(3) ELEMENTOS ÓPTICOS:

$\frac{P_r}{P_i} = R = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2$

Rotador FARADAY: $\theta = V \cdot B \cdot L$

CIRCULADOR: Pérd. inserc. = 1 dB; Relación aislami. = 40 dB

DIAFONÍA DEMUX:

$D(\lambda_1) = 10\log\frac{P_1(\lambda_1)}{P_2(\lambda_1)}$ 1→2

Compensar la disp. cromát. — RED BRAGG

$L_{BG} = \frac{C\Delta\tau}{2n_{av}} = \frac{cD\delta\lambda L}{2n_{av}}$

CONECTORES:

Pérdidas inserción: $IL = -10\log(P_{out}/P_{in})$

Reflectancia: $R = 10\log(P_R/P_{in})$

CONTACTO: Plano, PC/SPC, APC

FABRY PEROT:

$\tau = \frac{2dn_2}{c}$

$\phi_2 = k_0 n_2 d = \pi\nu\tau$

$\delta = 2\phi_2$

máx. transmis. $D = \frac{c}{2nL}$

$\nu_N = \frac{N}{\tau} = \frac{Nc}{2dn_2} \rightarrow d = N\frac{\lambda_2}{2}$

Sep. entre máx. trans. consecut. $FSR = \frac{1}{\tau} = \frac{c}{2dn_2}$; $\nu_N = N \cdot FSR$

FINESSE: $F = \frac{4R}{(1-R)^2}$

$\frac{I_t}{I_i} = \frac{1}{1+F\sin^2(\pi\nu\tau)}$ {max 1, min = 1+F}

$\frac{I_r}{I_i} = \frac{1}{1+\frac{1}{F\sin^2(\pi\nu\tau)}}$ {max = $\frac{F}{1+F}$, min = 0}

Anchura (FWHM): $\Delta\nu \approx \frac{1-R}{\pi\tau\sqrt{R}}$

Contraste: $C = \frac{(1+R)^2}{(1-R)^2} = 1+\left(\frac{2\mathcal{F}}{\pi}\right)^2 = 1+F$

Finura: $\mathcal{F} = \frac{FSR}{\Delta\nu} = \frac{\pi\sqrt{R}}{1-R}$

$\frac{I_t}{I_i} = \frac{1}{1+(C-1)\sin^2\left(\frac{\pi\nu}{FSR}\right)}$ ← Func. transmit. (Airy)

$\delta = \frac{2\pi n_{eff}}{\lambda_1}\Delta L$

FABRY-PEROT: $\delta = \frac{4\pi n_1 d}{\lambda} = \frac{4\pi n_1 d \cdot \nu}{c}$

$\frac{I_t}{I_i} = \frac{1}{1+F\sin^2\left(\frac{\delta}{2}\right)}$; $\delta = \frac{4\pi n\nu d\cos\theta L}{c}$

ACOPLADOR: $K_{1\to4} = \frac{P_4}{P_3+P_4}$ (cte. acoplo); $P_3 = P_1 - \frac{\text{pérd.}}{\text{inserc.}}3$; $P_4 = P_1 - \frac{\text{pérd.}}{\text{inserc.}}4$

$\begin{pmatrix}P_1(L)\\P_2(L)\end{pmatrix} = (1-\gamma)\begin{pmatrix}1-K & K\\K & 1-K\end{pmatrix}\begin{pmatrix}P_1(0)\\P_2(0)\end{pmatrix}$

$0 \le \gamma \le 1$; $\gamma = \frac{(P_1(0)+P_2(0)) - (P_1(L)+P_2(L))}{(P_1(0)+P_2(0))}$

Directividad: $RL = D = 10\log P_1/P_2$

Pérdidas exceso: $\Gamma = -10\log(1-\gamma) = 10\log\left(\frac{P_1}{P_3+P_4}\right)$

Pérdidas inserción $= IL = 10\log\left(\frac{P_1}{P_4}\right)$

REFLEX. BRAGG: Periodo espac. Λ, n_{av}; $\lambda_{Bragg} = 2n_{av}\Lambda$

DBR (Distr. Bragg Grating); FBG (Fiber Bragg Grating)

$n(z) = n_{av} + \Delta n(z) = n_{av} + \Delta n_0\cos\left(\frac{2\pi z}{\Lambda}\right)$

$L = N \cdot \Lambda$

$D = m \cdot \frac{c}{n_{eff}\Delta L}$

Reflect. max: $R_{max} = \text{Th}^2\left(\frac{\Delta n_0 \pi L}{n_{av} 2\Lambda}\right) = \text{Th}^2\left(\frac{\Delta n_0 \pi N}{n_{av}\cdot 2}\right)$; $N\uparrow \rightarrow R_{max} = 1$

Anch. relativa: $\frac{\Delta\lambda}{\lambda_{Bragg}} = \sqrt{\left(\frac{\Delta n_0}{n_{av}}\right)^2 + \left(\frac{2\Lambda}{L}\right)^2} = \sqrt{\left(\frac{\Delta n_0}{n_{av}}\right)^2 + \left(\frac{2}{N}\right)^2}$; $N\uparrow \rightarrow \frac{\Delta\lambda}{\lambda_{Bragg}} \approx \frac{\Delta n_0}{n_{av}}$

INTERF. ENTRE 2 HACES: $\Delta\phi = k_0(L_1-L_2)$

$P = \cos^2\left(\frac{k_0(L_1-L_2)}{2}\right) = \frac{1}{2}(1+\cos\Delta\phi)$

$P = \left[\frac{\sin\left(N\frac{\Delta\phi}{2}\right)}{N\sin\left(\frac{\Delta\phi}{2}\right)}\right]^2$; $\Delta\phi = k_0\Delta L$ cte

$P = \int_{\lambda_1}^{\lambda_2} DEP\,d\lambda = DEP\,\Delta\lambda$

Mach-Zehnder: $\Delta\phi = k_0 n_{eff}\Delta L = \beta_1 L_1 - \beta_2 L_2$; $k_0 = \frac{\pi\nu}{c}$; $L_1 = L_2 + \Delta L$

$P_3/P_1 = P_3/P_2 = \sin^2\left(\frac{\Delta\phi}{2}\right) = \frac{1}{2}(1-\cos\Delta\phi)$

$P_4/P_1 = P_3/P_2 = \cos^2\left(\frac{\Delta\phi}{2}\right) = \frac{1}{2}(1+\cos\Delta\phi)$

$\Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{2n_{eff}\Delta L}$ dist. entre max

$\Delta\lambda = \lambda_m - \lambda_{m+1} = n_{eff}\Delta L\left(\frac{1}{m(m+1)}\right)$ (grados)

(4) TRANSMISORES ÓPTICOS

$E_2 - E_1 = h\nu$; $h = 6{,}63\cdot10^{-34}$ Js

Ley Radiac. Planck: $k_B = 1{,}3807\cdot10^{-23}$ J/K

Densid. espectral $\rho(\nu) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/k_BT}-1}$ Js/m³

$\frac{N_2}{N_1} = e^{-h\nu/k_BT}$

$(N_2-N_1)<0 \Rightarrow g<0$ ABSORCIÓN; $(N_2-N_1)>0 \Rightarrow g>0$ BOMBEO

$I(z) = I(0)e^{gz}$

COEF. EINSTEIN: $R_{abs} = B_{12}\rho(\nu)N_1$; $R_{spon} = -\frac{N_2}{\tau_{spon}} = -A_{21}N_2$; $R_{stim} = -B_{21}\rho(\nu)N_2$

Equilibrio: $B_{12}\rho(\nu)N_1 - A_{21}N_2 - B_{21}\rho(\nu)N_2 = 0$

$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3}$; $B_{21} = B_{12}$

$R_{stim} - R_{abs} = B_{21}\rho(\nu)(N_2-N_1)$

Max. func. transf. con $\delta = 2m\pi$: $\frac{4\pi n_1 d\Delta\nu}{c} = 2\pi$

$\frac{dN(t)}{dt} = G - R$; $R = R_{rr} + R_{nr}$; $R_{rr} = R_{spon} + R_{stim}$

$\eta_{int} = \frac{\text{fot. generados}}{\text{fot. inyectados}} = \frac{R_{rr}}{R_T} = \frac{R_{rr}}{R_{rr}+R_{nr}}$

$R = R_{rr} + R_{nr} = \frac{N}{\tau_{rr}} + \frac{N}{\tau_{nr}}$; $\frac{1}{\tau_c} = \frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}}$; $R_{spon} = \frac{N}{\tau_{spon}}$

$\eta_{int} = \frac{\tau_{nr}}{\tau_{nr}+\tau_{rr}}$

$t=0$, $G=0$: $\frac{dN(t)}{dt} = -\frac{N(t)}{\tau_c}$; $N(t) = N(0)e^{-t/\tau_c}$

$R_{stim} = 0$ (LED): $\tau_{rr} = \tau_{spon}$; $\eta_{int} = \frac{\tau_c}{\tau_{spon}}$

EFICIENCIA DE CONV. DE POTENCIA: $\eta_{TOT} = \frac{P_{opt}}{P_{elect}} = \frac{P_{opt}}{V\cdot I}$

LED: $q = 1{,}6\cdot10^{-19}$ C

$P_{int} = \eta_{int}I\left(\frac{h\nu}{q}\right) = \eta_{int}I\frac{1{,}24}{\lambda(\mu m)}$

$\frac{I}{q}\eta_{int} = \frac{P_{int}}{h\nu}$

$P_{emit} = \eta_{ext}\eta_{int}I\frac{h\nu}{q}$

$\eta_{TOT} = \eta_{ext}\eta_{int}\frac{h\nu}{qV}$; $h\nu \approx qV$; $\eta_{TOT} = \eta_{ext}\eta_{int}$

Responsividad: $\mathcal{R} = \frac{P_{emit}}{I} = \eta_{ext}\eta_{int}\left(\frac{h\nu}{q}\right) = \frac{\eta_{TOT}}{V}$

$h\nu_{pico} = E_g + \frac{k_BT}{2}$

$R_{spon} = A_0\sqrt{h\nu - E_g}\cdot\exp\left[-\frac{(h\nu-E_g)}{k_BT}\right]$; $T = 300K \rightarrow k_BT \approx 25$ meV

Anchura FWHM: $\Delta\nu = \frac{1{,}8k_BT}{h}$; $\Delta\lambda = \frac{1{,}8k_BT\lambda^2}{hc} = 1{,}45k_BT\lambda^2_{pico}$

$hc = 1{,}24$ eV; $T = 300K \rightarrow \Delta\nu \approx 11$ THz

$\frac{\Delta\lambda}{\lambda^2_{pico}} = $ cte; $\Delta\lambda$: 30–150 nm

DIAGRAMA RADIAC.: $P(\theta) = P(0)\cos\theta$

$\frac{dN(t)}{dt} = G - R$; $G = \frac{I(t)}{qV_{activo}}$; $R = \frac{N(t)}{\tau_{spon}} + \frac{N(t)}{\tau_{nr}}$

$\frac{1}{\tau_c} = \frac{1}{\tau_{spon}} + \frac{1}{\tau_{nr}}$

En continua: $I(t) = $ cte $\rightarrow G = R \rightarrow \frac{dN(t)}{dt} = 0 \rightarrow \frac{I}{qV_{act}} = \frac{N}{\tau_c}$; $N = \frac{I\tau_c}{qV_{act}}$

$P = \eta_{ext}\cdot h\cdot\nu\frac{N}{\tau_{spon}}V_{act} = \eta_{ext}\frac{I\tau_c h\nu}{q\tau_{spon}} = \eta_{ext}\frac{I\tau_c}{\tau_{spon}}\left(\frac{h\nu}{q}\right)$

En alterna: $I(t) = I_b + I_m e^{j\omega_m t}$; $I_m \ll I_b$

$N(t) = N_b + N_m(\omega)e^{j\omega_m t}$; $N_m(\omega) = \frac{I_m\tau_c}{qV_{act}}\frac{1}{1+j\omega\tau_c}$

$P(t) = P_b + P_m(\omega)e^{j\omega_m t}$

$H(\omega) = \frac{1}{1+j\omega\tau_c}$; $h(t) = \frac{1}{\tau_c}e^{-t/\tau_c}u(t)$

$\eta_{ext}\cdot h\nu\frac{N_m(\omega)V_{act}}{\tau_{spon}}$

Encendido: $P(t) = P_{ON}(1-e^{-t/\tau_c})$

Apagado: $P(t) = P_{ON}(e^{-t/\tau_c})$

ANCHO BANDA MODULAC.

$|H(\omega)| = \frac{1}{\sqrt{1+(2\pi f\tau_c)^2}}$; Tiempo subida $T_r = (\ln 9)\tau_c \approx 2{,}2\tau_c$

$f_{3dB\,opt.} = \frac{\sqrt{3}}{2\pi\tau_c}$; $f_{3dB\,elect} = \frac{1}{2\pi\tau_c}$

$(|H(j\omega)| = 0{,}5)$ $(|H(j\omega)|^2 = 0{,}5)$

$P\cdot f_{3dB\,elect} = \eta_{ext}\left(\frac{h\nu}{q}\right)\frac{I}{2\pi\tau_{spon}} = $ cte

DIODO LÁSER

Densidad transparencia $N_0 = 1$–$1{,}5\cdot10^{18}$ cm⁻³; $G_{p_{mat}}(N) = \sigma_g(N-N_0)$

Sección de ganancia $\sigma_g = 200$–$300\cdot10^{-18}$ cm²

R_i: reflectiv. cara i

FACTOR CONFINAMIENTO: $G_{th} = \Gamma G_{mat} = \alpha_{int} + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) = \alpha_{cav}$ [cm⁻¹]

COND. OSCILACIÓN: $\sqrt{R_1R_2}\exp\left[\frac{(G-\alpha_{int})2L}{2}\right]\exp[-j2k_0n_{eff}L] = 1$

Mód. $G_{th} = \alpha_{int} + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$

Fase: $2k_0n_{eff}\cdot L = 2\pi m$ (nº modo)

EFICIENCIA: Si $R_1 = R_2$: $\eta_{slope} = \frac{1}{2}\eta_d\frac{h\nu}{q}\left[\frac{W}{A}\right]$; $\eta_{TOT} = \frac{h\nu}{qV}\eta_d\frac{(I-I_{th})}{I}$

ANCHO DE LÍNEA: $\Delta\nu = R_{spon}\cdot\frac{(1+\alpha^2)}{4\pi\langle P\rangle}$; $\alpha \approx 1$–5

PASAR A eV: $1J \xrightarrow{\cdot 1/q} 6{,}25\cdot10^{18}$ eV

ENERGÍA DEL GAP: se da a la frec. a la cual empieza a haber ganancia. $E_g = h\cdot\nu$

LÁSER FABRY PEROT: $R = \left(\frac{n_{eff}-n_{ext}}{n_{eff}+n_{ext}}\right)^2$; $n_{eff} \approx 3{,}5$; $n_{ext} \approx 1$; $R \approx 0{,}3$

MODOS LONGITUD. LÁSER FABRY PEROT: $k_0n_{eff}L = m\pi$; $\nu_m = m\frac{c}{n_{eff}2L}$; $\Delta\nu = \frac{c}{n_{eff}2L}$

$\lambda_m = \frac{n_{eff}2L}{m}$; $\Delta\lambda = \frac{\lambda^2}{n_{eff}2L}$; 0,1 nm < Δλ < 1 nm

$P_{cc} = \frac{P_{OFF}+P_{ON}}{2}$; Relación extinción $10\log\frac{P_{ON}}{P_{OFF}}$; $r_e = \frac{P_1(0)}{P_1(t)}$ (NRZ)

$P_{ON} = \eta_{slope}(I_{ON}-I_{th})$; $I_{th} = I_0\exp\left(\frac{T}{T_0}\right)$; T_0: temp. referencia

A dos temperaturas:

$T_1 \rightarrow P_{ON} = \eta_{slope}(I_{ON}-I_{th}(T_1))$; $P_{OFF} = \eta_{slope}(I_{OFF}-I_{th}(T_1))$

$P_{ON} - P_{OFF} = \eta_{slope}(I_{ON}-I_{OFF})$; Lo mismo pasa para T_2

Ec. de fotones: $\frac{dN_{ph}}{dt} = GN_{ph} + R_{sp} - \frac{N_{ph}}{\tau_{ph}}$; τ_{ph}: tiempo vida fotón

EC. BALANCE: $\frac{dN(t)}{dt} = \frac{I(t)}{qV_{act}} - R_{spon}R_{nrad} - R_{stim}$

$R_{spon} + R_{nrad} = \frac{N(t)}{\tau_{spon}} + \frac{N(t)}{\tau_{nr}} = \frac{N(t)}{\tau_c}$; $\frac{1}{\tau_c} = \frac{1}{\tau_{spon}} + \frac{1}{\tau_{nr}}$

$R_{stim} = G\frac{N_{ph}}{V_{act}}$; N_{ph}: nº photon. cavidad

$G = \Gamma g_{mat}v_g = G_N(N-N_0)V_{act}$

$\alpha_{mir} = \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$

A 2 temperat.: $\frac{I_{th}(T_1)}{I_{th}(T_2)} = \exp\left(\frac{T_1-T_2}{T_0}\right)$; T_1, T_2 en Kelvin

$G_N = \frac{\sigma_g v_g\Gamma}{V_{act}}$; $\frac{dN(t)}{dt} = \frac{I(t)}{qV_{act}} - \frac{N(t)}{\tau_c} - \frac{GN_{ph}}{V_{act}}$; $\frac{1}{\tau_{ph}} = \frac{c}{n_g}\left[\alpha_{int} + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)\right] = \frac{c}{n_g}(\alpha_{int}+\alpha_{mir})$ (α cavidad)

$P_{emitida} = \nu_g\cdot\alpha_{mir}N_{ph}h\nu$ (2 caras)

Cond. umbral: $G_{th}\tau_{ph} = 1$

POTENCIA-CORRIENTE: continua: $I = $ cte: $N_{ph} = \frac{R_{sp}}{\frac{1}{\tau_{ph}} - G}$

ANTES: $N_{ph} \approx 0$; $N = \frac{\tau_c I}{qV_{act}}$. EN MEDIO: $N_{th} = N_0 + \frac{1}{G_N\tau_{ph}V_{act}}$

VARIAC. CORRIENTE UMBRAL CON LA TEMPERATURA: $I_{th} = I_{th}(T_{ref})\exp\left[\frac{T-T_{ref}}{T_0}\right]$

DESPUÉS: $N_{ph} = \frac{\tau_{ph}}{q}(I-I_{th}) = \frac{1}{G}\left(\frac{I}{q} - \frac{N_{th}}{\tau_c}V_{act}\right)$

$I_{th} = \frac{qV_{act}}{\tau_c}\cdot N_{th}$; $V_{act} = W\cdot L\cdot d_{ac}$ (largo, ancho)

$P_{emit\,2\,caras} = \frac{N_{ph}}{\tau_{mir}}h\nu = \nu_g\alpha_{mir}\tau_{ph}\frac{h\nu}{q}(I-I_{th})$

$2m\pi = k_0(n_{eff}L_1 + L_2)$; $\frac{1}{\lambda_m} = \frac{m}{2(n_{eff}L_1+L_2)}$

$\Delta\lambda = \frac{\lambda_{m+1}\lambda_m}{2(n_{eff}L_1+L_2)} = \frac{\lambda^2}{2(n_{eff}L_1+L_2)}$

Las frec. de la cavidad $\nu_m = m\frac{c}{n_{eff}2L}$. Probamos m hasta llegar a una con ganancia positiva; m = 5, ν_5 (ejemplo) ⇒ $\lambda_5 = c/\nu_5$

$P(t) = P_1 + (P_2-P_1)(1-e^{-t/\tau_c})$

Tiempo de encendido: $t_d = \tau_c\cdot\ln\left(\frac{I_{ON}-I_{OFF}}{I_{ON}-I_{th}}\right)$

Para láseres con $R_1 \gg R_2$: $P_{total} = P_1 + P_2 \approx P_2$; $\eta_{slope} \approx \eta_d\frac{h\nu}{q}$

EFICIENCIA CUÁNT. DIFER. η_d: $P_{emit\,2\,caras} = \frac{\eta_{int}\alpha_{mir}}{(\alpha_{int}+\alpha_{mir})}\frac{h\nu}{q}(I-I_{th})$

$\eta_d = \frac{\eta_{int}\alpha_{mir}}{(\alpha_{int}+\alpha_{mir})}$

FABRY PEROT SIMÉTRICO: $R_1 = R_2$; $P_{emit.\,1\,cara} = \frac{1}{2}P_{emit.\,2\,caras}$

LÁSER DFB: Relación de supresión de modos laterales: FABRY PEROT

$SMSR = 10\log\left(\frac{P_{emitida}}{P_{modo\,sec}}\right)$

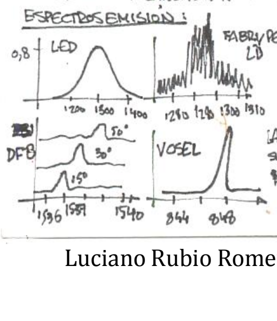
Densidad portadores en umbral [cm⁻³]: $N_{th} = N_0 + \frac{1}{G_N\tau_{ph}V_{act}} = N_0 + \frac{1}{\frac{\sigma_g v_g\Gamma}{V_{act}}\cdot\frac{1}{v_g\alpha_{cav}}}\cdot V_{act} = N_0 + \frac{\alpha_{cav}}{\sigma_g\Gamma}$

APLICACIONES:

- AISLADOR ÓPTICO:
- MUX/DEMUX DE CANALES WDM: AWG, MACH-ZENDER
- EXTRACCIÓN CANAL EN WDM: RED DE BRAGG
- FILTRO PASO BANDA EN λ: FABRY-PEROT, MACH-ZENDER
- COMPENSACIÓN DISPERSIÓN: RED DE BRAGG
- REDUCCIÓN POTENCIA ÓPTICA: FABRY-PEROT
- AMPLIFICACIÓN POT. ÓPTICA: RED BRAGG
- BLOQUEO POT. REFLEJADA EN DIR. CONTRARIA A LA PROPAGACIÓN: AISLADOR ÓPTICO, CIRCULADOR
- FILTRO ELIMINA BANDA EN λ: RED BRAGG

$\Delta\nu = FSR = f_2 - f_1$; $f_{pico} = f_1 = m\cdot FSR \rightarrow m$. Recalculamos para ese m el FSR'

ESPECTROS EMISIÓN:



Fabry: Aumenta λ con la I, porque $n_{eff} = f(T)$, $T = f(I)$. Aumenta SMSR con I

LÁSER DFB: se sintonizan subiendo la temperatura, ya $n_{eff} = f(T)$

	LED	LD-FP	LD-DFB	VCSEL
Pot. en fibra	↓	↑	↑	↑
Espectro	Ancho	Estr.	Muy estr.	Muy estrecho
Vel. modulac.	Baja-Media	↑ Alta	Muy Alta	Alta muy alta
Coste	↓	→	↑	↓
Acoplo a fibra	MM	SM	SM	MM
Ventan.	1,2	2,3	2,3	1
App.	Baja Tasa bin. corta dist.	Baja media Tasa y dist.	Alta y larga WDM	Alta corta