3.46 PHOTONIC MATERIALS AND DEVICES

Lecture 1: Optical Materials Design Part 1

Lecture

Notes

Goal: To develop principles for optical materials design.

Approach: Physical basis of properties; use properties in design.

Electromagnetic Field

Apply voltage: $\vec{E} = (\vec{r}, t)$

Apply current: $\vec{H} = (\vec{r}, t)$

Maxwell's Equations

(free space, no charge/current present)

$$\vec{\nabla} \times \vec{H} = \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \qquad \vec{\nabla} \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \cdot \vec{H} = 0$$

EM wave

Wave equation

$$\nabla^2 u - \frac{1}{c_0{}^2} \frac{\partial^2 u}{\partial t^2} = 0$$

u: scalar field profile

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(free space) speed of light

$$c_0 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3\times10^8 \text{ m/s}$$

ε_0 = permittivity of free space

= $\frac{1}{36\pi}\times10^{-9}$ Farad/m (MKS)

μ_0 = permeability of free space

= $4\pi\times10^{-7}$ Henry/m (MKS)

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

<u>Light in a Medium</u>

$$c = \frac{1}{\sqrt{\varepsilon\mu}}$$

$$\vec{D} = \varepsilon\vec{E} = \varepsilon_0\vec{E} + \underset{\substack{\uparrow \\ \text{polarization density}}}{\vec{P}}$$

static relation (time independent) between $\vec{P}$ and ε

$$\vec{P} = \varepsilon_0 \underset{\substack{\uparrow \\ \text{scalar electric susceptibility}}}{\chi} \vec{E}$$

$$\underset{\substack{\uparrow \\ \text{electric permittivity of medium}}}{\varepsilon} = \varepsilon_0(1+\chi)$$

$\frac{\varepsilon}{\varepsilon_0}$ = dielectric constant

	$\frac{\varepsilon}{\varepsilon_0}$ (static)
Si	11.7
Ge	16
$LiNbO_3$	43
$BaTiO_3$	3600

Static: $\nu = 0$

$$\nabla^2 u - \underbrace{\frac{1}{c^2}}_{\downarrow}\frac{\partial^2 u}{\partial t^2} = 0$$

$$c = \frac{1}{\sqrt{\varepsilon\mu}}$$

c = speed of light in medium

Refractive Index (n)

$$n = \frac{\text{speed of light in free space}}{\text{speed of light in medium}}$$

$$c = \frac{c_0}{n}$$

frequency dependence:

frequency: ν
wavelength (free space): λ_0

$$\lambda_0 \nu = c_0$$

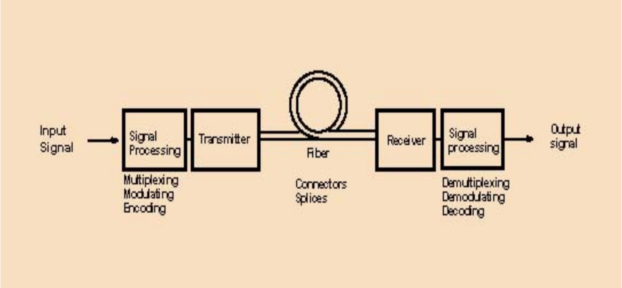
$$n(\nu) = \sqrt{\frac{\varepsilon(\nu)}{\varepsilon_0}} = \sqrt{1+\chi(\nu)}$$

MATERIALS DESIGN

- Performance Goals
- Constraints
- Methodology
- Tradeoffs
- Options
- Optimization

BUILDING A LEARNING CURVE

- Performance Goal
- Barriers
- Timeline (with iterations)
- Incremental Improvement



Fiber-optic communication system

Operating Wavelength and Frequently Used Components In Fiber-Optic Links.

Wave-length λ_0(μm)	Fiber	Source	Detector
0.87	Multimode step-index	LED AlGaAs	p-i-n Si
1.3	Multi-mode graded-index	Laser InGaAsP	p-i-n Ge
1.55	Single-mode	Laser InGaAsP	APD InGaAs

Systems Design

Laser		
P_s	mW	Power
σ_λ	nm	Spectral Bandwidth

Fiber		
α	dB/km	Attenuation
$\sigma_{\mathcal{T}}/L$	ns/km	Response Time
L	km	Length

Detector		
$\bar{n}_0$	photons/bit	Sensitivity
B_0	bits/s	Data Rate

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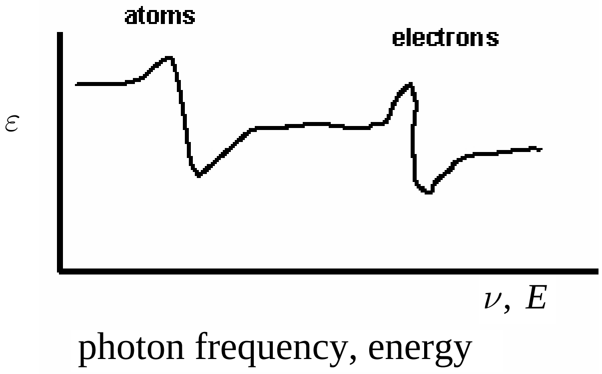
Waveguide Materials Selection

Resonances ⇒ absorption, dispersion



Resonance Frequency (ω_0)

Atoms $\omega_0 = \sqrt{\frac{k_{\text{bond}}}{m_{\text{atom}}}}$, $\omega \equiv 2\pi\nu$

(angular frequency)

Heavy atoms ↔ weak bonds
⇒ low ω_0, long λ response

Electrons

Localization ↔ high energy
⇒ high ω_0, short λ response

Wave Equation

Vacuum

$$\nabla^2 u - \frac{1}{c_0^{\,2}}\frac{\partial^2 u}{\partial t^2} = 0$$

Material

$$\nabla^2 u - \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} = 0$$

Nonlinear Optical Material

Maxwell's Equations valid
Wave Equation invalid

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \vec{P}}{\partial t^2}$$

Lecture

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Dispersion

Dipoles in material respond as harmonic oscillators

Dynamic Relation (time dependent) between P(t) and E(t)

$$\vec{E}(t) = a_1 \underbrace{\frac{d^2\vec{P}}{dt^2}}_{\text{accel.}} + a_2 \underbrace{\frac{d\vec{P}}{dt}}_{\text{vel.}} + a_3 \underbrace{\vec{P}}_{\text{x (position)}}$$

Linear differential equation

Resonances

Driven simple harmonic oscillators

$$\frac{d^2\vec{P}}{dt^2} = -\sigma\frac{d\vec{P}}{dt} - \omega_0{}^2\vec{P} + \omega_0{}^2\varepsilon_0\chi_0\vec{E}$$

$$\vec{P} = \underbrace{N}_{\text{\# charges/unit volume}}(\underbrace{e\vec{x}}_{\text{Dipole movement}}) = \varepsilon_0\chi(\nu)\vec{E}$$

$$\vec{P} = \varepsilon_0\left[\frac{\chi_0\omega_0{}^2}{(\omega_0{}^2 - \omega^2) - j\sigma\omega}\right]\vec{E}\ ,\ \chi_0 \equiv \frac{Ne^2}{m\varepsilon_0\omega_0{}^2}$$

(far away from resonance)

$$\chi(\nu) = \underbrace{\chi'(\nu)}_{\text{Re}} + j\underbrace{\chi''(\nu)}_{\text{Im}}$$