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Advanced Electromagnetics:
21st Century Electromagnetics

Nonlinear Materials

Lecture Outline

- Electric polarization
- Potential well description
- Nonsymmetric potential well
- Applications
- Notes

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Electric Polarization of Nonlinear Materials

In general, the relation between the applied electric field $\vec{E}$ and the electric polarization $\vec{P}$ is nonlinear so it can be expressed as a polynomial.

$$P = \underbrace{\varepsilon_0 \chi_e^{(1)} E}_{\text{Linear response}} + \underbrace{\varepsilon_0 \chi_e^{(2)} E^2 + \varepsilon_0 \chi_e^{(3)} E^3 + \cdots}_{\text{Nonlinear response}}$$

These terms are usually ignored. They tend to only become significant when the electric field is very strong.

$\chi_e^{(2)}$ is pronounced "chi two"

$\chi_e^{(3)}$ is pronounced "chi three"

$\vdots$

$\chi_e^{(n)} \equiv$ electric susceptibility

$\chi_e^{(1)}$ no units

$\chi_e^{(2)}$ m/V

$\chi_e^{(3)}$ m^2/V^2

$\vdots$

$\chi_e^{(n)}$ $\text{m}^{n-1}/\text{V}^{n-1}$

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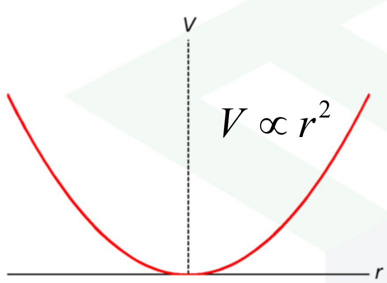
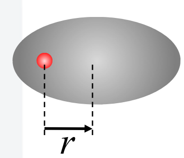
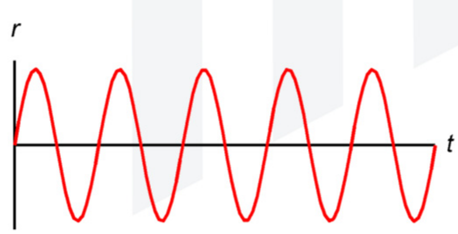
"Potential Well" Description



V is the "push" required to displace the charge by a distance r.



Linear materials have a parabolic potential well.
This leads to a resonator that oscillates as a perfect sinusoid.



Harmonic oscillation

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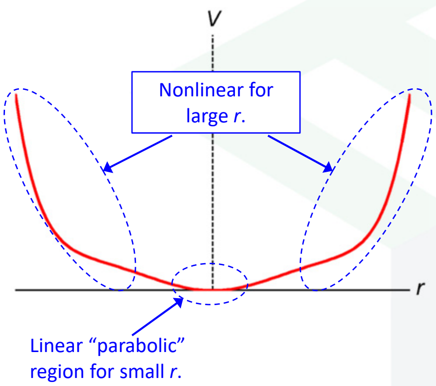
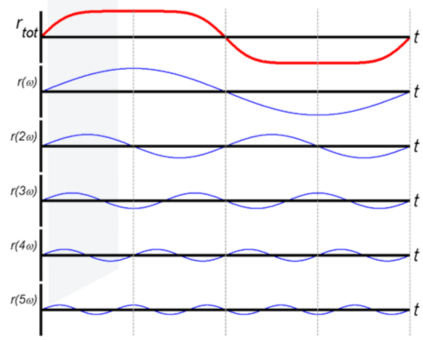
"Potential Well" for Nonlinear Materials



As bound charges are pushed very hard, the restoring force is no longer linear.

This results in **anharmonic oscillation**.

This type of resonance does not oscillate as a sinusoid. It can be seen as a series of sinusoids.



The oscillator is effectively resonating at multiple frequencies at the same time.

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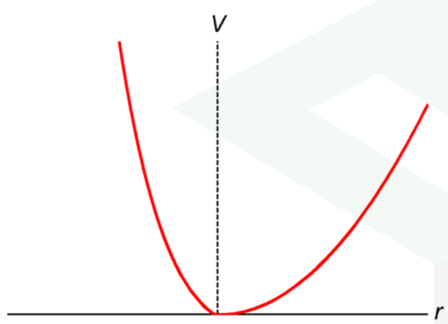
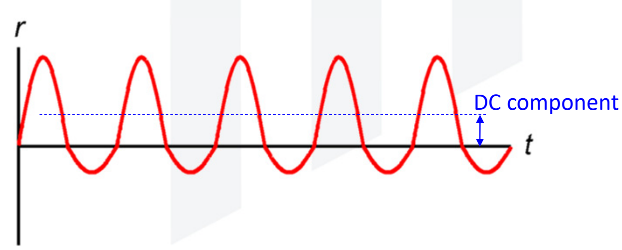
Nonsymmetric Potentials



This is a non-symmetrical potential and therefore exhibits a preferred direction for polarization.

The result is a rectified signal along with potentially other frequency content.



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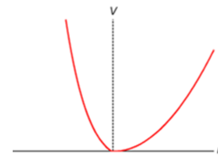
Applications of Nonlinear Materials

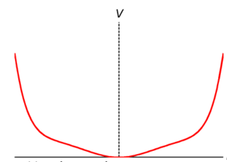
$\chi^{(1)}$ Materials
- Ordinary linear materials

$\chi^{(2)}$ Materials
- *Rectification* – can create a DC potential from an optical wave
- *Frequency doubling (second harmonic generation)* – can make lasers at otherwise impossible wavelengths.
- *Parametric mixing* – can provide sum and difference frequencies
- *Pockel's effect* – can introduce birefringence from an applied electric field.

$\chi^{(3)}$ Materials
- *Kerr effect* – field dependent dielectric constant
- *Third harmonic generation* – can generate very short wavelength waves.
- *Raman scattering* – the mechanical vibration of a molecule can shift the frequency of the wave
- *Brillouin scattering* – dielectric response changes with applied pressure
- *Two photon absorption* – two photons are absorbed simultaneously where as a single photon would not be absorbed.



Lacks inversion symmetry



Has inversion symmetry

Notes About Nonlinear Materials

- All materials are nonlinear. Some just have stronger nonlinear behavior than others.
- It generally requires very intense electric fields to observe nonlinear properties.
- At radio frequencies, materials tend to breakdown before becoming nonlinear.
- Nonlinear properties are commonly exploited at optical frequencies.