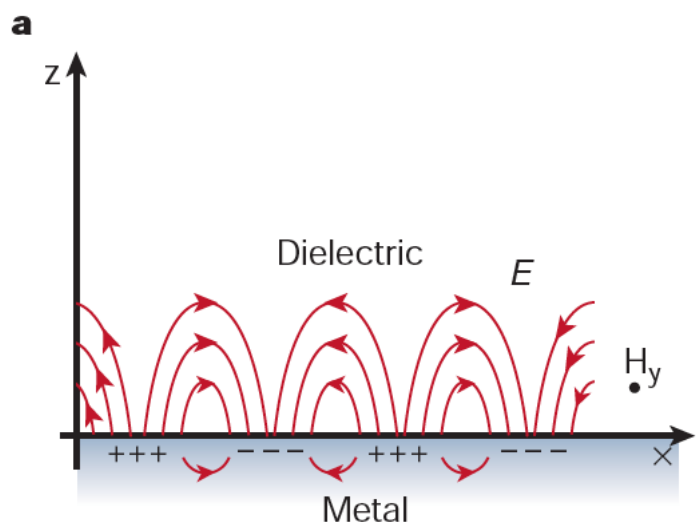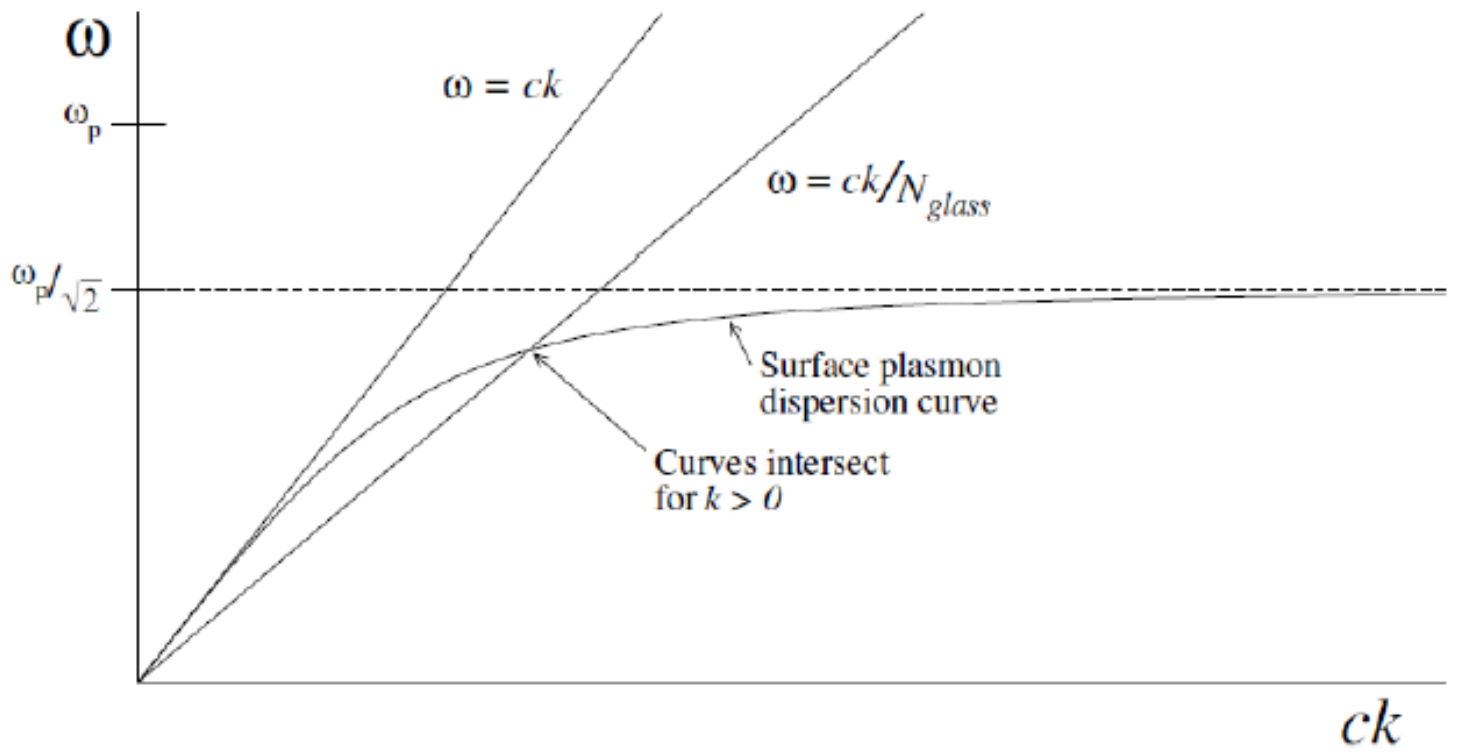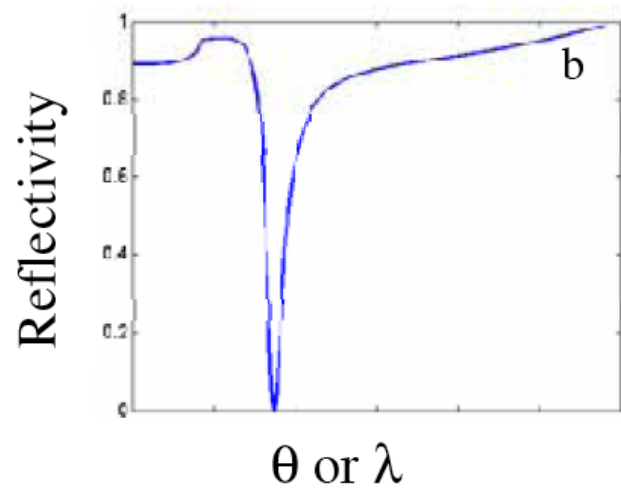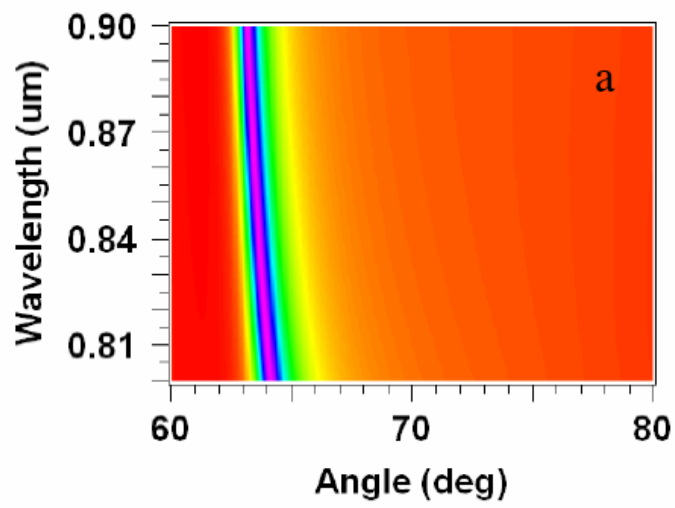
SPR Animations

http://www.youtube.com/watch?v=YAJ1b68mHtY
http://www.youtube.com/watch?v=pRzlzgALvqQ
http://www.youtube.com/watch?v=uyhxRIvw_cY
http://www.youtube.com/watch?v=wPaFxktbXmk
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http://www.youtube.com/watch?v=cRtwS6SAPy4

Plasmon

From Wikipedia, the free encyclopedia
  (Redirected from Plasmons)

In physics, a **plasmon** is a quantum of plasma oscillation. The plasmon is a quasiparticle resulting from the quantization of plasma oscillations just as photons and phonons are quantizations of light and mechanical vibrations, respectively. Thus, plasmons are collective oscillations of the free electron gas density, for example, at optical frequencies. Plasmons can couple with a photon to create another quasiparticle called a plasma polariton.

Since plasmons are the quantization of classical plasma oscillations, most of their properties can be derived directly from Maxwell's equations.

Contents

- 1 Explanation
- 2 Surface plasmons
- 3 Possible applications
- 4 See also
- 5 References
- 6 External links

Explanation

Plasmons can be described in the classical picture as an oscillation of free electron density against the fixed positive ions in a metal. To visualize a plasma oscillation, imagine a cube of metal is placed in an external electric field pointing to the right. Electrons will move to the left side (uncovering positive ions on the right side) until they cancel the field inside the metal. Now we switch the electric field off, and the electrons move to the right, repelled by each other and attracted to the positive ions left bare on the right side. They oscillate back and forth at the plasma frequency until the energy is lost in some kind of resistance or damping. Plasmons are a quantization of this kind of oscillation.

Plasmons play a large role in the optical properties of metals. Light of frequency below the plasma frequency is reflected, because the electrons in the metal screen the electric field of the light. Light of frequency above the plasma frequency is transmitted, because the electrons cannot respond fast enough to screen it. In most metals, the plasma frequency is in the ultraviolet, making them shiny (reflective) in the visible range. Some metals, such as copper[1] and gold, have electronic interband transitions in the visible range, whereby specific light energies (colors) are absorbed, yielding their distinct color. In semiconductors, the valence electron plasma frequency is usually in the deep ultraviolet,[2][3] which is why they too are reflective.

The plasmon energy can often be estimated in the free electron model as

$$E_p = \hbar \sqrt{\frac{ne^2}{m\epsilon_0}} = \hbar \cdot \omega_p,$$

where n is the conduction electron density, e is the elementary charge, m is the electron mass, ϵ_0 the permittivity of free space, $\hbar$ the Planck constant and ω_p the plasmon frequency.

Surface plasmons

Surface plasmons are those plasmons that are confined to surfaces and that interact strongly with light resulting in a polariton. They occur at the interface of a vacuum or material with a positive dielectric constant, and a negative dielectric constant (usually a metal or doped dielectric). They play a role in Surface Enhanced Raman Spectroscopy and in explaining anomalies in diffraction from metal gratings (Wood's anomaly), among other things. Surface plasmon resonance is used by biochemists to study the mechanisms and kinetics of ligands binding to receptors (i.e. a substrate binding to an enzyme).

More recently surface plasmons have been used to control colors of materials.[4] This is possible since controlling the material's surface shape controls the types of surface plasmons that can couple to it and propagate across it. This in turn controls the interaction of light with the surface. These effects are illustrated by the historic stained glass which adorn medieval cathedrals. In this case, the color is given by metal nanoparticles of a fixed size which interact with the optical field to give the glass its vibrant color. In modern science, these effects have been engineered for both visible light and microwave radiation. Much research goes on first in the microwave range because at this wavelength material surfaces can be produced mechanically as the patterns tend to be of the order a few centimeters. To produce optical range surface plasmon effects involves producing surfaces which have features <400 nm. This is much more difficult and has only recently become possible to do in any reliable or available way.

Gothic stained glass rose window of Notre-Dame de Paris. The colors were achieved by colloids of gold nano-particles.

Possible applications

Position and intensity of plasmon absorption and emission peaks are affected by molecular adsorption, which can be used in molecular sensors. For example, a fully operational prototype device detecting casein in milk has been fabricated. The device is based on detecting change in absorption of a gold layer.[5] Localized surface plasmons of metal nanoparticles can be used for sensing different types molecules, proteins, etc.

Plasmons are being considered as a means of transmitting information on computer chips, since plasmons can support much higher frequencies (into the 100 THz range, while conventional wires become very lossy in the tens of GHz). For plasmon-based electronics to be useful, the analog to the transistor, called a plasmonster, was invented.[6] In March 2010, S. Assefa et al. of IBM reported invention of ultra fast and noise free nanophotonic avalanche photodetectors which are poised to bring about the exaflop light circuit era.[7][8][9]

"We are now working on integrating all of our devices onto a microprocessor alongside transistors".[10] "The Avalanche Photodetector achievement, which is the last in a series of prior reports from IBM Research, is the last piece of the puzzle that completes the development of the "nanophotonics toolbox" of devices necessary to build the on-chip interconnects".[8] "With optical communications embedded into the processor chips, the prospect of building power-efficient computer systems with performance at the Exaflop level might not be a very distant future."[8]

Plasmons have also been proposed as a means of high-resolution lithography and microscopy due to their extremely small wavelengths. Both of these applications have seen successful demonstrations in the lab environment. Finally, surface plasmons have the unique capacity to confine light to very small dimensions which could enable many new applications.

Surface plasmons are very sensitive to the properties of the materials on which they propagate. This has led to their use to measure the thickness of monolayers on colloid films, such as screening and quantifying protein binding events. Companies such as Biacore have commercialized instruments which operate on these principles. Optical surface plasmons are being investigated with a view to improve makeup by L'Oréal among others.[11]

In 2009, a Korean research team found a way to greatly improve organic light-emitting diode efficiency with the use of plasmons.[12]

A group of European researchers led by IMEC has begun work to improve solar cell efficiencies and costs through incorporation of metallic nanostructures (using plasmonic effects) that can enhance absorption of light into different types of solar cells: crystalline silicon (c-Si), high-performance III-V, organic, and dye-sensitized solar cells. [13]

See also

- Surface plasmon resonance
- Waves in plasmas
- Plasma oscillation
- Spinplasmonics
- Transformation optics
- Extraordinary optical transmission
- Phonon

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External links

- A selection of free-download papers on Plasmonics in New Journal of Physics (http://www.iop.org/EJ/abstract/1367-2630/10/10/105001)
- http://www.plasmonicfocus.com
- http://www.sprpages.nl

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Categories: Plasma physics | Quasiparticles

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Plasma oscillation

From Wikipedia, the free encyclopedia

Plasma oscillations, also known as "**Langmuir waves**" (after Irving Langmuir), are rapid oscillations of the electron density in conducting media such as plasmas or metals. The oscillations can be described as an instability in the dielectric function of a free electron gas. The frequency only depends weakly on the wavelength. The quasiparticle resulting from the quantization of these oscillations is the plasmon.

Langmuir waves were discovered by American physicists Irving Langmuir and Lewi Tonks in the 1920s. They are parallel in form to Jeans instability waves, which are caused by gravitational instabilities in a static medium.

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Explanation

Consider a neutral plasma, consisting of a gas of positively charged ions and negatively charged electrons. If one displaces by a tiny amount all of the electrons with respect to the ions, the Coulomb force pulls back, acting as a restoring force.

'Cold' electrons

If the electrons are cold, it is possible to show that the charge density oscillates at the *plasma frequency*

$$\omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m^*}} \text{ (cgs units)} = \sqrt{\frac{n_e e^2}{m^* \varepsilon_0}} \text{ (SI units)} \left[rad/s\right],$$ where n_e is the number density of electrons,

e is the electric charge, m^* is the effective mass of the electron, and ε_0 is the permittivity of free space. Note that the above formula is derived under the approximation that the ion mass is infinite. This is generally a good approximation, as the electrons are so much lighter than ions. (One must modify this expression in the case of electron-positron plasmas, often encountered in astrophysics). Since the frequency is independent of the wavelength, these oscillations have an infinite phase velocity and zero group velocity.

Note that, if m^* is electron mass ($m^* = m_e$), plasma frequency ω_{pe} depends only on physical constants and

concentration of electrons n_e. The numeric expression for plasma ordinary frequency $f_{pe} = \omega_{pe} / 2\pi$ is

$$f_{pe} \approx 8980 \sqrt{n_e} \text{ Hz}$$

with number density n_e in cm^{-3}.

'Warm' electrons

If warm electrons are considered with an electron thermal speed $v_{e,th} = \sqrt{\dfrac{k_B T_e}{m_e}}$, the electron pressure acts as a restoring force as well as the electric field and the oscillations propagate with frequency and wavenumber related by

$$\omega^2 = \omega_{pe}^2 + 3k^2 v_{e,th}^2,$$

called the Bohm-Gross dispersion relation. If the spatial scale is large compared to the Debye length, the oscillations are only weakly modified by the pressure term, but at small scales the pressure term dominates and the waves become dispersionless with a speed of $\sqrt{3} \cdot v_{e,th}$. For such waves, however, the electron thermal speed is comparable to the phase velocity, i.e.,

$$v \sim v_{ph} \overset{\text{def}}{=} \frac{\omega}{k},$$

so the plasma waves can accelerate electrons that are moving with speed nearly equal to the phase velocity of the wave. This process often leads to a form of collisionless damping, called Landau damping. Consequently, the large-k portion in the dispersion relation is difficult to observe and seldom of consequence.

In a bounded plasma, fringing electric fields can result in propagation of plasma oscillations, even when the electrons are cold.

In a metal or semiconductor, the effect of the ions' periodic potential must be taken into account. This is usually done by using the electrons' effective mass in place of m.

See also

- Waves in plasmas
- plasmon
- Surface plasmon resonance
- Upper hybrid oscillation, in particular for a discussion of the modification to the mode at propagation angles oblique to the magnetic field
- In 2006, plasma physicists at the Universities of Texas and Michigan were able to photograph Langmuir waves, generated by a 30 TW laser pulse, for the first time.[1]
- Electron wake

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Categories: Waves in plasmas | Plasma physics

Polariton

From Wikipedia, the free encyclopedia

In physics, **polaritons** are quasiparticles resulting from strong coupling of electromagnetic waves with an electric or magnetic dipole-carrying excitation. They are an expression of the common quantum phenomenon known as level repulsion, also known as the anti-crossing principle. Polaritons describe the crossing of the dispersion of light with any interacting resonance.

Thus, a polariton is the result of the mixing of a photon with an excitation of a material. The most discussed types of polaritons are **phonon-polaritons**, resulting from coupling of an infrared photon with an optic phonon; **exciton-polaritons**, resulting from coupling of visible light with an exciton; **intersubband-polaritons**, resulting from coupling of an infrared or terahertz photon with an intersubband excitation; and **surface plasmon-polaritons**, resulting from coupling of surface plasmons with light (the wavelength depends on the substance and its geometry). Recently, special kinds of polaritons, called Bragg-polaritons or Braggoritons, have been observed [1] and studied theoretically.

Dispersion relation of polaritons in GaP. Red curves are the uncoupled phonon and photon dispersion relations, black curves are the result of coupling (from top to bottom: upper polariton, LO phonon, lower polariton).

Whenever the polariton picture is valid, the model of photons in crystals is insufficient. A major feature of polaritons is a strong dependency of the propagation speed of light through the crystal on the frequency. For exciton-polaritons, rich experimental results on various aspects have been gained in copper (I) oxide.

The polariton is a bosonic quasiparticle, and should not be confused with the polaron, a fermionic one, e.g. an electron plus attached phonon cloud.

See also

- Polaritonics
- Atomic coherence
- Polariton superfluid

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- This page was last modified on 23 July 2010 at 17:48.

Complex Dielectric Constant

Permittivity

From Wikipedia, the free encyclopedia

In electromagnetism, **permittivity** is the measure of how much resistance is encountered when forming an electric field in a medium. In other words, permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium. Permittivity is determined by the ability of a material to polarize in response to the field, and thereby reduce the total electric field inside the material. Thus, permittivity relates to a material's ability to transmit (or "permit") an electric field.

It is directly related to electric susceptibility, which is a measure of how easily a dielectric polarizes in response to an electric field.

In SI units, permittivity ε is measured in farads per meter (F/m); electric susceptibility χ is dimensionless. They are related to each other through

$$\varepsilon = \varepsilon_r \varepsilon_0 = (1 + \chi)\varepsilon_0$$

where ε_r is the relative permittivity of the material, and $\varepsilon_0 = 8.85\ldots \times 10^{-12}$ F/m is the vacuum permittivity.

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Explanation

In electromagnetism, the electric displacement field **D** represents how an electric field **E** influences the organization of electrical charges in a given medium, including charge migration and electric dipole reorientation. Its relation to permittivity in the very simple case of *linear, homogeneous, isotropic* materials with *"instantaneous" response* to changes in electric field is

$$\mathbf{D} = \varepsilon \mathbf{E}$$

where the permittivity ε is a scalar. If the medium is anisotropic, the permittivity is a second rank tensor.

In general, permittivity is not a constant, as it can vary with the position in the medium, the frequency of the field applied, humidity, temperature, and other parameters. In a nonlinear medium, the permittivity can depend on the strength of the electric field. Permittivity as a function of frequency can take on real or complex values.

In SI units, permittivity is measured in farads per meter (F/m or $A^2 \cdot s^4 \cdot kg^{-1} \cdot m^{-3}$). The displacement field $\mathbf{D}$ is measured in units of coulombs per square meter (C/m^2), while the electric field $\mathbf{E}$ is measured in volts per meter (V/m). $\mathbf{D}$ and $\mathbf{E}$ describe the interaction between charged objects. $\mathbf{D}$ is related to the *charge densities* associated with this interaction, while $\mathbf{E}$ is related to the *forces* and *potential differences*.

Vacuum permittivity

Main article: vacuum permittivity

The vacuum permittivity ε_0 (also called **permittivity of free space** or the **electric constant**) is the ratio $\mathbf{D}/\mathbf{E}$ in free space. It also appears in the Coulomb force constant $1/4\pi\varepsilon_0$.

Its value is[1]

$$\varepsilon_0 \stackrel{\mathrm{def}}{=} \frac{1}{c_0^2 \mu_0} = \frac{1}{35950207149.4727056\pi} \frac{\mathrm{F}}{\mathrm{m}} \approx 8.8541878176\ldots \times 10^{-12} \frac{\mathrm{F}}{\mathrm{m}}$$

where

c_0 is the speed of light in free space,[2]
μ_0 is the vacuum permeability.

Constants c_0 and μ_0 are defined in SI units to have exact numerical values, shifting responsibility of experiment to the determination of the meter and the ampere.[3] (The approximation in the second value of ε_0 above stems from π being an irrational number.)

Relative permittivity

Main article: relative permittivity

The linear permittivity of a homogeneous material is usually given relative to that of free space, as a relative permittivity ε_r (also called dielectric constant, although this sometimes only refers to the static, zero-frequency relative permittivity). In an anisotropic material, the relative permittivity may be a tensor, causing birefringence. The actual permittivity is then calculated by multiplying the relative permittivity by ε_0:

$$\varepsilon = \varepsilon_r \varepsilon_0 = (1 + \chi)\varepsilon_0$$

where

χ (frequently written χ_e) is the electric susceptibility of the material.

The susceptibility is defined as the constant of proportionality (which may be a tensor) relating an electric field $\mathbf{E}$ to the induced dielectric polarization density $\mathbf{P}$ such that

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E},$$

where ε_0 is the electric permittivity of free space.

The susceptibility of a medium is related to its relative permittivity ε_r by

$$\chi = \varepsilon_r - 1.$$

So in the case of a vacuum,

$$\chi = 0.$$

The susceptibility is also related to the polarizability of individual particles in the medium by the Clausius-Mossotti relation.

The electric displacement $\mathbf{D}$ is related to the polarization density $\mathbf{P}$ by

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 (1 + \chi) \mathbf{E} = \varepsilon_r \varepsilon_0 \mathbf{E}.$$

The permittivity ε and permeability μ of a medium together determine the phase velocity c of electromagnetic radiation through that medium:

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

Dispersion and causality

In general, a material cannot polarize instantaneously in response to an applied field, and so the more general formulation as a function of time is

$$\mathbf{P}(t) = \varepsilon_0 \int_{-\infty}^{t} \chi(t - t') \mathbf{E}(t') \, dt'.$$

That is, the polarization is a convolution of the electric field at previous times with time-dependent susceptibility given by $\chi(\Delta t)$. The upper limit of this integral can be extended to infinity as well if one defines $\chi(\Delta t) = 0$ for $\Delta t < 0$. An instantaneous response corresponds to Dirac delta function susceptibility $\chi(\Delta t) = \chi \delta(\Delta t)$.

It is more convenient in a linear system to take the Fourier transform and write this relationship as a function of frequency. Due to the convolution theorem, the integral becomes a simple product,

$$\mathbf{P}(\omega) = \varepsilon_0 \chi(\omega) \mathbf{E}(\omega).$$

This frequency dependence of the susceptibility leads to frequency dependence of the permittivity. The shape of the susceptibility with respect to frequency characterizes the dispersion properties of the material.

Moreover, the fact that the polarization can only depend on the electric field at previous times (i.e. $\chi(\Delta t) = 0$ for $\Delta t < 0$), a consequence of causality, imposes Kramers–Kronig constraints on the susceptibility $\chi(0)$.
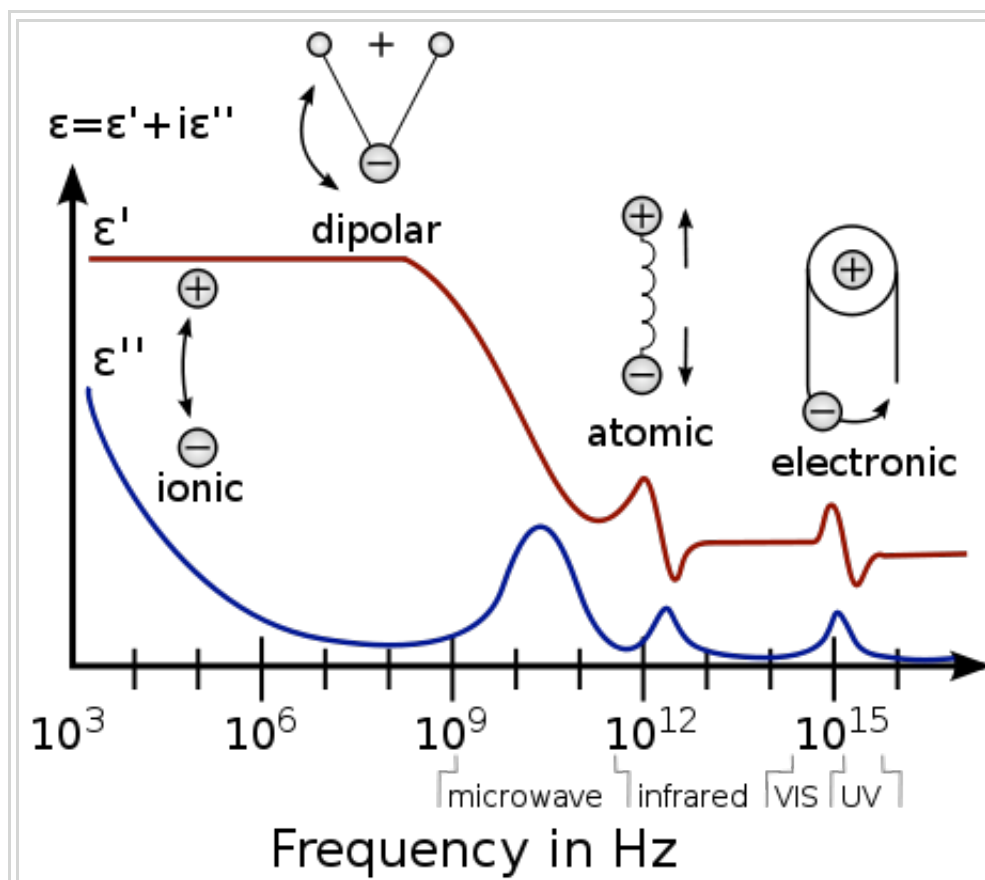
Complex permittivity

As opposed to the response of a vacuum, the response of normal materials to external fields generally depends on the frequency of the field. This frequency dependence reflects the fact that a material's polarization does not respond instantaneously to an applied field. The response must always be *causal* (arising after the applied field) which can be represented by a phase difference. For this reason permittivity is often treated as a complex function (since complex numbers allow specification of magnitude and phase) of the (angular) frequency of the applied field ω, $\varepsilon \longrightarrow \widehat{\varepsilon}(\omega)$. The definition of permittivity therefore becomes

$$D_0 e^{-i\omega t} = \widehat{\varepsilon}(\omega) E_0 e^{-i\omega t},$$

where

D_0 and E_0 are the amplitudes of the displacement and electrical fields, respectively, i is the imaginary unit, $i^2 = -1$.

A dielectric permittivity spectrum over a wide range of frequencies. ε' and ε'' denote the real and the imaginary part of the permittivity, respectively. Various processes are labeled on the image: ionic and dipolar relaxation, and atomic and electronic resonances at higher energies.[4]

It is important to realize that the choice of sign for time-dependence dictates the sign convention for the imaginary part of permittivity. The signs used here correspond to those commonly used in physics, whereas for

the engineering convention one should reverse all imaginary quantities.

The response of a medium to static electric fields is described by the low-frequency limit of permittivity, also called the static permittivity ε_s (also ε_{DC}):

$$\varepsilon_s = \lim_{\omega \to 0} \hat{\varepsilon}(\omega).$$

At the high-frequency limit, the complex permittivity is commonly referred to as ε_∞. At the plasma frequency and above, dielectrics behave as ideal metals, with electron gas behavior. The static permittivity is a good approximation for alternating fields of low frequencies, and as the frequency increases a measurable phase difference δ emerges between **D** and **E**. The frequency at which the phase shift becomes noticeable depends on temperature and the details of the medium. For moderate fields strength (E_0), **D** and **E** remain proportional, and

$$\hat{\varepsilon} = \frac{D_0}{E_0} = |\varepsilon| e^{i\delta}.$$

Since the response of materials to alternating fields is characterized by a complex permittivity, it is natural to separate its real and imaginary parts, which is done by convention in the following way:

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega) = \frac{D_0}{E_0} \left(\cos \delta + i \sin \delta \right).$$

where

> ε'' is the imaginary part of the permittivity, which is related to the dissipation (or loss) of energy within the medium.
> ε' is the real part of the permittivity, which is related to the stored energy within the medium.

The complex permittivity is usually a complicated function of frequency ω, since it is a superimposed description of dispersion phenomena occurring at multiple frequencies. The dielectric function $\varepsilon(\omega)$ must have poles only for frequencies with positive imaginary parts, and therefore satisfies the Kramers–Kronig relations. However, in the narrow frequency ranges that are often studied in practice, the permittivity can be approximated as frequency-independent or by model functions.

At a given frequency, the imaginary part of $\hat{\varepsilon}$ leads to absorption loss if it is positive (in the above sign convention) and gain if it is negative. More generally, the imaginary parts of the eigenvalues of the anisotropic dielectric tensor should be considered.

In the case of solids, the complex dielectric function is intimately connected to band structure. The primary quantity that characterizes the electronic structure of any crystalline material is the probability of photon absorption, which is directly related to the imaginary part of the optical dielectric function $\varepsilon(\omega)$. The optical dielectric function is given by the fundamental expression:[5]

$$\varepsilon(\omega) = 1 + \frac{8\pi^2 e^2}{m^2} \sum_{c,v} \int W_{cv}(E) \left[\varphi(\hbar\omega - E) - \varphi(\hbar\omega + E) \right] \, dx.$$

In this expression, $W_{cv}(E)$ represents the product of the Brillouin zone-averaged transition probability at the energy E with the joint density of states,[6][7] $J_{cv}(E)$; ϕ is a broadening function, representing the role of scattering in smearing out the energy levels.[8] In general, the broadening is intermediate between Lorentzian and Gaussian;[9][10] for an alloy it is somewhat closer to Gaussian because of strong scattering from statistical fluctuations in the local composition on a nanometer scale.

Classification of materials

Materials can be classified according to their permittivity and conductivity, σ. Materials with a large amount of loss inhibit the propagation of electromagnetic waves. In this case, generally when $\sigma/(\omega\varepsilon') \gg 1$, we consider the material to be a good conductor. Dielectrics are associated with lossless or low-loss materials, where $\sigma/(\omega\varepsilon') \ll 1$. Those that do not fall under either limit are considered to be general media. A *perfect dielectric* is a material that has no conductivity, thus exhibiting only a displacement current. Therefore it stores and returns electrical energy as if it were an ideal capacitor.

Lossy medium

In the case of lossy medium, i.e. when the conduction current is not negligible, the total current density flowing is:

$$J_{\text{tot}} = J_c + J_d = \sigma E - i\omega\varepsilon' E = -i\omega\hat{\varepsilon} E$$

where

      σ is the conductivity of the medium;
      ε' is the real part of the permittivity.
      $\hat{\varepsilon}$ is the complex permittivity

The size of the displacement current is dependent on the frequency ω of the applied field E; there is no displacement current in a constant field.

In this formalism, the complex permittivity is defined as[11]:

$$\hat{\varepsilon} = \varepsilon' - i\frac{\sigma}{\omega}$$

In general, the absorption of electromagnetic energy by dielectrics is covered by a few different mechanisms that influence the shape of the permittivity as a function of frequency:

- First, are the relaxation effects associated with permanent and induced molecular dipoles. At low frequencies the field changes slowly enough to allow dipoles to reach equilibrium before the field has measurably changed. For frequencies at which dipole orientations cannot follow the applied field due to

the viscosity of the medium, absorption of the field's energy leads to energy dissipation. The mechanism of dipoles relaxing is called dielectric relaxation and for ideal dipoles is described by classic Debye relaxation.

- Second are the resonance effects, which arise from the rotations or vibrations of atoms, ions, or electrons. These processes are observed in the neighborhood of their characteristic absorption frequencies.

The above effects often combine to cause non-linear effects within capacitors. For example, dielectric absorption refers to the inability of a capacitor that has been charged for a long time to completely discharge when briefly discharged. Although an ideal capacitor would remain at zero volts after being discharged, real capacitors will develop a small voltage, a phenomenon that is also called *soakage* or *battery action*. For some dielectrics, such as many polymer films, the resulting voltage may be less than 1-2% of the original voltage. However, it can be as much as 15 - 25% in the case of electrolytic capacitors or supercapacitors.

Quantum-mechanical interpretation

In terms of quantum mechanics, permittivity is explained by atomic and molecular interactions.

At low frequencies, molecules in polar dielectrics are polarized by an applied electric field, which induces periodic rotations. For example, at the microwave frequency, the microwave field causes the periodic rotation of water molecules, sufficient to break hydrogen bonds. The field does work against the bonds and the energy is absorbed by the material as heat. This is why microwave ovens work very well for materials containing water. There are two maxima of the imaginary component (the absorptive index) of water, one at the microwave frequency, and the other at far ultraviolet (UV) frequency. Both of these resonances are at higher frequencies than the operating frequency of microwave ovens.

At moderate frequencies, the energy is too high to cause rotation, yet too low to affect electrons directly, and is absorbed in the form of resonant molecular vibrations. In water, this is where the absorptive index starts to drop sharply, and the minimum of the imaginary permittivity is at the frequency of blue light (optical regime).

At high frequencies (such as UV and above), molecules cannot relax, and the energy is purely absorbed by atoms, exciting electron energy levels. Thus, these frequencies are classified as ionizing radiation.

While carrying out a complete *ab initio* (that is, first-principles) modelling is now computationally possible, it has not been widely applied yet. Thus, a phenomenological model is accepted as being an adequate method of capturing experimental behaviors. The Debye model and the Lorentz model use a 1st-order and 2nd-order (respectively) lumped system parameter linear representation (such as an RC and an LRC resonant circuit).

Measurement

> *Main article: dielectric spectroscopy*

The dielectric constant of a material can be found by a variety of static electrical measurements. The complex permittivity is evaluated over a wide range of frequencies by using different variants of dielectric

spectroscopy, covering nearly 21 orders of magnitude from 10^{-6} to 10^{15} Hz. Also, by using cryostats and ovens, the dielectric properties of a medium can be characterized over an array of temperatures. In order to study systems for such diverse exciting fields, a number of measurement setups are used, each adequate for a special frequency range.

Various microwave measurement techniques are outlined in Chen *et al.*.[12] Typical errors for the Hakki-Coleman method employing a puck of material between conducting planes are about 0.3%.[13]

- Low-frequency time domain measurements (10^{-6}-10^3 Hz)
- Low-frequency frequency domain measurements (10^{-5}-10^6 Hz)
- Reflective coaxial methods (10^6-10^{10} Hz)
- Transmission coaxial method (10^8-10^{11} Hz)
- Quasi-optical methods (10^9-10^{10} Hz)
- Fourier-transform methods (10^{11}-10^{15} Hz)

At infrared and optical frequencies, a common technique is ellipsometry. Dual polarisation interferometry is also used to measure the complex refractive index for very thin films at optical frequencies.

See also

- Density functional theory
- Electric field screening
- Green-Kubo relations
- Green's function (many-body theory)
- Linear response function
- Rotational Brownian motion
- Electromagnetic Permeability

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Further reading

- *Theory of Electric Polarization: Dielectric Polarization*, C.J.F. Böttcher, ISBN 0-444-41579-3
- *Dielectrics and Waves* edited by A. von Hippel, Arthur R., ISBN 0-89006-803-8
- *Dielectric Materials and Applications* edited by Arthur von Hippel, ISBN 0-89006-805-4.
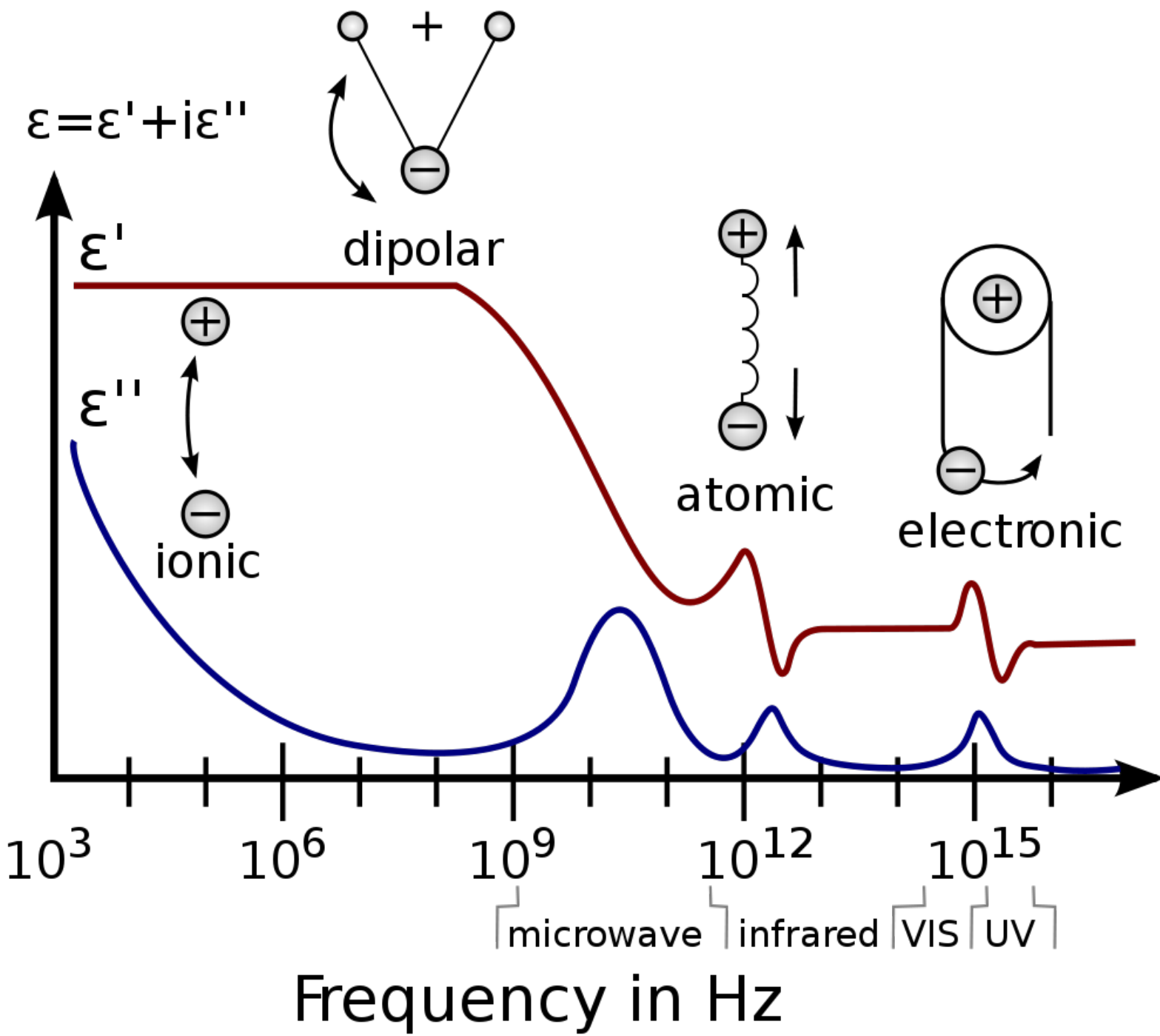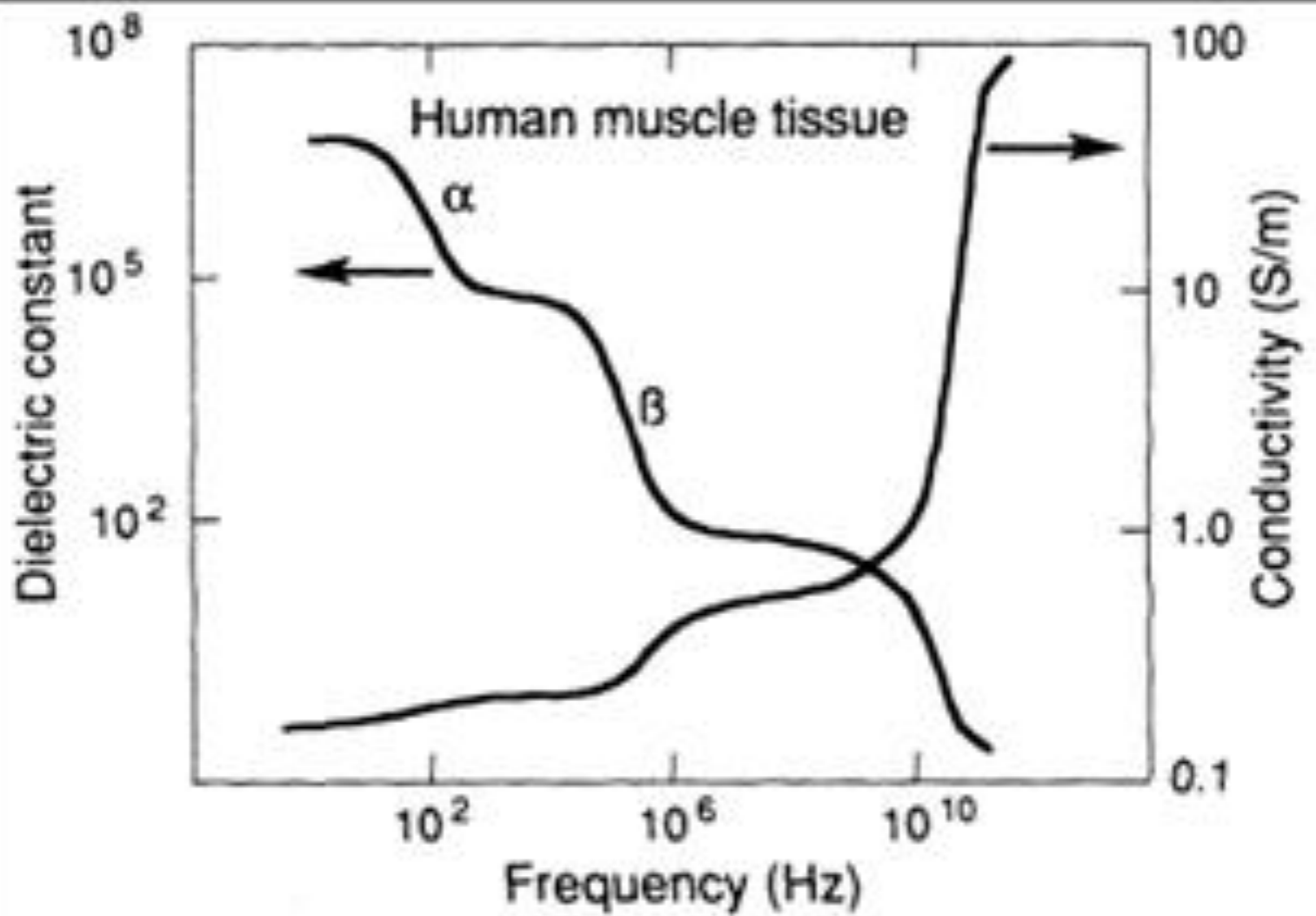
External links

- Electromagnetism (http://lightandmatter.com/html_books/0sn/ch11/ch11.html) , a chapter from an online textbook
- What's all this trapped charge stuff . . . (http://keith-snook.info/capacitor-soakage.html) , A different approach to some capacitor problems
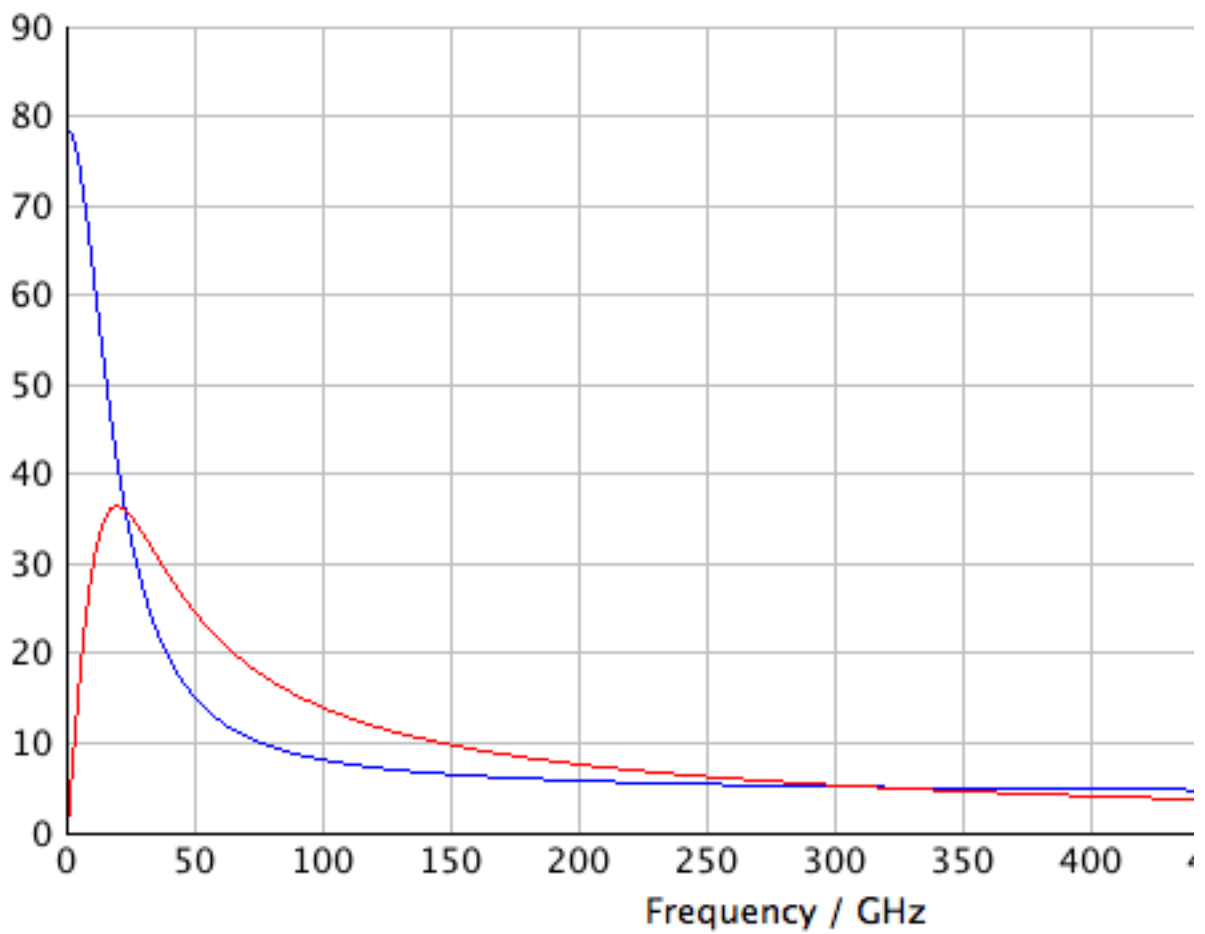
Retrieved from "http://en.wikipedia.org/wiki/Permittivity"

Categories: Condensed matter physics | Electric and magnetic fields in matter | Physical quantities | Fundamental physics concepts

$\varepsilon=\varepsilon'+i\varepsilon''$

ε'

ε''

dipolar

atomic

electronic

ionic

microwave   infrared   VIS   UV

10^3 10^6 10^9 10^{12} 10^{15}

Frequency in Hz

Graph of Real and Imaginary Dielectric Constant of Water aga

Frequency / GHz

Temperature 25 °C   (Plot)

SILICON

GOLD

DRUDE

ε_{imag}

ε_{real}

DEBYE

ε_{real}

ε_{imag}

LORENTZ

ε_{real}

ε_{imag}

Quantum-mechanical interpretation

In terms of quantum mechanics, permittivity is explained by atomic and molecular interactions.

At low frequencies, molecules in polar dielectrics are polarized by an applied electric field, which induces periodic rotations. For example, at the microwave frequency, the microwave field causes the periodic rotation of water molecules, sufficient to break hydrogen bonds. The field does work against the bonds and the energy is absorbed by the material as heat. This is why microwave ovens work very well for materials containing water. There are two maxima of the imaginary component (the absorptive index) of water, one at the microwave frequency, and the other at far ultraviolet (UV) frequency. Both of these resonances are at higher frequencies than the operating frequency of microwave ovens.
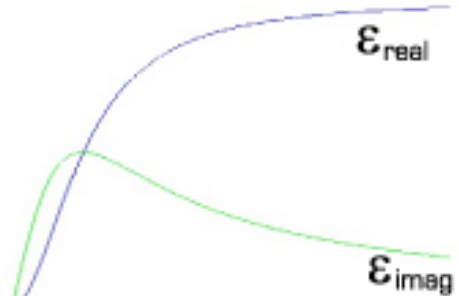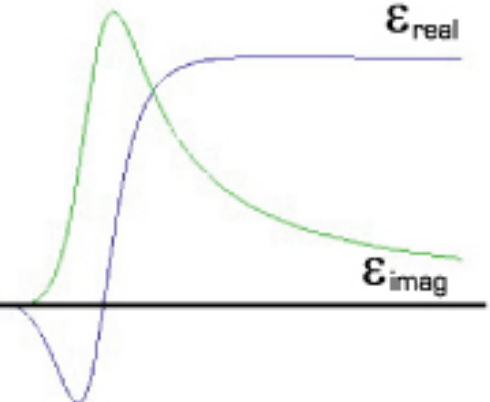
At moderate frequencies, the energy is too high to cause rotation, yet too low to affect electrons directly, and is absorbed in the form of resonant molecular vibrations. In water, this is where the absorptive index starts to drop sharply, and the minimum of the imaginary permittivity is at the frequency of blue light (optical regime).

At high frequencies (such as UV and above), molecules cannot relax, and the energy is purely absorbed by atoms, exciting electron energy levels. Thus, these frequencies are classified as ionizing radiation.

While carrying out a complete *ab initio* (that is, first-principles) modelling is now computationally possible, it has not been widely applied yet. Thus, a phenomenological model is accepted as being an adequate method of capturing experimental behaviors. The Debye model and the Lorentz model use a 1st-order and 2nd-order (respectively) lumped system parameter linear representation (such as an RC and an LRC resonant circuit).

Debye relaxation

Debye relaxation is the dielectric relaxation response of an ideal, noninteracting population of dipoles to an alternating external electric field. It is usually expressed in the complex permittivity ε of a medium as a function of the field's frequency ω:

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + i\omega\tau},$$

where ε_∞ is the permittivity at the high frequency limit, $\Delta\varepsilon = \varepsilon_s - \varepsilon_\infty$ where ε_s is the static, low frequency permittivity, and τ is the characteristic relaxation time of the medium.

This relaxation model was introduced by and named after the chemist Peter Debye (1913).[5]

Variants of the Debye equation

- Cole–Cole equation
- Cole–Davidson equation
- Havriliak–Negami relaxation
- Kohlrausch–Williams–Watts function (Fourier transform of stretched exponential function)

In metals: damping due to electron collisions at a rate $\Gamma = 1/\tau$ resulting in

$$\varepsilon_r'(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2} = 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2}$$

$$\varepsilon_r''(\omega) = \omega_p^2 \frac{\Gamma/\omega}{\omega^2 + \Gamma^2} = \frac{\omega_p^2 \tau}{\omega(1 + \omega^2 \tau^2)}$$

Collision times in metals $\sim 10^{-14}$ s, so at optical frequencies $\omega^2 \tau^2 \gg 1$

In this high frequency limit $\quad \varepsilon_r'(\omega) \approx 1 - \frac{\omega_p^2}{\omega^2} \quad$ and $\quad \varepsilon_r''(\omega) \approx \frac{\omega_p^2}{\omega^3 \tau} = \frac{\omega_p^2 \Gamma}{\omega^3}$

Lorentz model : bound electrons and a resonance frequency ω_0

$$\vec{r}(\omega) = \frac{-e}{m} \frac{\vec{E}(\omega)}{(\omega_0^2 - \omega^2 - i\omega\Gamma)} \quad \text{and} \quad \chi(\omega) = \frac{Ne^2}{\epsilon_0 m} \frac{1}{\omega_0^2 - \omega^2 - i\Gamma\omega}$$

Drude model : conduction electrons are not bound to atoms $\Rightarrow \omega_0 \rightarrow 0$

$$\vec{r}(\omega) = \frac{e}{m} \frac{\vec{E}(\omega)}{(\omega^2 + i\Gamma\omega)} \quad \text{and} \quad \chi(\omega) = -\frac{Ne^2}{\epsilon_0 m} \frac{1}{\omega^2 + i\Gamma\omega}$$

corresponding to the real and imaginary susceptibility

$$\chi'(\omega) = -\frac{\omega_p^2}{\omega^2 + \Gamma^2} \qquad\qquad \chi''(\omega) = \omega_p^2 \frac{\Gamma/\omega}{\omega^2 + \Gamma^2}$$

and the real and imaginary parts of the complex dielectric function

$$\varepsilon_r'(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2} \qquad\qquad \varepsilon_r''(\omega) = \omega_p^2 \frac{\Gamma/\omega}{\omega^2 + \Gamma^2}$$

Vacuum permittivity

From Wikipedia, the free encyclopedia

The physical constant ε_0, commonly called the **vacuum permittivity**, **permittivity of free space** or **electric constant**, relates the units for electric charge to mechanical quantities such as length and force.[1] For example, the force between two separated electric charges (in vacuum) is given by Coulomb's law:

$$F_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

where q_1 and q_2 are the charges, and r is the distance between them. Likewise, ε_0 appears in Maxwell's equations, which describe the properties of electric and magnetic fields and electromagnetic radiation, and relate them to their sources.

Contents

- 1 Value
- 2 Terminology
- 3 Historical origin of the parameter ε_0
    - 3.1 Rationalization of units
    - 3.2 Determination of a value for ε_0
- 4 Permittivity of real media
- 5 See also
- 6 Notes

Value

The value of ε_0 is *defined* by the formula

$$\varepsilon_0 = \frac{1}{\mu_0 c_0^2}$$

where c_0 is the speed of light in vacuum,[2] and μ_0 is the parameter that international Standards Organizations call the "magnetic constant" (commonly called vacuum permeability). Since μ_0 has the *defined* value $4\pi \times 10^{-7}$ H m^{-1},[3] and c_0 has the *defined* value 299 792 458 m·s^{-1},[4] it follows that ε_0 has a *defined* value given approximately by

$\varepsilon_0 \approx 8.854\ 187\ 817... \times 10^{-12}$ F·m^{-1} (or A^2·s^4·kg^{-1}·m^{-3} in SI base units, or C^2·N^{-1}·m^{-2} or C·V^{-1}·m^{-1} using other SI coherent units).[5][6]

The ellipsis (...) does not indicate experimental uncertainty, but the arbitrary termination of a nonrecurring decimal. The historical origins of the electric constant ε_0, and its value, are explained in more detail below.

Under the proposals to redefine the ampere as a fixed number of elementary charges per second,[7] the electric constant would no longer have an exact fixed value. Instead, it would be defined by the equation

$$\varepsilon_0 = \frac{e^2}{2\alpha h c_0}$$

where e is the elementary charge, α is the fine structure constant and h is the Planck constant. The relative uncertainty in the value would be the same as that of the fine structure constant, currently 6.8×10^{-10}.[5]

Terminology

Historically, the parameter ε_0 has been known by many different names. The terms "vacuum permittivity" or its variants, such as "permittivity in/of vacuum",[8][9] "permittivity of empty space",[10] or "permittivity of free space"[11] are widespread. Standards Organizations worldwide now use "electric constant" as a uniform term for this quantity,[5] and official standards documents have adopted the term (although they continue to list the older terms as synonyms).[12][13]

Another historical synonym was "dielectric constant of vacuum", as "dielectric constant" was sometimes used in the past for the absolute permittivity.[14][15] However, in modern usage "dielectric constant" typically refers exclusively to a relative permittivity $\varepsilon/\varepsilon_0$ and even this usage is considered "obsolete" by some standards bodies in favor of relative static permittivity.[13][16] Hence, the term "dielectric constant of vacuum" for the electric constant ε_0 is considered obsolete by most modern authors, although occasional examples of continuing usage can be found.

As for notation, the constant can be denoted by either ε_0 or ϵ_0, using either of the common glyphs for the letter epsilon.

Historical origin of the parameter ε_0

As indicated above, the parameter ε_0 is a measurement-system constant. Its presence in the equations now used to define electromagnetic quantities is the result of the so-called "rationalization" process described below. But the method of allocating a value to it is a consequence of the result that Maxwell's equations predict that, in free space, electromagnetic waves move with the speed of light. Understanding why ε_0 has the value it does requires a brief understanding of the history of how electromagnetic measurement systems developed.

Rationalization of units

The experiments of Coulomb and others showed that the force F between two equal point-like "amounts" of

electricity, situated a distance r apart in free space, should be given by a formula that has the form

$$F = k_e Q^2/r^2,$$

where Q is a quantity that represents the amount of electricity present at each of the two points, and k_e is Coulomb's constant. If one is starting with no constraints, then the value of k_e may be chosen arbitrarily.[17] For each different choice of k_e there is a different "interpretation" of Q: to avoid confusion, each different "interpretation" has to be allocated a distinctive name and symbol.

In one of the systems of equations and units agreed in the late 19th century, called the "centimetre-gram-second electrostatic system of units" (the cgs esu system), the constant k_e was taken equal to 1, and a quantity now called "gaussian electric charge" q_s was defined by the resulting equation

$$F = q_s{}^2/r^2.$$

The unit of gaussian charge, the statcoulomb, is such that two units, a distance of 1 centimetre apart, repel each other with a force equal to the cgs unit of force, the dyne. Thus the unit of gaussian charge can also be written 1 dyne$^{1/2}$ cm. "Gaussian electric charge" is not the same mathematical quantity as modern (rmks) electric charge and is not measured in coulombs.

The idea subsequently developed that it would be better, in situations of spherical geometry, to include a factor 4π in equations like Coulomb's law, and write it in the form:

$$F = k'_e q'_s{}^2/4\pi r^2.$$

This idea is called "rationalization". The quantities q'_s and k_e' are not the same as those in the older convention. Putting $k_e'{=}1$ generates a unit of electricity of different size, but it still has the same dimensions as the cgs esu system.

The next step was to treat the quantity representing "amount of electricity" as a fundamental quantity in its own right, denoted by the symbol q, and to write Coulomb's Law in its modern form:

$$F = q^2/4\pi\epsilon_0 r^2.$$

The system of equations thus generated is known as the rationalized metre-kilogram-second (rmks) equation system, or "metre-kilogram-second-ampere (mksa)" equation system. This is system used to define the SI units.[18] The new quantity q is given the name "rmks electric charge", or (nowadays) just "electric charge". Clearly, the quantity q_s used in the old cgs esu system is related to the new quantity q by

$$q_s = q/(k'_e \epsilon_0)^{1/2}.$$

Determination of a value for ε_0

One now adds the requirement that one wants force to be measured in newtons, distance in metres, and charge

to be measured in the engineers' practical unit, the coulomb, which is defined as the charge accumulated when a current of 1 ampere flows for one second. This shows that the parameter ε_0 should be allocated the unit $C^2 \cdot N^{-1} \cdot m^{-2}$ (or equivalent units - in practice "farads per metre").

In order to establish the numerical value of ε_0, one makes use of the fact that if one uses the rationalized forms of Coulomb's law and Ampère's force law (and other ideas) to develop Maxwell's equations, then the relationship stated above is found to exist between ε_0, μ_0 and c_0. In principle, one has a choice of deciding whether to make the coulomb or the ampere the fundamental unit of electricity and magnetism. The decision was taken internationally to use the ampere. This means that the value of ε_0 is determined by the values of c_0 and μ_0, as stated above. For a brief explanation of how the value of μ_0 is decided, see the article about μ_0.

Permittivity of real media

By convention, the electric constant ε_0 appears in the relationship that defines the electric displacement field **D** in terms of the electric field **E** and classical electrical polarization density **P** of the medium. In general, this relationship has the form

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}.$$

For a linear dielectric, **P** is assumed to be proportional to **E**, so one has

$$\mathbf{D} = \varepsilon \mathbf{E} = \varepsilon_r \varepsilon_0 \mathbf{E}$$

where ε is the permittivity and ε_r the relative static permittivity. In vacuum, the polarization $\mathbf{P} = \mathbf{0}$, so $\varepsilon_r = 1$ and $\varepsilon = \varepsilon_0$.

See also

- Casimir effect
- Coulomb's law
- Electromagnetic wave equation
- ISO 31-5
- Mathematical descriptions of the electromagnetic field
- Sinusoidal plane-wave solutions of the electromagnetic wave equation
- Dimensional formula

Notes

1. ^ "electric constant" (http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=121-11-03) . *Electropedia: International Electrotechnical Vocabulary (IEC 60050)*. Geneva: International Electrotechnical Commission. http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=121-11-03. Retrieved 2010-04-02.
2. ^ Quote from NIST: "The symbol c_0 (or sometimes simply c) is the conventional symbol for the speed of light in vacuum. " See NIST *Special Publication 330*, p. 18 (http://physics.nist.gov/Pubs/SP330/sp330.pdf)
3. ^ See the last sentence of the NIST definition of ampere (http://physics.nist.gov/cuu/Units/ampere.html) .

4. ∧ See the last sentence of the NIST definition of meter (http://physics.nist.gov/cuu/Units/meter.html) .
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6. ∧ A summary of the definitions of c_0, μ_0 and ε_0 is provided in the 2006 CODATA Report: CODATA report, pp. 6-7 (http://physics.nist.gov/cuu/Constants/codata.pdf)
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11. ∧ B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, 1991)
12. ∧ International Bureau of Weights and Measures (2006). "The International System of Units (SI)" (http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf) (PDF). p. 12. http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf.
13. ∧ *a b* Braslavsky, S.E. (2007). "Glossary of terms used in photochemistry ((http://www.iupac.org/publications/pac/2007/pdf/7903x0293.pdf) IUPAC recommendations 2006)". *Pure and Applied Chemistry* **79** (3): 293–465; see p. 348.. doi:10.1351/pac200779030293 (http://dx.doi.org/10.1351%2Fpac200779030293) . http://www.iupac.org/publications/pac/2007/pdf/7903x0293.pdf
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