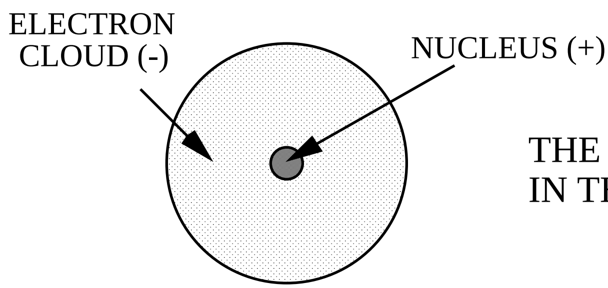
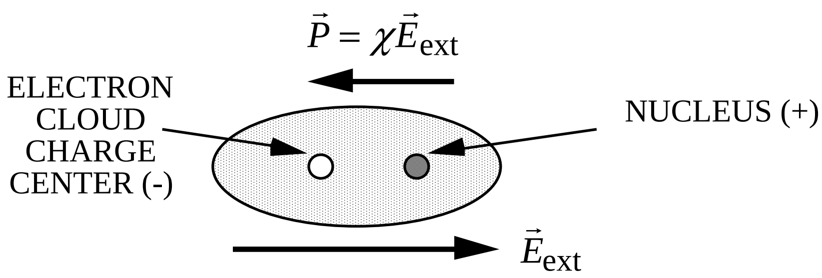
Debye Model for Dielectrics (1)

The Debye model has been used to predict the interaction of EM waves with materials since the early 1900s. Molecules are represented by the nucleus with a positive charge center and the electron cloud, which has a negative charge center. In the absence of an external field, the charge centers are coincident as shown below.



THE CHARGE CENTERS ARE COINCIDENT
IN THE ABSENCE OF AN EXTERNAL FIELD

When an external field is applied, the charge centers separate. The response of the molecule is expressed in terms of a polarization vector, $\vec{P}(t)$.



Each molecule of material is essentially an oscillating dipole.

Debye Model for Dielectrics (2)

The separation is referred to as electronic polarization and χ is the susceptibility. It takes time for the molecules to respond to the impressed field. The time dependent form of the polarization vector is

$$P(t) = \underbrace{P_o}_{\chi(0)E_{\text{ext}}} e^{-t/\tau}$$

where τ is the relaxation constant (about 10^{-15} second).

The Debye model is never seen in real materials, but it can be approached for single particle non-interacting systems like gases. The assumptions are that all of the dipoles are identical, independent, and relaxation times are the same. In fact, dipoles are spatially and temporally coupled, relaxation times vary, and other types of polarization exist.

Other types of polarization:

Ionic: mutual displacement of the molecule charge centers (relaxation constant about 10^{-13} second)

Orientational: rotation of the molecule (relaxation constant about 10^{-11} second)

Self Induced Transparency (1)

The modern view is that media have a far more complex EM relaxation behavior than previously realized. Much of this has arisen from research involved with ultra-short pulse lasers interacting with materials. New theories have been devised. The most promising in the Dissado-Hill model that takes all of the spatial and temporal factors into account:

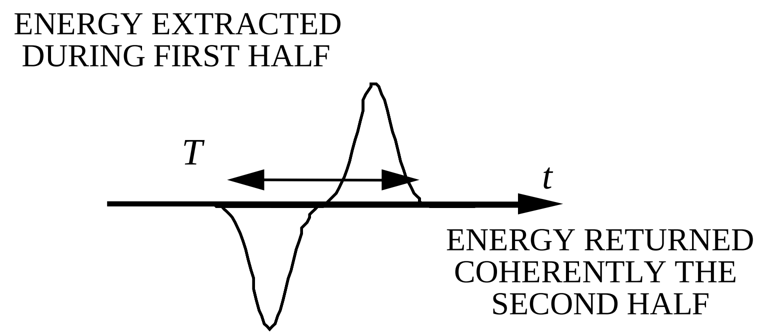
- Individual polarized molecules (dipoles) have a homogeneous lifetime, T_o.
- In the coupled environment, the dipoles have an inhomogeneous lifetime, T_c, that can be greater than or less than T_o. The inhomogeneous lifetime depends on the number of other dipoles and their distances, as well as their relaxation times.
- Absorption of a wave passing through a material takes time. If $T_o > T_c$ then energy extracted from the wave as it passes through the material can be returned back to the wave.

This condition is called self-induced transparency the wave can penetrate the medium without loss and therefore any radar absorbing material would be useless. This effect *may* have been observed at optical frequencies (interpretation of the data is in question).

Self Induced Transparency (2)

Self-induced transparency occurs when the waveform duration T satisfies $T_o > T > T_c$. Then the wave penetrates the medium without loss. Coherency of the wave is maintained. Energy is extracted by the dipoles from the first half of the wave. The extracted energy is returned during the wave during the second half if the homogeneous lifetime is not exceeded.

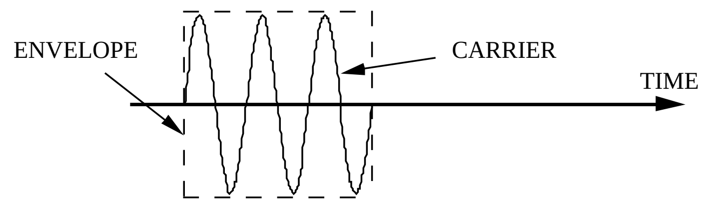
The area theorem is a statement of this condition: Efficient penetration of an absorbing material occurs when the area under the energy vs. time curve of the wave in the material satisfies $\int E dt = 0$ and $\int |E|^2 dt \neq 0$. An example is shown below:



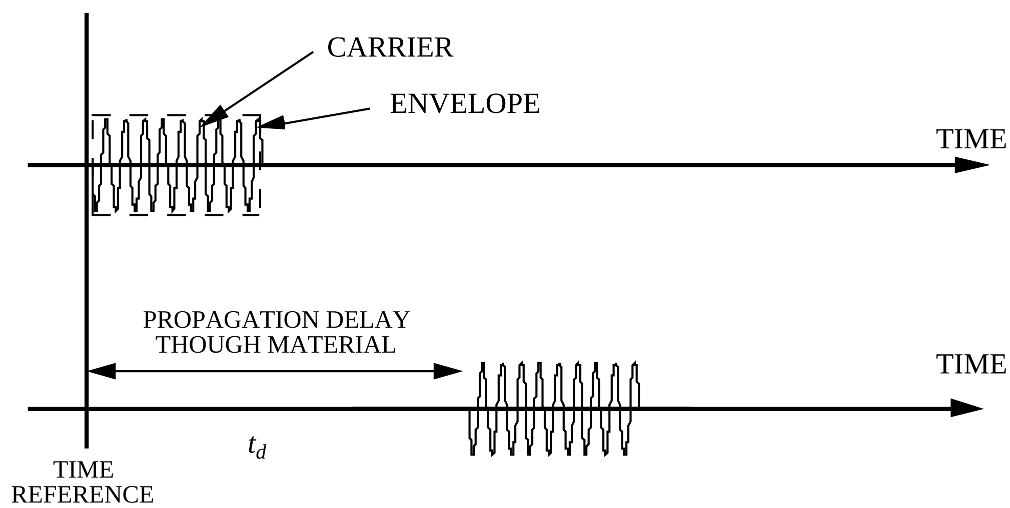
New insight into the behavior of materials has given rise to the concept of "crafting" waveforms for specific materials. That is, waveforms are designed to efficiently penetrate a specific material.

Precursors (1)

Examine the transmitted wave that has a very narrow pulse:

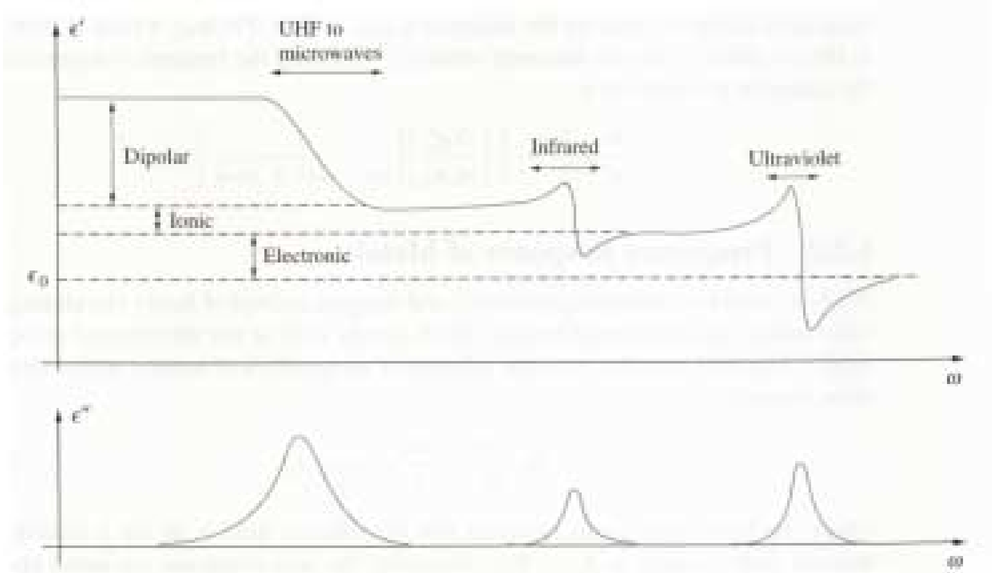


When a conventional waveform passes through a material, the waveform out of the material is a time delayed replica of the waveform at the input. (We assume that the waveform has a long pulse width compared to the relaxation time of the material.) The group velocity v_g is usually taken as the velocity of energy propagation in the material. (Neglecting any distortions due to dispersion.)



Precursors (2)

The group velocity is less than the phase velocity, $v_p = \frac{2\pi f}{\beta}$, which in turn is less than the velocity of light in a vacuum (except for anomalous cases). Below: dielectric constant vs. frequency for a material ($\varepsilon = \varepsilon' - j\varepsilon''$). Note that high frequencies travel faster than low frequencies because $u_p = \frac{1}{\sqrt{\mu\varepsilon'}}$.



Precursors are features in waves transmitted through media due to the ultra-fast rise and fall times of the pulse envelope. They occur because the transferal of energy is not instantaneous.

Precursors (2)

There are two types of precursors:

1. Sommerfeld: Due to the high frequency components of the pulse envelope
    - Travels at the speed of light
    - Largely independent of the medium
2. Brillouin: Due to the low frequency components of the pulse envelope
    - Depends on the waveform properties (rise/fall times, carrier frequency, initial and final values, etc.)
    - Depends on medium properties (mobility of carriers)
    - Penetrates more deeply into the medium ($\sim z^{-1/2}$ vs. $\sim e^{-z}$ for Sommerfeld)

EXAMPLE: AMPLITUDE VS TIME PLOT

FROM T. W. BARRETT, *INTRODUCTION TO ULTRA-WIDEBAND RADAR SYSTEMS*