EM wave propagation in complex media

Electromagnetics
and
Remote Sensing Lab
(ERSLab)

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Outline

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Dielectric constant
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Frequency behavior of material media

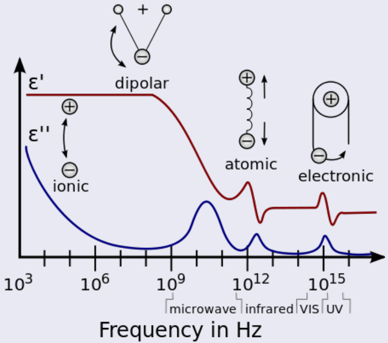
Frequency response

The characterization of the frequency response of material media is of paramount importance to fully understand the behavior of EM within the material media. This can be done by describing the frequency behavior of the:

- Complex permittivity $\epsilon(\omega)$.
- Complex permeability $\mu(\omega)$.
- Complex conductivity $\sigma(\omega)$.

A material that calls for a non-flat frequency behavior of at least one of its electrical parameters is termed as dispersive.

Dispersion



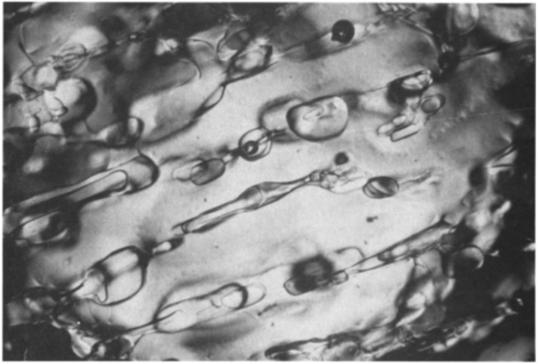
Dispersion depends on the mechanisms, occurring at micro-scale, in the dielectric medium, e.g.; ionic and dipolar relaxation, and atomic and electronic resonances at higher energies

Natural media

They can be roughly classified as:

- Homogeneous. Material media whose properties do not depend on space, e.g., pure water, ice, etc.
- Heterogeneous. Material media whose properties are space variant, e.g., sea ice, dry soil, wet soil, etc.

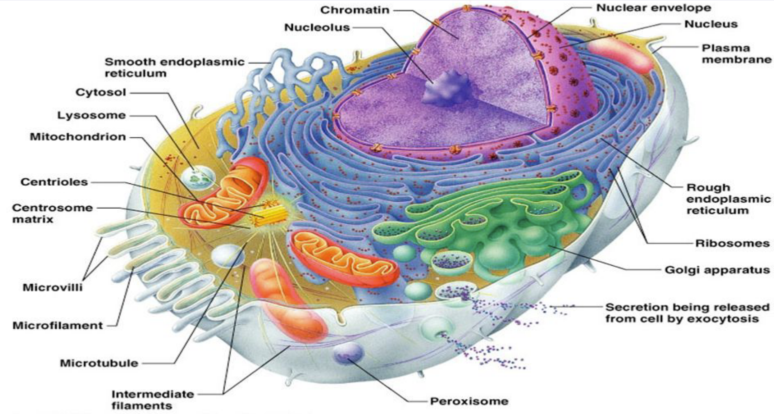
Remote sensing - sea ice



This photomicrograph shows a thin section of sea ice containing brine channels. — Credit: Weeks and Assur, 1969

Natural media

Cell and organelles



Natural media

Living cells are heterogeneous mixtures

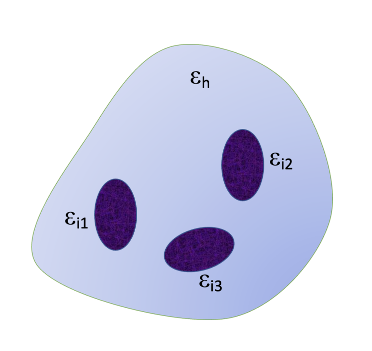
They are of high complexity. In addition to the different ions and biomolecules, the membranous organelles inside the cells add more interfaces within the cell.

Frequency response

Dielectric properties of cells are frequency-dependent The relative permittivity is always high at very low frequencies, and by increasing frequencies, the values tend to suffer from stepwise decrements or dielectric dispersions that occur at specific range of frequencies.

Natural media

Heterogeneous substances



The heterogeneous medium consists of an host material, whose dielectric constant is ϵ_h, in which there is a random concentration of ellipsoidal particle with a dielectric constant ϵ_i.

Outline

Dielectric constant of the mixture

The dielectric constant of the mixture is given by:

$$\epsilon_m(\mathbf{r};\hat{\mathbf{p}}) = \epsilon_a(\hat{\mathbf{p}}) + \epsilon_f(\mathbf{r};\hat{\mathbf{p}}) \tag{1}$$

The average value of the dielectric constant

- $\epsilon_a(\hat{\mathbf{p}}) = \langle \epsilon_m(\mathbf{r};\hat{\mathbf{p}}) \rangle$ is the average (or effective) value of the dielectric constant of the mixture.
  - It is not a function of the position.
  - It may depend on the polarization $\hat{\mathbf{p}}$ of the incident wave. This happens when the ellipsoids that characterize the inclusions have a preferred orientation. If the latter are randomly oriented there is no polarization selectivity.

It affects the propagation constant of the EM wave

Dielectric constant of the mixture

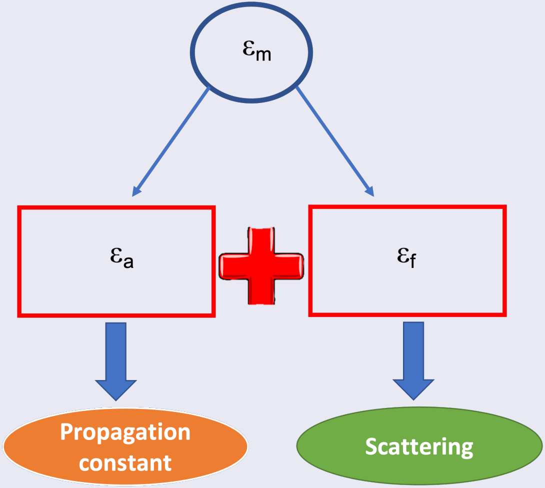
The fluctuating component of the dielectric constant

- $\epsilon_f(\mathbf{r}; \hat{\mathbf{p}})$ is the fluctuating component that mainly accounts for the deviations wrt the average value of the dielectric constant.
  - It depends on the spatial coordinates.
  - It depends on the polarization of the incident wave.
  - Its average value is equal to zero.

Its statistical spatial distribution is linked to volumetric scattering

Dielectric constant of the mixture

Dielectric constant -> wave propagation



Outline

Average value of the dielectric constant

- From now on, the average value of the dielectric constant $\epsilon_a(\cdot)$ is termed simply as dielectric constant and is written as ϵ.

$$\epsilon = \epsilon_a = \epsilon' - j\epsilon'' \qquad (2)$$

- ϵ' is typically termed as dielectric constant.
- $\epsilon'' = \frac{\sigma}{\omega\epsilon_o}$ is the dielectric loss factor.

- The conductivity of a material is a measure of the ability of its charge to be transported throughout its volume by an applied electric field.
- Its permittivity is a measure of the ability of its dipoles to rotate or its charge to be stored by an applied external field.

Complex permittivity

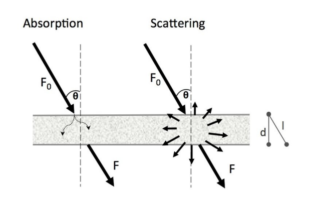
Permittivity characterizes the electrical properties of materials:

- The real part gives the contrast with respect to vacuum.
- The imaginary part gives the electromagnetic loss of the material.
- Loss tangent is defined as the imaginary part divided by the real part of permittivity.

$$tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{\sigma}{\omega\epsilon} \tag{3}$$

Total em loss in a medium consists of:

- Absorption loss (electromagnetic power transformed into other forms of energy, such as heat).
- Scattering loss (energy is caused to travel in directions other than that of incident radiation).
- Penetration depth provides an approximate value to the maximum depth of the medium that contributes to the signal backscattering.



Displacement and conduction currents

From the Maxwell-Ampere law:

$$\begin{aligned}\nabla \times \mathbf{H} = \; & \mathbf{J}_o + \mathbf{J}_c + j\omega\epsilon\mathbf{E} \\ & \mathbf{J}_o + \sigma_s\mathbf{E} + j\omega\left(\epsilon^{'} - j\epsilon^{''}\right)\mathbf{E} \\ & \mathbf{J}_o + \left(\sigma_s + \omega\epsilon^{''}\right)\mathbf{E} + j\omega\epsilon^{'}\mathbf{E} \\ & \mathbf{J}_o + \sigma_l\mathbf{E} + j\omega\epsilon^{'}\mathbf{E}\end{aligned} \tag{4}$$

- σ_s is the static field conductivity.
- 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.

Dielectric constant of the mixture

Dielectric constant -> wave propagation

Tissue	Frequency					
	0.5 GHz		2 GHz		5 GHz	
	ϵ_r'	σ	ϵ_r'	σ	ϵ_r'	σ
Skin (Dry)	44.91	0.728	38.56	1.265	35.77	3.06
Skin (Wet)	48.62	0.704	43.52	1.335	39.61	3.574
Fat	5.54	0.042	5.32	0.085	5.02	0.242
Muscle	57.32	0.843	54.16	1.508	50.13	4.24
Bone	12.94	0.10	11.65	0.31	10.04	0.962
White Matter	41	0.473	36.73	1.001	33.44	2.858
Blood	63.25	1.383	59.02	2.186	53.95	5.395

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.

Note that σ_l is frequency dependent. From now on, σ_l is written as σ.

Outline

Uniform plane wave

A uniform plane wave propagating along the $\hat{z}$ direction

- The propagation vector is given by:

$$\mathbf{S} = \mathbf{a} + j\mathbf{k} = S\hat{z} = (\alpha + j\beta)\,\hat{z} \quad (5)$$

- A generic transverse component of the wave in the time domain is given by:

$$e(z,t) = E_o e^{-\alpha z} cos(\omega t - \beta z) \quad (6)$$

To evaluate α and β

$$\gamma^2 = S \cdot S = (\alpha + j\beta)(\alpha + j\beta) = -\omega^2 \mu \left(\epsilon' - j\frac{\sigma}{\omega}\right) \quad (7)$$

Uniform plane wave

- By equating separately real and imaginary parts one obtains (note that, without any ambiguity, hereinafter $\epsilon = \epsilon'$):

$$\beta^2 - \alpha^2 = \omega^2 \epsilon \mu \tag{8}$$
$$2\alpha\beta = \sigma\omega\mu \tag{9}$$

- Solving for β eq.(9) one obtains $\beta = \frac{\sigma\omega\mu}{2\alpha}$ that can be inserted in (8) to obtain:

$$\alpha^2 + \omega^2 \mu\epsilon\alpha^2 - \frac{\omega^2\mu^2\sigma^2}{4} = 0 \tag{10}$$

- since $k = \omega\sqrt{\epsilon\mu} = k_o n$ the following solution is obtained:

$$\alpha^2 = \frac{-k^2 \pm \sqrt{k^4 + \omega^2\mu^2\sigma^2}}{2} \tag{11}$$

Uniform plane wave

- Since the argument of the square root in eq.(11) is larger than k^2, to guarantee that $\alpha \geq 0$, the positive sign is selected:

$$\alpha^2 = \frac{-k^2 + \sqrt{k^4 + \omega^2\mu^2\sigma^2}}{2} \tag{12}$$

- which can be written as:

$$\alpha^2 = \frac{k^2\left(\sqrt{1 + \frac{\omega^2\mu^2\sigma^2}{k^4}} - 1\right)}{2} \tag{13}$$

Uniform plane wave

The propagation vector becomes:

$$\alpha = \frac{k}{\sqrt{2}}\sqrt{\sqrt{1+\frac{\sigma^2}{\omega^2\epsilon^2}}-1} \quad (14)$$

$$\beta = \frac{k}{\sqrt{2}}\sqrt{\sqrt{1+\frac{\sigma^2}{\omega^2\epsilon^2}}+1} \quad (15)$$

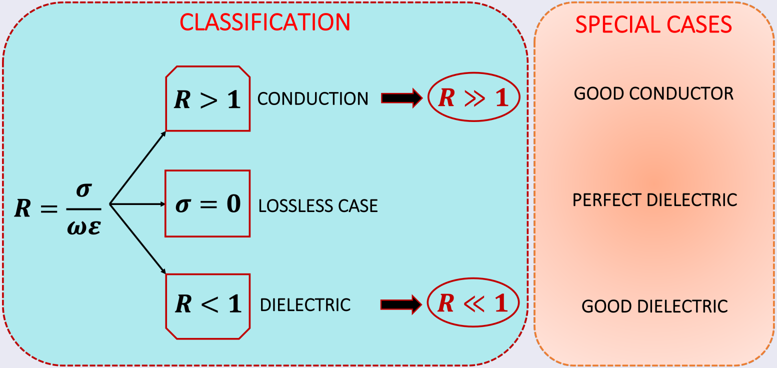
R

- The metric $R = \frac{\sigma}{\omega\epsilon}$ is the ratio between the norms of the conduction and the displacement currents.

Outline

Special cases

Special cases are obtained according to R



Special cases - Lossless

Lossless - pure dielectric

$$\alpha = 0 \tag{16}$$

$$\beta = k = k_o n = \omega\sqrt{\mu\epsilon} \tag{17}$$

Good dielectric: $R \ll 1$

α

$$\alpha = \frac{k}{\sqrt{2}}\sqrt{\sqrt{1+R^2}-1} \approx \frac{k}{\sqrt{2}}\sqrt{1+\frac{R^2}{2}-1} = \frac{kR}{2} = \frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon}} \tag{18}$$

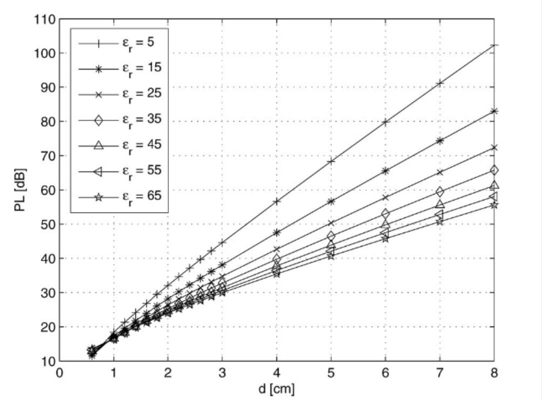
β

$$\beta \approx \frac{k}{\sqrt{2}}\sqrt{1+\frac{R^2}{2}+1} = k\sqrt{1+\frac{R^2}{4}} \approx k\left(1+\frac{R^2}{8}\right) \tag{19}$$

$$\frac{\alpha}{\beta} \ll 1$$

Path Loss in a Wireless Body Area Network (WBAN)

A WBAN consists of a wireless network with devices placed close to, attached on, or implanted into the human body. Wireless communication within human body experiences loss in the form of attenuation and absorption.



Good conductor: $R \gg 1$

α and β

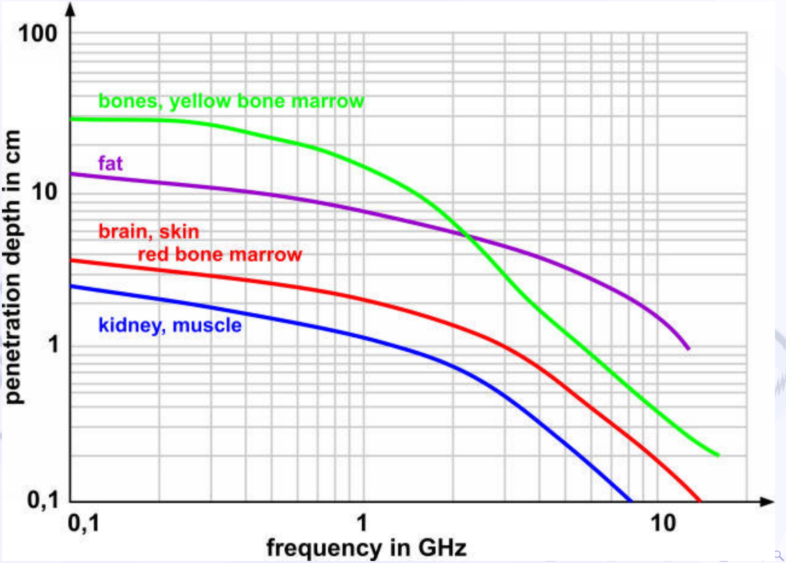
$$\alpha \approx \beta \approx k\sqrt{\frac{R}{2}} = \sqrt{\frac{\sigma\omega\mu}{2}} = \frac{1}{\delta} \tag{20}$$

- The propagation constant becomes:

$$\gamma = \frac{1+j}{\delta} \tag{21}$$

- δ is known as penetration length, i.e., the distance where the modulus of the field reaches the value $e^{-\alpha z} = e^{-\frac{z}{\delta}} = e^{-1}$.

Good conductor - Penetration length



Good conductor: $R \gg 1$

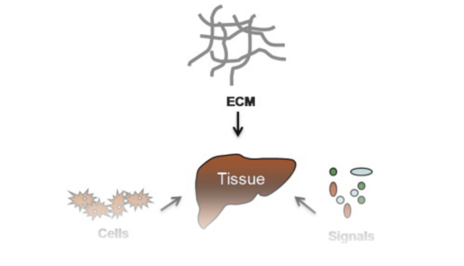
Remarks for a good conductor

- Neither α nor β depend on ϵ'.
- Eq.(20) can be equivalently rewritten as: $\alpha \approx \beta \approx = \sqrt{\pi f \mu \sigma}$. Since the conductivity of most materials changes very slowly with frequency, this expression indicates that α (and β) increases approximately in proportion to the square root of frequency for good conductors.
- R is frequency dependent, hence conductors can be "good conductors" according to the frequency.

Biological tissues

Definition

They consist of cells, the extracellular matrix (ECM), and the signaling systems that are encoded by genes in the nuclei of the cells and then activated through cues from the ECM or other cell.



Cells

A fundamental brick in the wall

The smallest unit that can live on its own and that makes up all living organisms and the tissues of the body. A cell has three main parts: the cell membrane, the nucleus, and the cytoplasm. The cell membrane surrounds the cell and controls the substances that go into and out of the cell.

They are composite structures

Living cells and tissues are composed of different types of molecules, ranging from the simple free moving ions and polar water molecules, to the more complex biomolecules such as carbohydrates, proteins, DNA and lipids

Outline

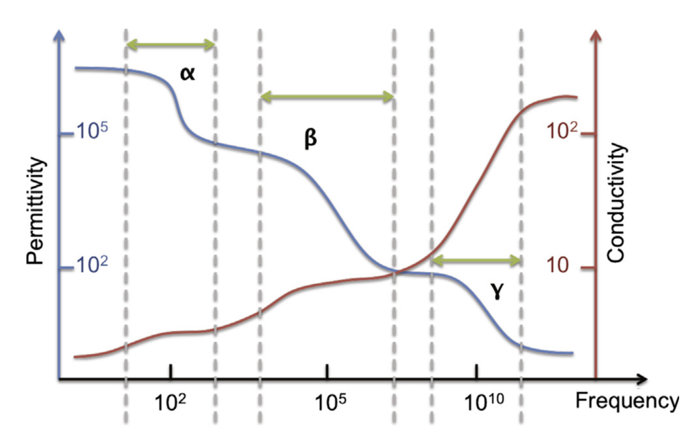
Cell polarization

They can get polarized

Exposing cells or tissues to an external electric field affects the distribution of charges and other molecules in them, such that the ions tend to move over distances (thus, acting as conductors), while other molecules reorient themselves in space and get polarized.

This makes cells a dielectric substance that has the ability to get polarized

Complex permittivity spectrum of biological cells



Electrical cell polarization

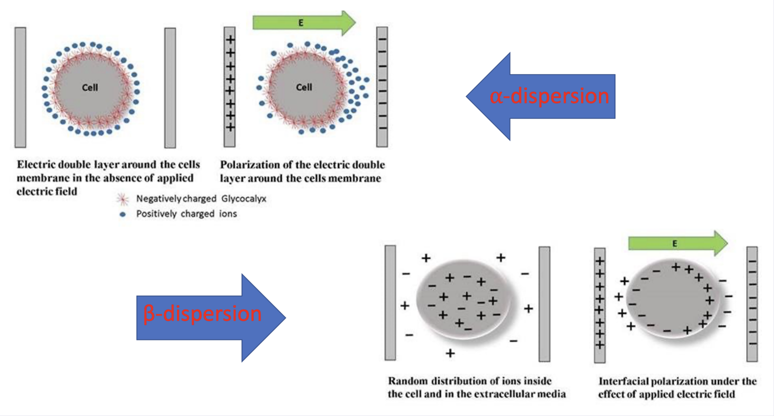
A deeper understanding of cell dispersive behavior

Cells are modeled as highly conductive cytoplasmic spheres having free ions that are surrounded by insulating non-conductive cell membranes.

- Cell membranes separate the internal compartment from the external media which is also conductive.
- The highly negative charge of cell membranes is normally neutralized by an adsorbed cloud of counter ions forming an electric double layer

Electrical polarization

Electrical cell polarization



Electrical cell polarization

Main mechanisms on a micro-scale

The Complex permittivity spectrum of biological cells shows the distinct dispersion phases at their respective frequency, permittivity and conductivity ranges.

- α-dispersions are generally associated with the diffusion processes of ionic species or electronic double-layer polarization.
- β-dispersions are due to interfacial polarization across the cellular plasma membranes and their interactions with the extra and intra-cellular electrolytes.
- γ-dispersions are caused by the aqueous content of the biological species and the presence of small molecules.

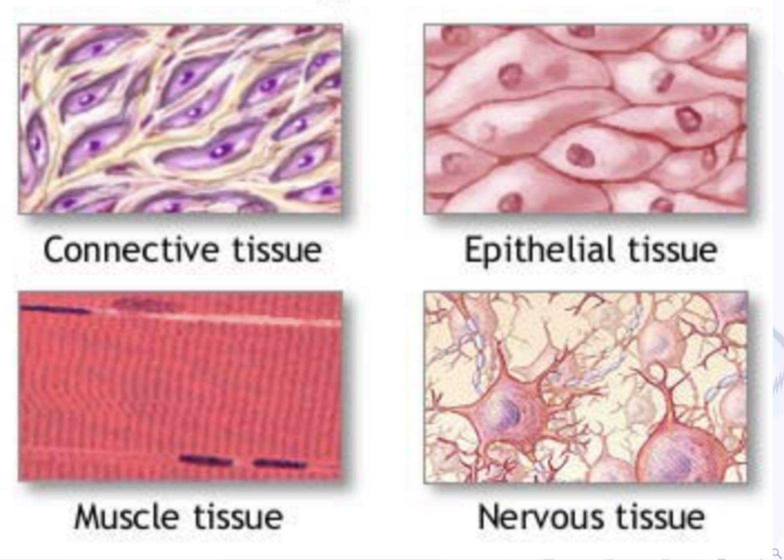
Biological tissues

Definition

There are 4 basic types of tissue: connective tissue, epithelial tissue, muscle tissue, and nervous tissue.

- Connective tissue supports other tissues and binds them together (bone, blood, and lymph tissues).
- Epithelial tissue provides a covering (skin, the linings of the various passages inside the body).
- Muscle tissue includes striated (also called voluntary) muscles that move the skeleton, and smooth muscle, such as the muscles that surround the stomach.
- Nerve tissue is made up of nerve cells (neurons) and is used to carry “messages” to and from various parts of the body.

Biological tissues



Electrical properties of biological tissues

The electrical properties of biological tissues and cell suspensions have been of interest for over a century for many reasons. They determine the pathways of current flow through the body and, thus, are very important in the analysis of a wide range of biomedical applications:

- the functional electrical stimulation;
- the diagnosis and treatment of various physiological conditions with weak electric currents;
- radio-frequency hyperthermia;
- electrocardiography;
- body composition.

Biological tissues

To analyze the response of a tissue to electric stimulation, we need data on the specific conductivity and relative permittivity of the tissues or organs.

Microscopic approach

It is complicated by the variety of cell shapes and their distribution inside the tissue as well as the different properties of the extracellular media.

Macroscopic approach

The material is described as having a permittivity and a conductivity. Even on a macroscopic level, the electrical properties are complicated. They can depend on:

- The tissue orientation relative to the applied field (directional anisotropy).
- The frequency of the applied field (the tissue is neither a perfect dielectric nor a perfect conductor).
- They can be time- and space-dependent (e.g., changes in tissue conductivity during electropermeabilization).

Biological tissues

Dielectric properties of some tissues

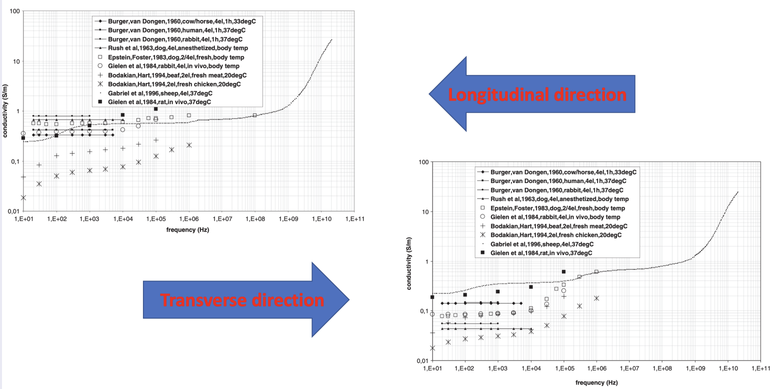
Large differences exist in electric properties of biological materials that arise, to a large extent, from the fluid content of the material.

- Relatively good conductors: blood and brain.
- Relatively poor conductors: lungs, skin, fat, and bone.
- Intermediate conductors: liver, spleen, and muscle.

Data on specific conductivity and relative permittivity of biological tissues are mostly available only at frequencies above 100 Hz. For most tissues, with the exception of anistrotropic tissues, the dielectric properties are almost no frequency-dependent between 100 Hz and 100 kHz.

Biological (anisotropic) tissues

Specific conductivity for skeletal muscle



Biological tissues

Biological tissues actually display some characteristics of both insulators and conductors because they contain dipoles as well as charges that can move, but in a restricted manner.

Heterogeneous materials

For materials that are heterogeneous in structure:

- Charges may become trapped at interfaces between different media.
- In addition to the conventional polarization, as positive and negative ions move in opposite directions under the applied field, internal charge separations can then result within the material, producing an effective internal polarization that acts like a very large dipole.

Outline

Dispersion

Dispersion

For most materials the relative permittivity varies with the frequency of the applied signal, i.e.; σ and ϵ_r are frequency-dependent. Such a variation is called dispersion.

- Biological tissues exhibit several different dispersions over a wide range of frequencies.

Electrical polarization

The most important phenomenon associated with a dielectric material is its polarization, which consists of the change of the distribution of its molecular and atomic charges when it is subjected to the action of an electric field.

- When an electric field is applied to a dielectric it produces a very small electric current called dielectric loss, and its constituent particles, ions or molecules suffer small dislocations or rearrangements, thus altering their equilibrium positions.

Debye model

Relaxation time

- These molecular parts do not leave nor reach their state of equilibrium instantaneously: a variable amount of time is necessary for this change of positions to take place.

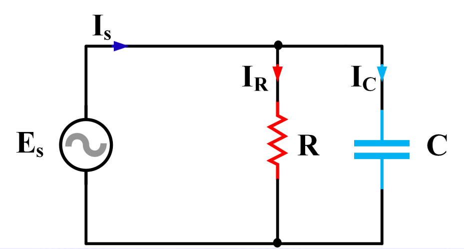
This time lapse necessary for the material to respond to the electric field applied is called relaxation time.

Debye relaxation model

In 1929, Debye conceived a simple model for the relaxation process in which he supposed a unique relaxation time for all molecules.

A simple tissue electrical model

The Debye model admits a simple circuit interpretation. We can represent the tendencies to store energy and to dissipate power by using a circuit model that consists of the parallel combination of the capacitor and conductor.



A simple tissue electrical model

Let's consider a sample of material whose cross-section is *A* and whose thickness is *d*.

- The ability of the material to store energy can be represented by a capacitor with capacitance:

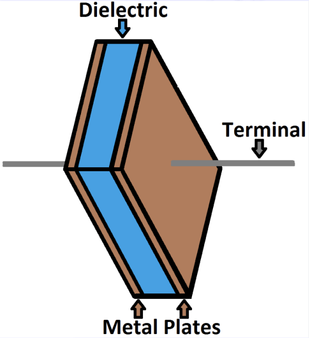
$$C = \epsilon \frac{A}{d} \tag{22}$$

- The ability of the material to dissipate power can be represented by a conductor with conductance:

$$G = \sigma \frac{A}{d} \tag{23}$$

A simple tissue electrical model

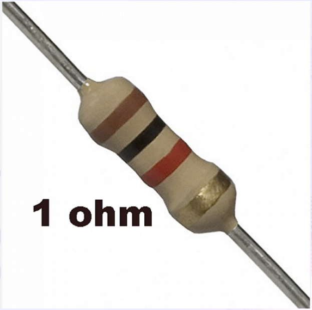
The permittivity characterizes the material's ability to trap or store charge or to rotate molecular dipoles, whereas the conductivity describes its ability to transport charge.



The energy stored in a material

$$u = \frac{\epsilon E^2}{2} \qquad (24)$$

A simple tissue electrical model



The power dissipated in a material

$$p = \frac{\sigma E^2}{2} \qquad (25)$$

A simple tissue electrical model

When the circuit is subjected to an alternating voltage $V(t) = V_o cos(\omega t)$

- A conduction current will flow:

$$I_c = GV \tag{26}$$

- The charge $Q = CV$ on the capacitor plates changes with the frequency f giving rise to a displacement current:

$$I_d = \frac{dQ}{dt} = -\omega C V_o sin(\omega t) \tag{27}$$

- The total current is the sum of the conduction and displacement currents, which are 90 degrees apart in phase:

$$I = GV + \frac{dQ}{dt} = -\omega C V_o sin(\omega t) + GV \tag{28}$$

A simple tissue electrical model

- Eq.(28) in the phasor domain reads as follows:

$$I = j\omega\epsilon\frac{A}{d}V + \sigma\frac{A}{d}V = (\sigma + j\omega\epsilon)\,\frac{A}{d}V \qquad (29)$$

- By factorizing $j\omega\epsilon_o$:

$$I = j\omega\epsilon_o\left(\epsilon_r - j\frac{\sigma}{\omega\epsilon_o}\right)\frac{A}{d}V \qquad (30)$$

- The quantity in the brackets is the complex-valued relative permittivity:

$$\epsilon = \epsilon' - j\epsilon'' \qquad (31)$$

- with $\epsilon' = \epsilon_r$ and $\epsilon'' = \frac{\sigma}{\omega\epsilon_o}$

Dielectric dispersion of water in tissues

Debye model

- For a Debye-type response, which corresponds to parallel RC elements, dispersion can be represented as follows

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 - j\omega\tau} + \frac{\sigma}{j\omega\epsilon_o} \quad (32)$$

- with $\tau = \frac{1}{RC}$ being the relaxation time, ϵ_∞ and ϵ_s represent the relative permittivity at frequencies well above and well below the dispersion.

The Debye model works fine for materials that exhibit a single relaxation time. However, this is rarely the case and, in particular, this situation does not apply for biological tissues.

Outline

The dispersion behavior

Biological tissues exhibit several different dispersion over a wide range of frequencies.

- Dispersion can be understood in terms of the orientation of the dipoles and the motion of the charge carriers.

Limitations of Debye model

According to Debye relaxation process:

- All dipoles in the system relax with the same relaxation time (which is called a single relaxation time approximation).
- The system response function is purely exponential.
- Debye relaxation appears usually in liquids or in the case of point-defects of almost perfect crystals.

Limitations of Debye model

Real materials show non-Debye relaxation

This fact is due to the occurrence of

- Multiple interaction processes.
- To the presence of more than one molecular conformational state or type of polar molecule.
- To polarization processes whose kinetics are not first order.
- To the presence of complex intermolecular interactions.

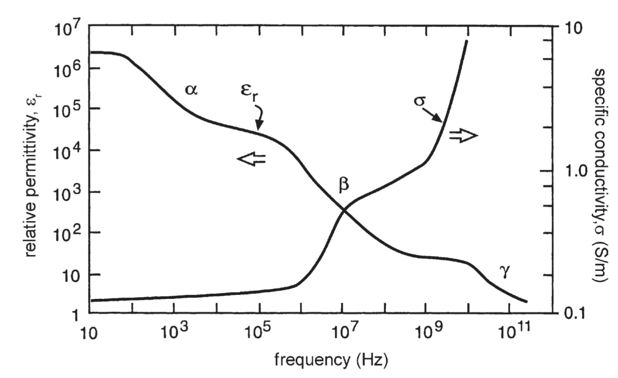
Dispersion regions

- At relatively low frequencies, the permittivity is relatively high and the conductivity is relatively low. This is due to the fact that it is relatively easy for the dipoles to orient in response to the change in the applied field, whereas the charge carriers travel larger distances over which a greater opportunity exists for trapping at an interface.
- As the frequency increases, the dipoles are less able to follow the changes in the applied field, and the corresponding polarization disappears. In contrast, the charge carriers sample shorter distances during each half-cycle and are less likely to be trapped.
- As frequency increases, the permittivity decreases and, because trapping becomes less important, the conductivity increases.

Dielectric dispersion in tissues

Biological tissues

Biological tissues exhibit several different dispersion over a wide range of frequencies.



Outline

Deviations from Debye relaxation

Dielectric response arising from multiple first-order processes

- The dielectric response consists of multiple Debye terms, one for each relaxation time of the system:

$$\epsilon(\omega) = \epsilon_\infty + \frac{\Delta\epsilon_1}{1 - j\omega\tau_1} + \frac{\Delta\epsilon_2}{1 - j\omega\tau_2} + \dots \quad (33)$$

- with $\Delta\epsilon_n$ is the limit of the dispersion characterized by time constant τ_n represent.

Deviations from Debye relaxation

Dielectric response arising from multiple first-order processes

- If the relaxation times are well separated such that $\tau_1 \ll \tau_2 \ll \ldots$, a plot of the dielectric properties as a function of frequency well exhibit clearly resolved dispersion regions.
- If the relaxation times are not well separated, the material will exhibit a broad dispersion encompassing all the relaxation times and the dispersion regions mentioned above become, in the limit, part of a continuous distribution of relaxation times.

Deviations from Debye relaxation

Dielectric response arising from multiple first-order processes

$$\epsilon(\omega) = \epsilon_\infty + (\epsilon_s - \epsilon_\infty) \int_0^\infty \frac{\rho(\tau)}{1 - j\omega\tau} \quad (34)$$

- where $\rho(\tau)$ is a normalized distribution function:

$$\int_0^\infty \rho(\tau) = 1 \quad (35)$$

According to eq.(34), all the dielectric dispersion data can be represented once an appropriate distribution function is provided and known

Outline

Deviations from Debye relaxation

Different models can be obtained by a suitable choice of $\rho(\tau)$

- Cole-Cole.
- Davidson-Cole.
- Havriliak and Negami.
- etc.

Cole-Cole model

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 - (j\omega\tau)^\alpha} + \frac{\sigma}{j\omega\epsilon_o} \tag{36}$$

Dielectric dispersion of water in tissues

- ϵ_∞ is the permittivity at field frequencies such that $\omega\tau \gg 1$ (typical values are 2.5 for bones and 3.5 for all the other tissues).
- ϵ_s is the static permittivity.
- α is the distribution parameter bounded between 0 and 1.
- σ is the ionic conductivity.
- ϵ_o is the permittivity of free space (i.e., 8.854×10^{-12}F/m).

Dielectric dispersion of water in tissues

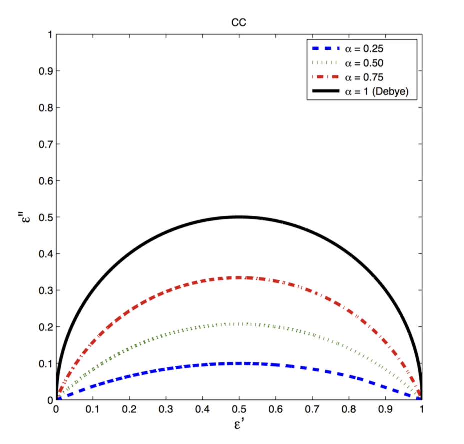
Cole-Cole and Debye model

- The Cole-Cole model reduces to the Debye model when $\alpha = 1$.
- In circuit terms, the Cole-Cole model generalizes the Debye circuit model by replacing the capacitor with a "Constant Phase Element" (CPE) with a complex-valued impedance given by

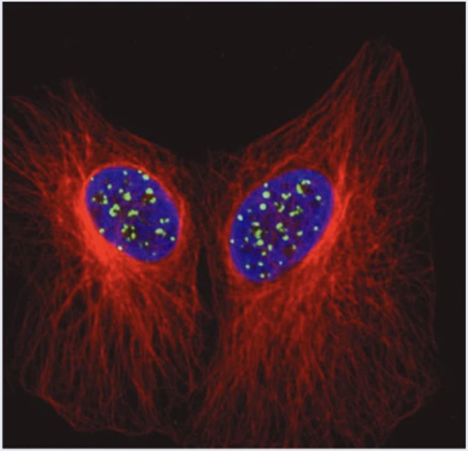
$$Z_{CPE} = A(j\omega)^{-n} \tag{37}$$

- with A being a parameter and $n = \alpha$.
- This CPE impedance reduces to a simple resistance for $n = 0$ and to a capacitive reactance for $n = 1$.

Cole-Cole model at variance of α



Microtubules - see the red filaments



Microtubules

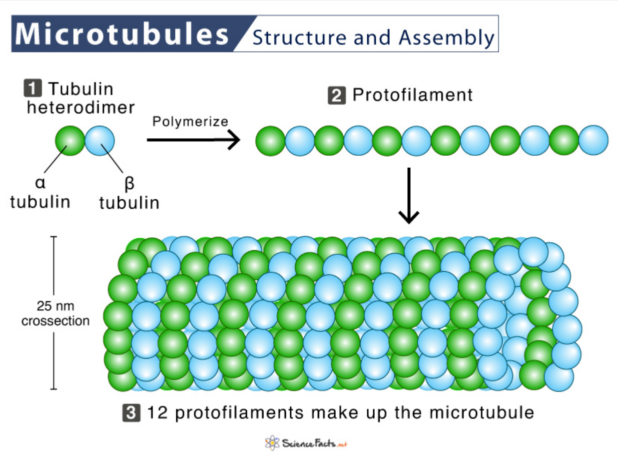
What they are

Microtubules are major components of the cytoskeleton. They are rigid hollow rods approximately 25 nm in diameter that undergo continual assembly and disassembly within the cell. They play a key role:

- To determine cell shape.
- To help prepare the cell for cell division and migration.
- To act as a railway track on which motor proteins transport materials within the cell.
- To the separation of chromosomes during mitosis.

Microtubules

Structure & Asssembly



Microtubules

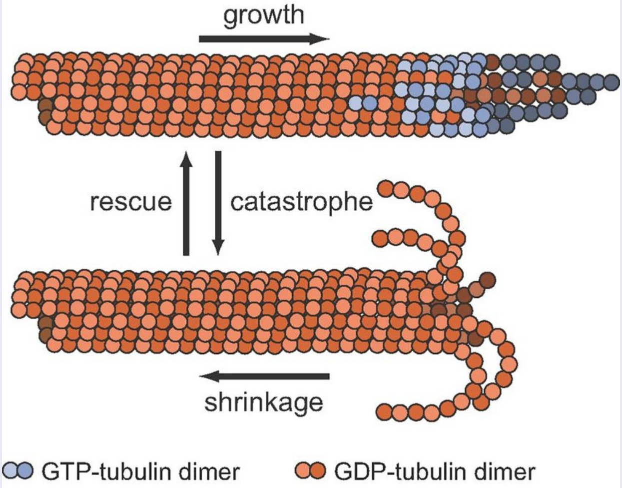
Structure & Asssembly

Microtubules are composed of a single type of globular protein called tubulin, i.e., a dimer consisting of two polypeptides: α-tubulin and β-tubulin.

- Tubulin dimers polymerize to form microtubules, which generally consist - in general - of 13 linear protofilaments assembled around a hollow core.
- The protofilaments are arranged in parallel. Consequently, microtubules are polar structures with two distinct ends: a fast-growing plus end and a slow-growing minus end.
- This polarity is an important consideration in determining the direction of movement along microtubules.

Microtubules

Dynamic instability



Microtubules

Dynamic properties

Microtubules dynamic properties are tightly regulated by cellular microtubules associated proteins (MAPs) and are modulated in a variety of ways by many microtubule-targeted drugs.

- Some the most effective chemotherapeutics, such as the taxanes, are microtubule interfering drugs. Their efficacy has been demonstrated in the clinic for the treatment of a wide variety of human cancers, including breast, lung, ovarian, and prostate, as well as haematological malignancies and childhood cancers.
- Many studies suggest that microtubule dynamics are altered in cancer cell divisions.

Microtubules

Protein-based cellular functions & EM fields

Being able to control protein-based cellular functions with an electromagnetic field could open an exciting spectrum of possibilities for advancing biotechnological processes. Besides, it paves the way for the development of new biomedical theranostic approaches to treat various diseases where specific proteins are known targets.

Theranostic

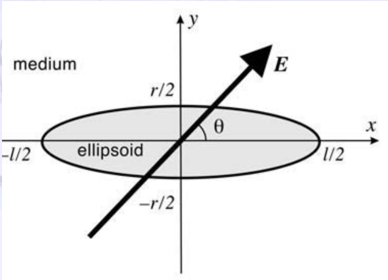
Theranostics is a term derived from a combination of the words therapeutics and diagnostics. In this emerging field of medicine, drugs and/or techniques are uniquely combined to simultaneously or sequentially diagnose and treat medical conditions

Outline

Electroorientation

Its is a phenomenon that takes place when an electric field is acting on the microtubules

- The microtubule can be modeled as an ellipsoid with rotational symmetry of radius *r* and length *l*.



Electroorientation

- When the ellipsoid is placed with its long axis at angle θ to the electric field $\mathbf{E}^*$, the electrostatic torque exerted on the ellipsoid is calculated by

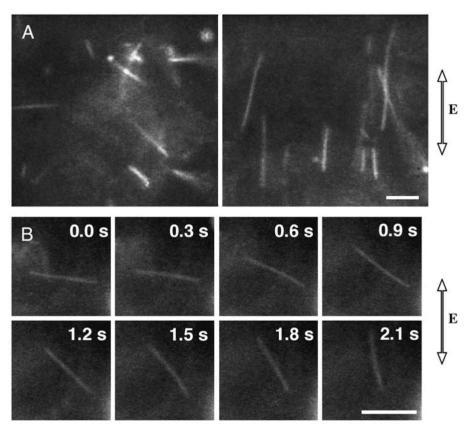
$$\mathbf{T}_e = 1/2\Re\left(\mathbf{p}^* \times \mathbf{E}^*\right) \tag{38}$$

- where $\mathbf{p}^*$ is the dipole moment induced in the ellipsoid.
- If we take the coordinate x in the direction of the longest axis of the ellipsoid and coordinate y perpendicular to it (both x and y are in the plane parallel to the direction of applied electric field), the orientation of the ellipsoid is caused by the torque about the z axis, which is perpendicular to the direction of electric field.

ERSLab

F. Nunziata

Electroorientation

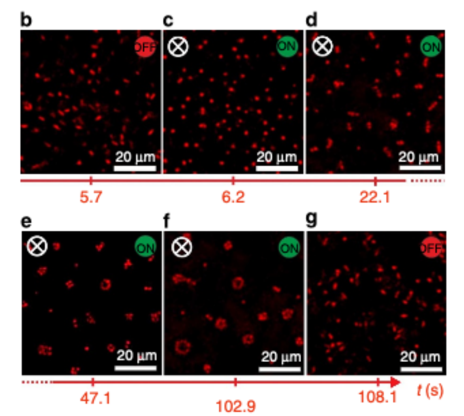


Electroorientation

Electroorientation

- Orientation of microtubules is random in the absence of the electric field (A - Right).
- Upon application of the electric field, the microtubules are oriented parallel to the direction of the field line (A - Left).
- (B) Sequential images of a single microtubule after the onset of the electric field taken at intervals of $0.3\mu s$.
- Arrows indicate the direction of the applied electric field.

Simple ellipsoidal colloids can reversibly self-assemble into regular tubular structures when subjected to an alternating electric field



Electroorientation

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