EIE4449 Optical Communication 光通信 Cluesheet

Communication with light

Data → Encoder → Transmitter → Transmission Media → Receiver → Decoder

(ADC) Antenna/modulator/ O/E converter (optical/electrical) | Copper/ free space/ Fiber | Antenna/ E/O converter | (DAC)

(Shannon Channel Capa: $C = B\log_2(1+SNR)$)

light: $f_c \uparrow \rightarrow BW \uparrow$ (elec 1% × 1.8GHz = 18 MHz; Optical 1% × 193 THz = 1.9 THz) (λ=1550nm)

Spectral Range 光谱范围

$f = \frac{c}{\lambda}$, $c = f\lambda$

Δf: freq range

$\Delta\lambda$: wavelength range

$\frac{df}{d\lambda}$: $\Delta f = \frac{c}{\lambda^2}\Delta\lambda$ (assume $\Delta f \to 0$)

Challenges of laser loss: diverging beam, environment

Need light guiding mechanism.

{Hollow core (空芯) — mirrors, high reflection loss

new design — core 纤芯, cladding 包层

Charles Kuen Kao (高锟): SiO_2

Developed a technique for measuring 20 cm silica glass 纯块状 with 0.0002% error (20 dB/km attenuation req), pure bulk SiO_2 at 4 dB/km

Single mode structure with cladding

Impurities (not scattering) are main cause of high fiber loss. Commu req: 20 dB/km at 0.6 μm (possible)

Bending loss is small

Good mech property, possible to fabricate

Fiber

Optical Fiber: waveguide for light

- Jacket: outer protective shield
- buffer: protective coating
- cladding: outer part, keep wave in core
- core: inner part, wave propagates

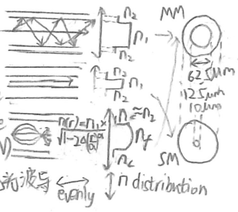
mode: rays travelling down the guide with same int. angle

Types {
- step-index multimode 阶跃折射率多模
- Step-index singlemode 突变型单模 /monomode
- graded-index multimode 渐变折射率多模 (GRIN)

$n(r) = n_1\sqrt{1-2\Delta(\frac{r}{a})^\alpha}$

MM: 62.5 μm, 125 μm; SM: 10 μm

Regular optical waveguide 正规光波导 (evenly n distribution)



cladding NA, θ_{max}, n_2, n_1, core

$\sin\theta_c = \frac{n_2}{n_1}$

For step-idx $NA_{step} = n_1\cos\theta_c = \sqrt{n_1(1-\frac{n_2^2}{n_1^2})} = \sqrt{n_1^2-n_2^2} \approx n_1\sqrt{2\Delta}$

Num Aperture (NA) = $n_{out}\sin(\theta_{max})$ 数值孔径

a cone of acceptance for light

light gathering power $\propto NA^2$

Ray Optics

$AB + BC = 2d\cos\theta$

$\delta_1 = 2\pi\frac{n_1(AB+BC)}{\lambda} - 2\delta_R = \frac{4\pi n_1 d\cos\theta}{\lambda} - 2\delta_R = 2m\pi$

(phase) (optical path) half-wave loss

? 2BC

(total int. reflection) $\theta_c < \theta < \pi/2$

$\Rightarrow m_{max} = \frac{2dn_1\cos\theta_c}{\lambda} - \frac{\delta_R}{\pi} = \frac{2d}{\lambda}\sqrt{n_1^2-n_2^2} - \frac{\delta_R}{\pi} = \frac{2V}{\pi} - \frac{\delta_R}{\pi}$

(cond. for mode to prop.)

$V = \frac{\pi d}{\lambda}\sqrt{n_1^2-n_2^2} = \frac{2\pi a}{\lambda}NA$ (core radius)

{≤2.4: only funda LP_{01}; >2.4: multimode

when num of modes (M) is large: $M \approx \frac{V^2}{2} = a^2(\frac{2\pi}{\lambda})^2 n_1^2\Delta$

$\lambda_c = \frac{2\pi a}{2.405}NA = 1.2\,\mu m$ (optimal) ↓λ cutoff → several λ; restricted range

$V \propto \%P_{clad}$

Material (Thin, long, flex, transparent) (diff compositions (n))

only (Silica) glass & plastics (with dopants)

Dopants for Glass { B_2O_3, Ge_2O_3, P_2O_3
- $n\uparrow$: GeO_2^*, P_2O_5
- $n\downarrow$: $B_2O_3^*$
- Amp, $\downarrow\Delta\lambda$, $\Delta P\uparrow$: (Rare earth): Er, Nd 铒 钕 (for optical amp/modulator/oscillator)

→ Plastic optical fiber (POF) 有机玻璃 全氟化合物高分子

more lossy, often PMMA (or perfluornated polymer, loss↓), cheaper (use for automobile app.), flex, larger strain, biocompat, very short distance, very low bitrate

High longitudinal breaking stress ≈ metal wire but can be elongated only by 2%

Trans Charac. (Signal degradation: loss/attenuation/noise, dispersion/distortion)

① Attenuation

$\frac{dP}{dz} = -\alpha_p P \Rightarrow P(z) = P(0)e^{-\alpha_p z}$

α (in dB): α(dB/km) $= -\frac{10}{L}\log_{10}(\frac{P_{out}}{P_{in}}) = -\frac{10}{L}\log_{10}(\frac{P_{in}e^{-\alpha_p L}}{P_{in}}) = \alpha_p 10\log e = 4.34\alpha_p$

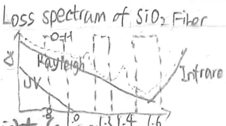
α = 100~1000 for coaxial, 10^{-1}~1 for fiber

Power independent {
- Mat. absorption 原子共振
  - Intrinsic (atomic resonance) Infra-red, UV light
  - Extrinsic (atomic absorption of ext. particles)
    - OH bond* (peak at λ=2.7, 1.4, 0.95, 0.7 μm) remove O-H
    - Impurity absorption of trans. metal ion: Fe, Cr, Cu
- Rayleigh scattering 瑞利散射 when $d \ll \lambda \Rightarrow \sim n$, $\alpha_R = \frac{C}{\lambda^4}$
- Bending loss (macrobending, microbending: imperfect smooth)

$\alpha_m = \alpha_1\frac{P_{core}}{P} + \alpha_2\frac{P_{clad}}{P}$ (模式损耗) shed high order mode; low order → high order

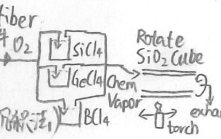
Power dependent (high-power, non-linear) (problematic for SMF) {
- Raman effect 喇曼效应 ∝ photon → lower f. when P>1W: stimu Raman Scat (SRS) loss↑
- Brillouin effect optical + acoustic vibration of glass → $f_{opt}\downarrow$ (~10GHz) 受激布里渊散射效应 ≥10 mW → normally P<10mW thus not dominant, but will in multi-wavelen sys (WDM)
- Self-Phase Modu (SPM 自相位调制) cross-ph Modu (XPM 交叉相位调制)
- Four-wave mixing (FWM 四波混频)

Loss spectrum of SiO_2 Fiber



To make a fiber

① Preform 预制件 making (using MCVD) (改进化学气相沉积法)



② Fibre Draw Tower

② Dispersion: v dependant on mode and λ

for SI-MMF $\delta T = \frac{L}{V_{g2}} - \frac{L}{V_{g1}} = \frac{L}{V_g\sin\theta_c} - \frac{L}{V_g} = \frac{Ln_1}{c}(\frac{n_1}{n_2}-1) = \frac{Ln_1^2}{cn_2}\Delta \approx \frac{Ln_1}{c}\Delta = \frac{L(NA)^2}{2cn_1}$

Assume uniform dist. with $\sigma^2 = \frac{\delta T_{mod}^2}{12}$ (reality is much better) {mode coupling/mixing, differential mode loss (preferential attenuation)

for GRIN: $\sigma = \frac{L(NA)^2}{20\sqrt{3}cn_1}$ for α=2 → $\sigma_{GRIN} \ll \sigma_{SI\text{-}MMF}$ (theoretical)

wave $E(t,z) = Ae^{i(\omega t - \beta z)}$ 波矢; $v_{ph} = \frac{\omega}{\beta}$ 相速, $v_g = \frac{d\omega}{d\beta}$ 群速

pulse spread: $\Delta\tau = |D|\Delta\lambda L$

[D] = ps/nm/km $D = \frac{1}{L}\frac{\partial\tau}{\partial\lambda} = -\frac{2\pi c}{\lambda^2}$

chromatic dispersion { mat. dispersion; waveguide dispersion: geometrical structure of an optical fiber (vary for λ)

can be tuned to dispersion shifted fiber (DSF 色散位移光纤) / compensation fiber (DCF 色散补偿光纤)

$D_{tot} = 0$ when λ=1.55 μm

Light Sources

① LED (low modu freq <200MHz, wide spectral linewidth 30~100nm, high dispersion, rel. large divergence)

{spontaneous emission 自发辐射 recombine of ⓔ ⓗ ⇒ ~~hν

Stimulated emission 受激辐射 (Right) further recomb → more photon

Light Amp by the Stim Emi of Radiation (LASER)

need population inv (粒子数反转)

E_2, E_1, $h\nu_{12}$ (normal dominate); (more in phase)

P-N J. incoherent opt rad; forward dir; conductive band; valence band

surface emitting (SELED) — active region, metal

edge emitting (EELED)

Rel. I (sin); // plane, ⊥ plane; -90 0 90

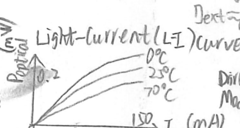
Internal Quantum Efficiency (% of radiative recombine of ⓗ ⓔ) $\eta_0 = \frac{R_r}{R_r+R_{nr}}$ $P_e = \eta_{ext}\eta_0\frac{Ihc}{q\lambda}$

lifetime $\tau_{r/nr} = \frac{\Delta n}{R_{r/nr}}$ → inj carrier density 注入载流子密度 $\tau = \frac{1}{\frac{1}{\tau_r}+\frac{1}{\tau_{nr}}}$

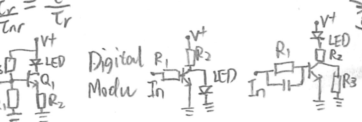
$\Rightarrow \eta_0 = \frac{1}{1+\frac{\tau_r}{\tau_{nr}}} = \frac{\tau}{\tau_r}$

$\eta_{ext} = \frac{1}{n(n+1)^2}$

Light-Current (L-I) curve



Analog Modu; Digital Modu; Direct Modu



② Semiconductor Injection Laser Diode (LD) (high modu freq ~10Gb/s, narrow linewidth, low divergence)

{Gain medium with feedback (spontaneous → stimulus) : Optical gain; Current inject

Higher density forward current (pump) → population inv. : Optical feedback

• Fabry-Perot (FP) Laser; Cleaved Facets ≈ mirror; $R_m = (\frac{n-1}{n+1})^2$

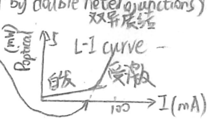
Lasing threshold I_{th} (should be small by double heterojunctions) 双异质结

$I(2L)/I_0 = R_1R_2e^{2L(\Gamma g-\alpha)} \geq 1$

Γ (opti confinement factor, %P in active)

α absorption coeffi of material

L-I curve 自发 受激 (Cond for lasing: Gain: same A; Phase: same φ)



$\frac{4\pi nL}{\lambda} = 2\pi m$, $\frac{2Ln}{\lambda} = m$, $\delta f = \frac{c}{2Ln}$, $\Delta\lambda = \frac{\lambda^2}{2Ln}\delta f$

gain curve (mat absorb); cavity mode 谐振腔模

Wide spectrum → chromatic dispersion sol: single longitudinal mode (SLM)

{λ-selective structure (DFB, DBR, ECL)

Short cavity (VCSEL)

• Distri Feedb Laser (DFB) — Bragg cond $k\lambda_B = 2n_{eff}\Lambda \Rightarrow \lambda_B = \frac{2n_{eff}\Lambda}{k}$

SLM, Use grating rather than mirror, can dense wavelen div mux (DWDM 密集波分复用)

P>1mW, spectral width 100kHz~100MHz, Side mode suppression ratio >50dB.

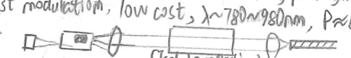
1/4 wave shifted DFB

• Vertical Cavity Surface Emitting Laser (VCSEL 垂直腔面发射激光器)

Distr. Bragg reflector (DBR) mirror, easy packaging (testing), fast modulation, low cost, λ~780~980nm, P≈0.1mW (-10dBm)

VCSEL; Edge emit; Laser chip; Anti-reflection coat; Ext Cavity Laser (ECL)

Laser Diode: Monitor Diode, Laser Chip, Collimation Lens 准直, Optical Isolator (Isolate reflection), Focusing Lens, Optical Fiber



Integrated Tunable (λ) Laser: multicontact, Front grating; $\Delta I \to \Delta n \to \Delta\Lambda \to \Delta\lambda$

③ Photodetectors (Photomultipliers, Photoconductors, phototransistors, photodiodes (PD, PIN & Avalanche PD))

response time (gov. by transit time) $T_{tr} = \frac{W\text{ (depletion width)}}{V_s\text{ (avg drift velo)}}$

Quantum Efficiency $\eta = \frac{I_p/q\text{ (free carrier gen)}}{P_0/h\nu\text{ (photon incidence)}}$

Responsivity $R = \frac{\text{photocurrent}}{\text{incident opt Power}} = \frac{I_p}{P_0} = \frac{\eta q}{h\nu}$

APD η may >1 (due to int. current gain from ionization)

Photodetector Receiver

Noise Source { (PIN, APD) quantum noise, dark current noise, surface leakage noise, thermal noise; (APD) avalanche multiplication noise

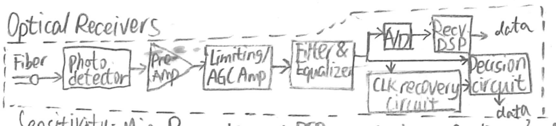
Noise Source { (PIN & APD) quantum noise/shot noise $I(t) = I_{p_{avg}} + i_q(t)$ fluctuation $\overline{\sigma_{sh}^2} = 2qI_pM^2F(M)B$ discrete nature ⓔⓔ

Dark current noise: thermal generation of carriers I_D (dark current) → shot noise $\overline{i_{shD}^2} = 2qI_DM^2F(M)B$ ∝ A (active area)

Surface leakage noise (I_s), thermal noise

(APD) Avalanche multiplication noise

Optical Receivers



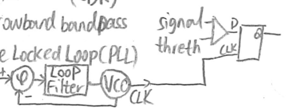
Sensitivity: Min P_{signal} to meet BER req., typical 10^{-9}~10^{-12} or 10^{-3}~10^{-4} (with FEC)

limiting Amp: additional gain, guarantee a fixed output swing without dipping distortion

Clock Recovery & Data Regeneration (CDR)

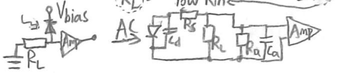
CLK { RZ: present
NRZ: generate CLK { Narrowband bandpass
Phase Locked Loop (PLL)

(non-linear)



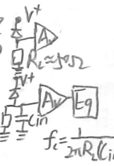
Pre-amplifiers (amplify current from PIN detector)

noise $\langle i_T \rangle^2 = \frac{4k_B TB}{R_L}$ → high R_{in} BW $f_{3dB} = \frac{1}{2\pi R_T C_T}$ → low R_{in}



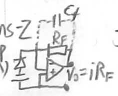
• Low-Z PreAmp

• High-Z PreAmp



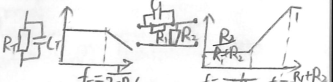
$f_c = \frac{1}{2\pi R_L (C_{in} + C_d)}$

• Trans-Z Amp (TIA)



$f_H = \frac{1}{2\pi R_i C_t}$ $(R_i \approx \frac{R_F}{1+A})$

• Eq



$f_T = \frac{1}{2\pi R_T C_T}$ $f_1 = \frac{1}{2\pi R_1 C_1}$, $f_2 = \frac{R_1 + R_2}{2\pi R_1 R_2 C_1}$

BER (P_e) → $Poi(n) = \frac{e^{-N_p} N_p^n}{n!}$

$P_0 = 0$, $P_1 = N_p h\nu / T$, $P(0) = P(1) = \frac{1}{2}$ ⇒ $\bar{N}_p = \frac{N_p}{2}$, $\bar{P} = \frac{N_p h\nu}{2T}$ $P_e = \frac{1}{2}[\underbrace{P(1|0)}_{0} + \underbrace{P(0|1)}_{P(n=0)=e^{-N_p}}] = \frac{1}{2}e^{-N_p}$