Electromagnetic properties of materials

Electromagnetics
and
Remote Sensing Lab
(ERSLab)

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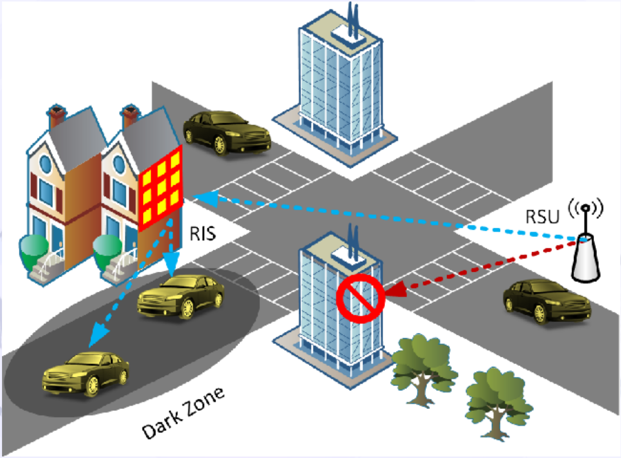
Outline

Reconfigurable intelligent surface (RIS)

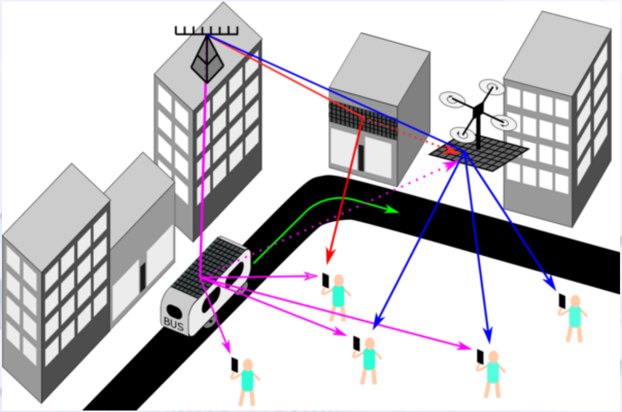
It is a programmable structure that can be used to control the propagation of electromagnetic waves by changing the electric and magnetic properties of the surface.

- By placing these surfaces in an environment, the properties of radio channels can be controlled. This opens up new opportunities:
  - To improve the performance of wireless systems, i.e.; 5g and 6g.
  - To foster mobile edge computing (MEC) paradigm by providing RIS-aided reflected link to off-load data.

Reconfigurable intelligent surfaces



Reconfigurable intelligent surfaces



EM cloaking

Definition

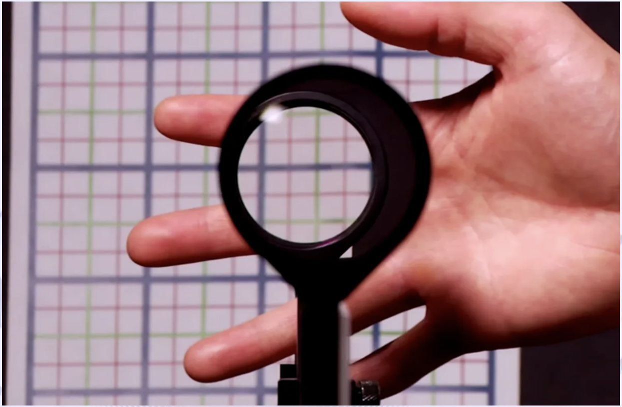
It means making an object "invisible" for electromagnetic radiation in a certain frequency range.

- An object is invisible if:
  - it does not reflect waves back to the source;
  - it does not scatter waves in other directions;
  - it does not create any shadow, i.e., there is no scattering in the forward direction.

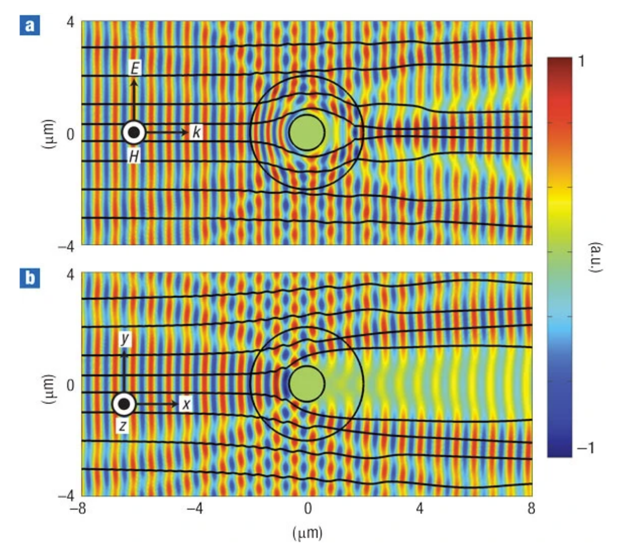
In simple terms. . .

this means that - to be invisible - the object should not disturb the fields existing outside the object

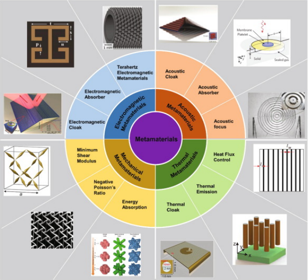
Optical cloaking



Optical cloaking



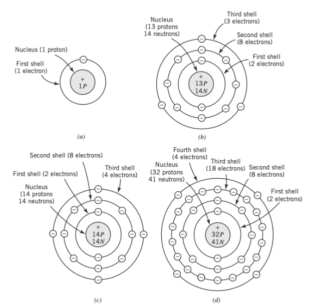
Metamaterials



Definition

They are artificially structured materials used to control and manipulate light, sound, and many other physical phenomena. Their properties are derived both from the inherent properties of their constituent materials, as well as from the geometrical arrangement of those materials.

Atoms, elements, molecules



Atom

An atom of an element consists of a very small but massive nucleus that is surrounded by a number of negatively charged electrons revolving about the nucleus. The nucleus contains neutrons, which are neutral particles, and protons, which are positively charged particles.

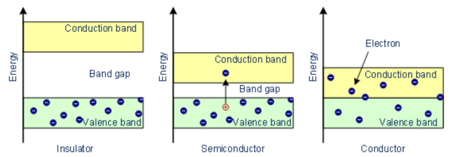
Electrons

Valence band

The outer shell of an atom is referred to as the valence band and the electrons occupying that band are known as valence electrons.

- Electrons of any atom exist only in discrete states and possess only discrete amounts of energy (quanta) corresponding to the discrete radii of their corresponding orbital shells.
- An electron moving from a lower- to a higher-energy orbit absorbs an energy quanta.
- An electron moving from a higher- to a lower-energy orbit radiates an energy quanta.
- An electron that maintains its orbit neither absorbs nor radiates energy.

Dielectrics, semiconductors, conductors



Valence and conduction bands...

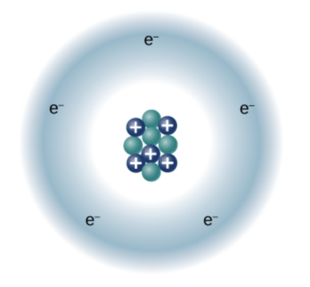
- are partially overlapped in conductors;
- are separated by a large band gap in insulators (aka dielectrics);
- call for a band gap (smaller than insulators) in semi-conductors.

Outline

Dielectrics

No free charge

Ideal dielectrics do not contain any free charges (such as in conductors).

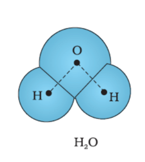


Their atoms and molecules are macroscopically neutral

Polar vs non-polar dielectrics

dielectrics

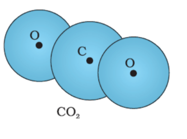
polar



A polar molecule is one in which the centres of positive and negative charges are separated

There is a permanent dipole moment even in absence of external field

non-polar



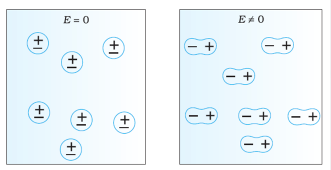
A non-polar molecule is one in which the centers of positive and negative charges coincide.

There is no permanent di-pole

Polar vs non-polar dielectrics

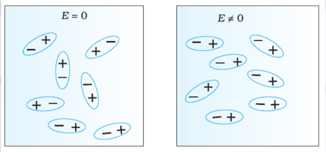
When an external static field $\mathbf{E}_a$ is applied

the dielectric exhibits a polarization effect that manifests itself in both polar and non-polar dielectrics.



Non-polar dielectric

the centroids of the bound negative and positive charges shift slightly in positions (assumed to be an infinitesimal distance) relative to each other, thus creating numerous electric dipoles.



Polar dielectric

The dipoles which, in absence of the static field are randomly oriented, align with the applied field

Static permittivity

The polarization effect

can be macroscopically described introducing an electric polarization vector **P**.

- The **P** vector accounts for:
  - The generation of dipoles in non-polar dielectrics.
  - The orientation of dipoles in polar dielectrics.
- In terms of constitutive relationship:
  - We start from the vacuum $\mathbf{D} = \epsilon_o \mathbf{E}_a$ obtaining
  - $\mathbf{D} = \epsilon_o \mathbf{E}_a + \epsilon_o \chi_e \mathbf{E}_a = \epsilon_o \mathbf{E}_a + \mathbf{P}$
  - with χ_e known as electric susceptibility
  - In conclusion, in a dielectric within a static electric field, the constitutive relationship reads as follows:

$$\mathbf{D} = \epsilon_s \mathbf{E}_a \quad \text{with} \quad \epsilon_s = \epsilon_o (1 + \chi_e) \tag{1}$$

ϵ_s is the static permittivity

Static permittivity

- It is usual to define a relative permittivity

$$\epsilon_{sr} = \frac{\epsilon_s}{\epsilon_o} = 1 + \chi_e \tag{2}$$

- which is typically termed as dielectric constant

Dielectric constant

The dielectric constant of a dielectric material is a parameter that indicates the relative (compared to vacuum) charge (energy) storage capabilities of a dielectric material; the larger its value, the greater its ability to store charge (energy).

Dielectric constant of some materials

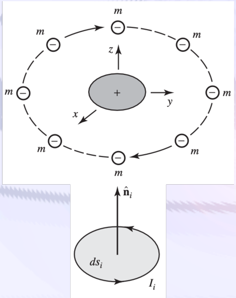
Substance	Dielectric Constant
Vacuum	1
Air	1.00054
Glass	5-10
Nylon	3.5
Polyethylene	2.3
Polystyrene	2.6
Rubber	2-3
Teflon	2.1
Water (20°C)	80

Outline

Magnetic materials

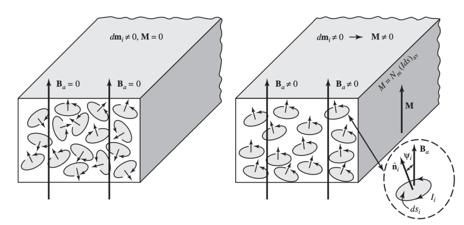
Definition

Magnetic materials are those that exhibit magnetic polarization when they are subjected to an applied magnetic field.



Each orbiting electron can be modeled by an equivalent small electric current loop whose current flows in the direction opposite to the electron orbit

Magnetic polarization



Magnetic polarization

In the absence of an applied magnetic field the magnetic dipoles and their corresponding electric loops are oriented in a random fashion. When a magnetic field $\mathbf{B}_o$ is applied, the magnetic dipoles tends to align in the direction of $\mathbf{B}_o$.

Magnetic polarization

Magnetic polarization vector

The realignment of the magnetic dipoles can be macroscopically described by a magnetic polarization vector **M** that accounts for the realignment of the magnetic dipoles and the spin of the electrons about their axis.

- In terms of constitutive relationship:
  - We start from the vacuum $\mathbf{B} = \mu_o \mathbf{H}_a$ obtaining
  - $\mathbf{B} = \mu_o (\mathbf{H}_a + \mathbf{M}) = \mu_o (\mathbf{H}_a + \chi_m \mathbf{H}_a)$
  - with χ_m known as magnetic susceptibility
  - In conclusion, in a magnetic material within a static magnetic field, the constitutive relationship reads as follows:

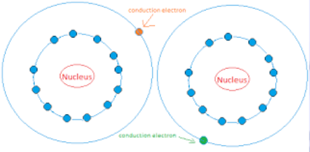
$$\mathbf{B} = \mu_s \mathbf{H}_a \quad \text{with} \quad \mu_s = \mu_o(1 + \chi_m) \tag{3}$$

Outline

Conductors

Definition

Conductors are material whose valence electrons are not held very tightly and can migrate from one atom to another.



- These valence electrons are known as free electrons, and for metal conductors they are very large in number.
- With no applied external field, the free electrons move with different velocities in random directions producing zero net current through the surface of the conductor.

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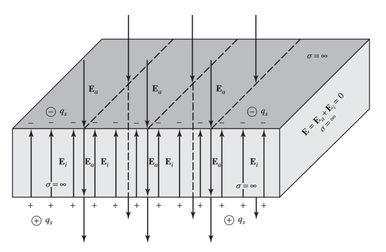
Conductivity

When a static electric field is applied to the conductor, the electrons still move in random directions but drift slowly (with a velocity $\mathbf{v}_e$) in the negative direction of the applied electric field $\mathbf{E}_a$



Conductors

- The convection current **J** is related to the drift velocity of charges: $\mathbf{J} = q_v \mathbf{v}$, with q_v being the charge density.
- The static electric field generates a charge drift in the conductor whose velocity is given by: $\mathbf{v}_e = \mu_e \mathbf{E}$, with μ_e defined as electron mobility.
- Hence $\mathbf{J} = q_{ve} \mathbf{v}_e = -q_{ve} \mu_e \mathbf{E}$, with q_{ve} being the electron charge density.
- By contrasting this formula with the constitutive relationship $\mathbf{J} = \sigma \mathbf{E}$, one can define the static conductivity of a conductor as follows:

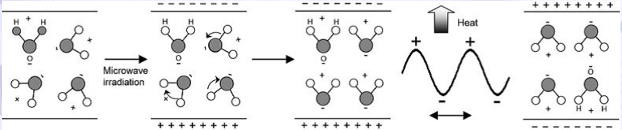
Static conductivity

$$\sigma_s = -q_{ve} \mu_e \tag{4}$$

A.C. variations in materials

Alternating fields

When the applied fields begin to alternate in polarity, the polarization vectors **P** and **M**, and in turn the permittivity and permeability, are affected and they are functions of the frequency of the alternating fields.



The reverse in polarity of the applied field is also responsible for the heating of materials using microwaves.

Outline

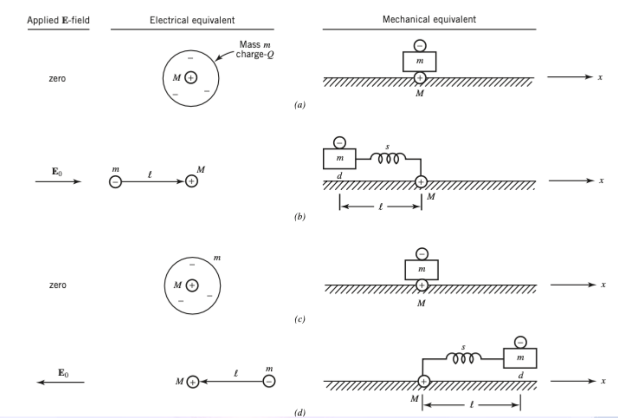
Lorentz Oscillator model

The model

It describes an electron orbiting a massive, stationary nucleus as a spring-mass-damper system.

- The electron is modeled to be connected to the nucleus via a hypothetical spring and its motion is damped by via a hypothetical damper.
- The damping force ensures that the oscillator's response is finite at its resonance frequency.
- For a time-harmonic electric field applied to the system, the dipole moment, polarization, susceptibility, and dielectric function can be obtained using mechanic laws.

Lorentz Oscillator model



The entire mechanical equivalent of a typical atom then consists of the classical mass-spring system moving along a platform with friction.

Lorentz Oscillator model

- An electron with (negative) mass charge m is is bound to a fixed nucleus, with (positive) mass charge M, by a distance l by a force obeying Hooke's Law.
- The distance l oscillates in time due to an external dynamic electric field $\mathbf{E_o}$.
- The positive charge remains stationary and the negative charge moves relative to the positive along a platform that exhibits a friction (damping) coefficient d.
- The force that links the two charges is modeled by a spring whose spring (tension) coefficient is s.
- The force acts to restore the electron with a characteristic frequency ω_o.
- The oscillation experiences damping characterized by a damping rate.

Lorentz Oscillator model

- When a time-harmonic field of angular frequency ω is applied to an atom, the forces of the system that describe the movement of the negative charge of mass m relative to the stationary nucleus and that are opposed by damping (friction) and tension (spring) can be represented by:

$$m\frac{d^2 l}{dt^2} + d\frac{dl}{dt} + sl = QE_o e^{j\omega t} \tag{5}$$

- It is a second-order differential equation whose terms (from the left) represents: forces associated with mass times acceleration, damping times velocity, and spring times displacement.
- The term on the right side represents the driving force of the time-harmonic applied field (of peak value QE_o).

Complex permittivity

Solving the Lorentz oscillator model - steady-state solution

Assuming that the oscillating dipoles, which represent the numerous atoms of a material, are all similar and there is no coupling between the dipoles (atoms), the macroscopic steady-state electric polarization $P(t)$ can be obtained which, in turns, gives the permittivity

$$\epsilon = \frac{\epsilon}{\epsilon_o} = \epsilon' - j\epsilon'' \tag{6}$$

The permittivity is a complex-valued function. . .

that reduces to a real-valued one when there is no damping.

Kramers-Kronig relations

Real and imaginary parts of the complex permittivity are linked

The Kramers-Kronig relations shows that the real and imaginary parts of the transfer function of a causal (i.e. physical) system are related. If one is known than the other can be calculated from it.

$$\epsilon = \frac{\epsilon}{\epsilon_o} = \epsilon' - j\epsilon'' \tag{7}$$

The permittivity is a complex-valued function. . .

that reduces to a real-valued one when there is no damping.

- $\epsilon^{'}$ is an even function of the frequency.
- $\epsilon^{''}$ is an odd function of the frequency.

Kramers-Kronig relations

Real and imaginary parts of the complex permittivity are linked

For a linear and time-invariant system the property of causality translates from the requirement of a vanishing impulse response for time smaller than zero in time domain directly to the Kramers-Kronig relations in frequency domain.

Applications of Kramers-Kronig Relations

The Kramers-Kronig relations allow one to calculate the refractive index profile of a material solely from its frequency-dependent absorption losses, which can be measured over a large spectral range.

Outline

Maxwell-Ampere law

$$
\begin{aligned}
\nabla \times \mathbf{H} = \quad & \mathbf{J}_o + \mathbf{J}_c + j\omega\epsilon\mathbf{E} \\
& \mathbf{J}_o + \sigma_s\mathbf{E} + j\omega\left(\epsilon^{'} - j\epsilon^{''}\right)\mathbf{E} \\
& \mathbf{J}_o + \left(\sigma_s + \omega\epsilon^{''}\right)\mathbf{E} + j\omega\epsilon^{'}\mathbf{E} \\
& \mathbf{J}_o + \sigma_l\mathbf{E} + j\omega\epsilon^{'}\mathbf{E}
\end{aligned} \tag{8}
$$

- σ_l is the equivalent conductivity that is equal to $\sigma_s + \omega\epsilon^{''} = \sigma_s + \sigma_a$, with σ_a termed as alternating conductivity.
- σ_s is the static field conductivity.

Maxwell-Ampere law

Equivalent conductivity

The equivalent conductivity (σ_l) consists of the static portion σ_s and the alternating one σ_a caused by the rotation of the dipoles as they attempt to align with the applied field when its polarity is alternating.

- The phenomenon (rotation of dipoles) that contributes the alternating conductivity is referred as dielectric hysteresis and generates heat. The heat generated by this radio frequency process is used for:
  - Industrial heating processes (e.g., microwave cooking).
  - Selective heating of human tissue for tumor treatment.
  - Selective heating of certain compounds in materials.