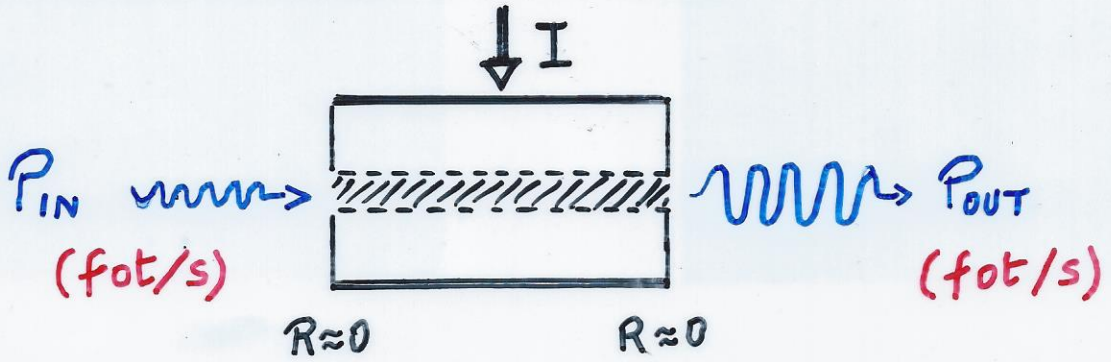
Amplificadores ópticos

Idea básica

* Si $R_1, R_2 \to 0 \Rightarrow I_{Th} \to \infty$ (oscil. imposible)
* I ($\ll I_{Th}$) aporta ganancia a la zona activa
* P_{IN} (fotones/s) $\Rightarrow$ emisión estimulada en z.a.



Problemas

* La naturaleza de la luz es aleatoria.
* Un O.A. modifica la estadística de la luz.
* Emisión espontánea amplificada.
* Conclusión: es necesario un estudio estadístico.

En general, si $x(\tau)$ es el nº fotones contados en un tiempo τ, tendremos:

$$x(\tau) = \underbrace{\langle x(\tau)\rangle}_{\text{(inform.)}} + \underbrace{\{x(\tau) - \langle x(\tau)\rangle\}}_{\text{(fluctuación)}}$$

$\hookrightarrow$ Ruido cuántico

Expresiones estadísticas fundamentales

En general:

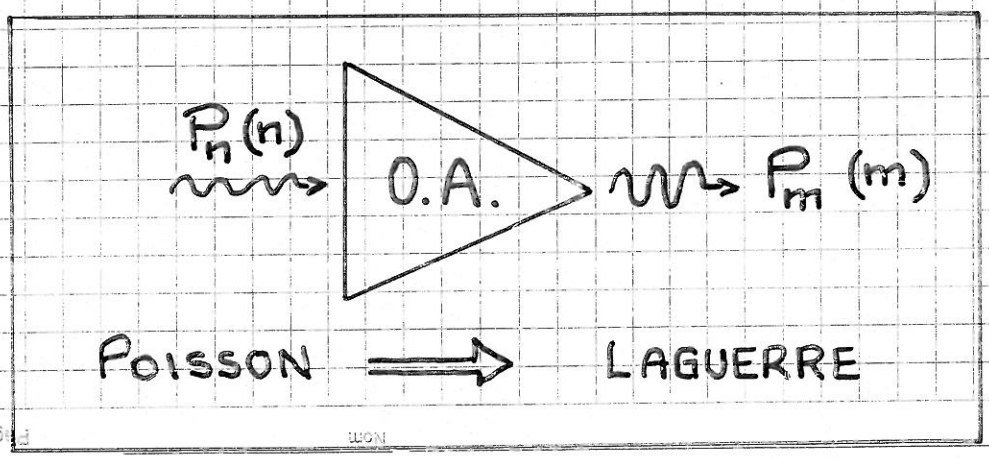
$$\langle m^r \rangle = \sum_m m^r P_{n,m}$$

Momento de 1er orden:

$$\frac{d\langle m \rangle}{dt} = (a-b)\langle m \rangle + c$$

Momento de 2º orden:

$$\frac{d\langle m^2 \rangle}{dt} = 2(a-b)\langle m^2 \rangle + (a+b+2c)\langle m \rangle + c$$



MOMENTO DE 2º ORDEN

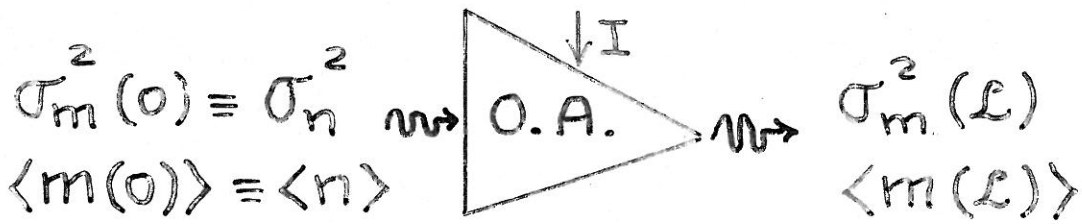
$$v\frac{d\langle m^2\rangle}{dz} = 2(a-b)\langle m^2\rangle + (a+b+2c)\langle m\rangle + c$$

Definimos : $\sigma_m^2 \equiv \langle m^2\rangle - \langle m\rangle^2$

Resultado :

$$\sigma_m^2(\mathcal{L}) = \underbrace{G_s^2\left[\sigma_n^2 - \langle n\rangle\right]}_{\text{(Exceso)}} + \underbrace{G_s\langle n\rangle}_{\text{(Shot)}} + \underbrace{\frac{c}{a-b}(G_s-1)}_{\text{(Shot)}} +$$

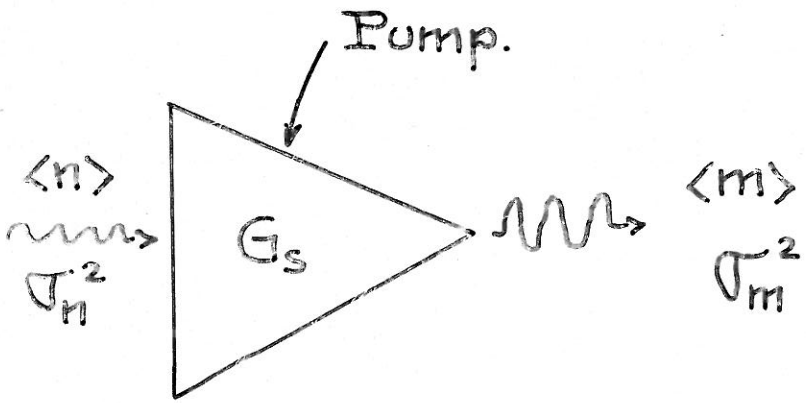
$$+ \underbrace{2G_s\frac{a}{a-b}(G_s-1)\langle n\rangle}_{\text{(Batido)}} + \underbrace{\frac{c}{a}\left(\frac{a}{a-b}\right)^2(G_s-1)^2}_{\text{(Batido)}}$$



Caracterización estadística TWOA (resumen)

* $\langle m \rangle = G_s \langle n \rangle + \rho (G_s - 1)$

* $\sigma_m^2 = G_s^2 (\sigma_n^2 - \langle n \rangle) + G_s \langle n \rangle + \rho (G_s - 1) + \underbrace{2 \rho G_s (G_s - 1) \langle n \rangle + \rho^2 (G_s - 1)^2}_{\text{Dominantes (?!)}}$



$G_s \equiv \exp(g \mathcal{L})$

* SN

* I

RELACION SEÑAL RUIDO

Hipótesis:

* Luz coherente a la entrada : $\sigma_n^2 = \langle n \rangle$
* $G_s \gg 1$ (usual)
* Amplificador monomodo : $c = a$

Aproximadamente:

$$\sigma_m^2 = 2 f G_s^2 \langle n \rangle + f^2 G_s^2$$

$$SNR^{OUT} \equiv \frac{\langle m \rangle^2_{SEÑAL}}{\sigma_m^2} \approx \frac{\langle n \rangle^2}{f(2\langle n \rangle + f)}$$

Si $\langle n \rangle \gg f \Rightarrow \boxed{SNR^{OUT} \approx \frac{\langle n \rangle}{2f} \sim F_{IN}}$

Amplificador ideal:

$$f = 1 \Rightarrow SNR^{OUT} = \frac{\langle n \rangle}{2} = \frac{SNR^{IN}}{2}$$

$$NF\,(ideal) = 3\,dB$$

Caracterización estadística TWOA (resumen

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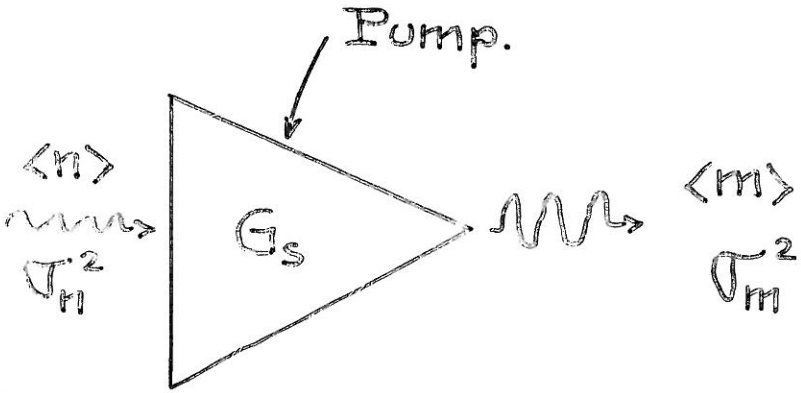
* $\sigma_m^2 = G_s^2 (\sigma_n^2 - \langle n \rangle) + G_s \langle n \rangle + \rho (G_s - 1) + \underbrace{2 \rho G_s (G_s - 1) \langle n \rangle + \rho^2 (G_s}_{\text{Dominantes (?!)}}$



$G_s \equiv \exp(g \mathcal{L})$

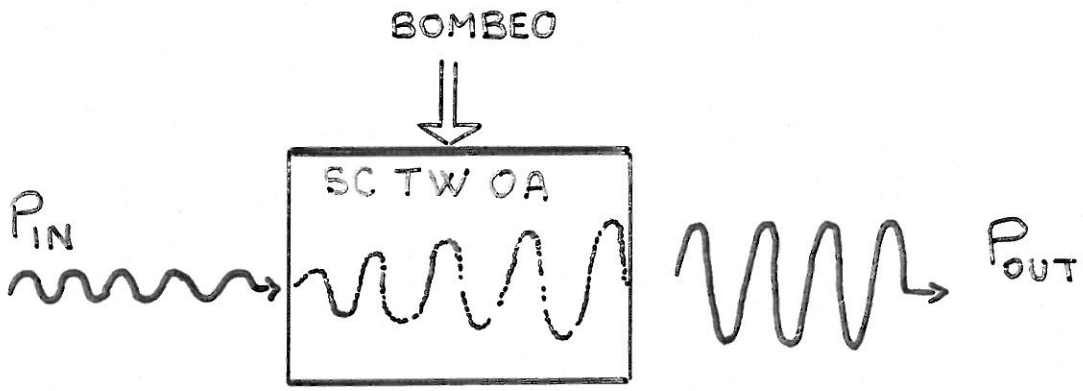
Siempre que

* $\sigma_n^2 = \langle n \rangle$
* $G_s \gg 1$

Si, además, $\langle n \rangle \gg 1$:

* $\sigma_m^2 \approx 2 \rho G_s^2 \langle n \rangle$
* $SNR_{OUT} \approx SNR_{IN} / 2$
* $N.F. \approx 2 \rho \quad (\geq 2)$

AMPLIFICADOR OPTICO



Características:

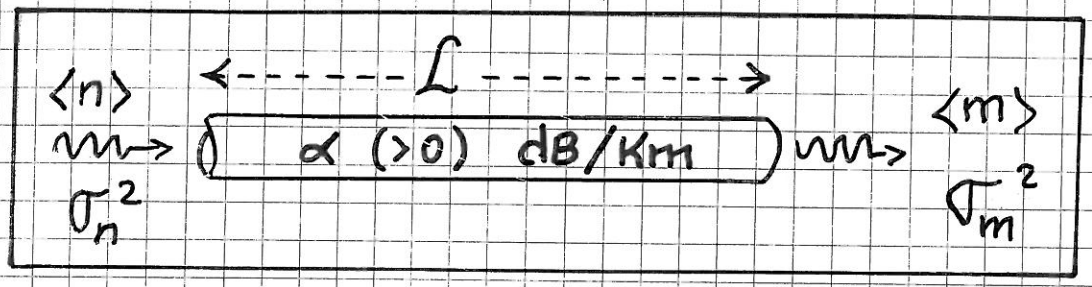
* Esencialmente un laser, pero con P_{IN} y P_{OUT}
* $R_1 = R_2 \approx 10^{-5}$ $\Rightarrow$ Opera por debajo de I_{Th}
* Ancho de banda ~ 40 THz
* Ganancia 20 - 30 dB
* Figura de ruido 5 - 7 dB
* Acoplo fibra - amplif. ≈ 3,5 dB
* No linealidad por saturación
* Bajo consumo (mW) y caro (9M€)
* Comportamiento monomodo

Caracterización estadística fibra óptica

* De manera análoga al PIN :

$$a \equiv 0 \quad y \quad c \equiv 0 \Rightarrow f \equiv 0$$

* ¿ Concepto de gancia ~ atenuación ?



(monomodo)

* $G_s \equiv \dfrac{P_{OUT}}{P_{IN}} = \dfrac{\langle m \rangle}{\langle n \rangle} \equiv A \qquad \left(\alpha \equiv -\dfrac{10}{\mathcal{L}} \log A \right)$

<u>Ecuaciones OUT - IN</u> :

* $\langle m \rangle = A \langle n \rangle \qquad \left(A = 10^{-\frac{\alpha \mathcal{L}}{10}} \right)$

* $\sigma_m^2 = A^2 (\sigma_n^2 - \langle n \rangle) + A \langle n \rangle$

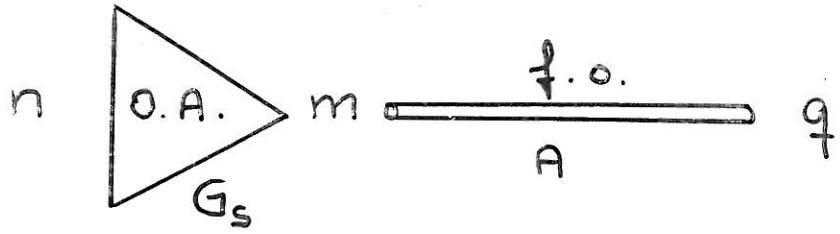
Si $\sigma_n^2 = \langle n \rangle$, (cohencia) ,

* $\sigma_m^2 = \langle m \rangle \Rightarrow$ Coherencia (out)

* $SNR_{OUT} = A \langle n \rangle = A \cdot SNR_{IN}$

* $NF = 1/A \qquad (\geq 1)$

Sección amplif.-fibra



* Hipótesis: $\sigma_n^2 = \langle n \rangle$; $G_s A = 1$; $G_s \gg 1$

* $$\begin{cases} \langle m \rangle = G_s \langle n \rangle + f\,(G_s - 1) \approx G_s \langle n \rangle + f\, G_s \\ \sigma_m^2 \approx 2 f\, G_s^2 \langle n \rangle \end{cases}$$

Salida de la fibra:

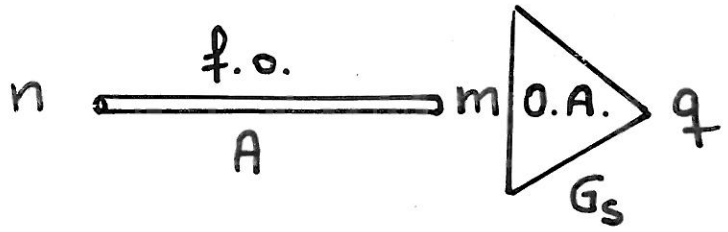
* $\langle q \rangle = A \langle m \rangle \approx A G_s \langle n \rangle + A f G_s = \langle n \rangle + f$
* $$\begin{aligned} \sigma_q^2 &= A^2 (\sigma_m^2 - \langle m \rangle) + A \langle m \rangle = \\ &= 2 f \langle n \rangle - A \langle n \rangle - f A + \langle n \rangle + f \\ &\approx (2f + 1) \langle n \rangle \end{aligned}$$

Relación Señal-ruido:

$$SNR \approx \frac{\langle n \rangle^2}{(2f+1)\langle n \rangle} = \frac{\langle n \rangle}{2f+1}$$

$$N.F._{AO-FO} \approx 2f + 1$$

sección fibra-amplif.



* Hipótesis $\sigma_n^2 = \langle n \rangle$; $G_s \cdot A = 1$
  $G_s \gg 1$

* $\begin{cases} \langle m \rangle = A \langle n \rangle \\ \sigma_m^2 = A \langle n \rangle \end{cases}$

Salida del O.A. :

* $\langle q \rangle = G_s \langle m \rangle + (G_s - 1) \rho$

* $\sigma_q^2 \cong G_s \langle m \rangle + \rho G_s + 2 \rho G_s^2 \langle m \rangle + \rho^2 G_s^2$

$$= \langle n \rangle + \rho G_s + 2 \rho G_s \langle n \rangle + \rho^2 G_s^2$$

$$\approx \rho G_s \left(2 \langle n \rangle + \rho G_s \right)$$

<u>Relación señal-ruido :</u>

$$SNR \approx \frac{\langle n \rangle^2}{\rho G_s (2 \langle n \rangle + \rho G_s)}$$

* Si $\langle n \rangle \to \infty \Rightarrow SNR \to \dfrac{\langle n \rangle}{2 \rho G_s}$

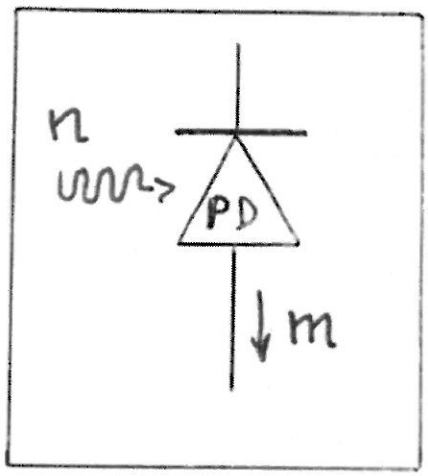
y $N.F._{FO-AO} = NF_{AO} \times G_s$

Caracterización estadística PIN ($I_D \approx 0$)

* Coefic. emisión estimulada : $a \equiv 0$
* " " espontánea : $c \equiv 0$
* Parámetro emis. " : $\rho = 0$
* Concepto de ganancia : G_s (?)

$$G_s \equiv \eta \qquad \text{(eficiencia)}$$

Ecuaciones OUT-IN :

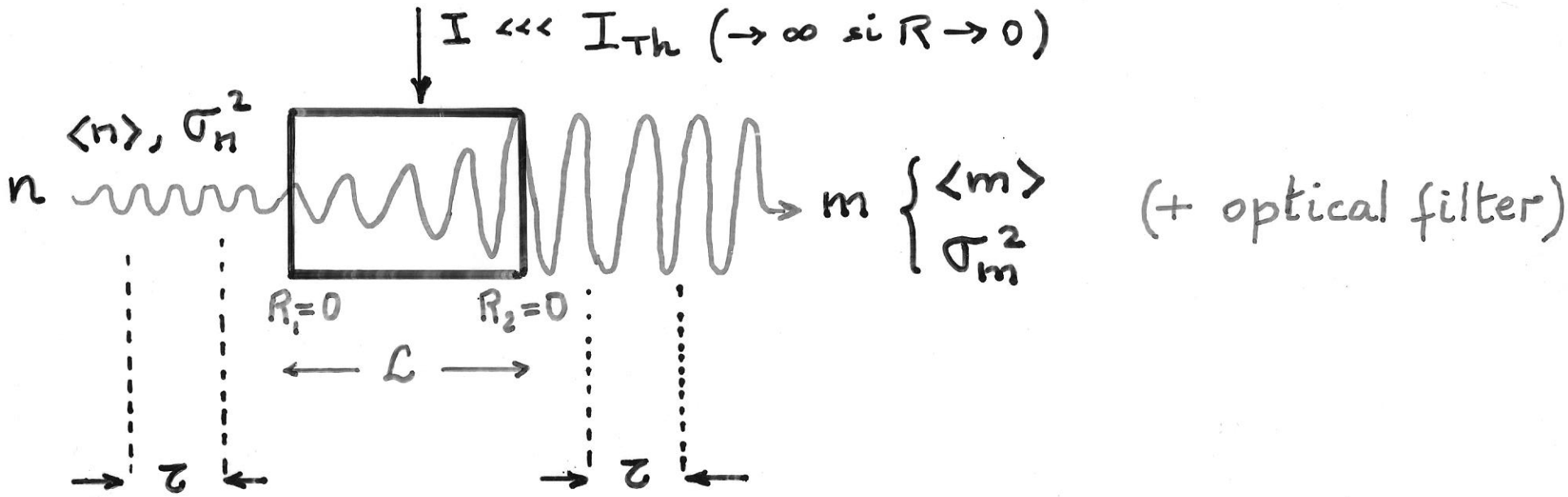


* $\langle m \rangle = \eta \langle n \rangle$ (foto-e^-)
* $\sigma_m^2 = \eta^2 (\sigma_n^2 - \langle n \rangle) + \eta \langle n \rangle$

Si $\sigma_n^2 = \langle n \rangle$, (coherencia) ,

* ! $\sigma_m^2 = \langle m \rangle$! $\Rightarrow$ Coherencia (out)
* $SNR_{OUT} = \eta \langle n \rangle = \eta \, SNR_{IN}$
* $N.F. = 1/\eta \quad (\geq 1)$

Travelling Wave Optical Amplifier



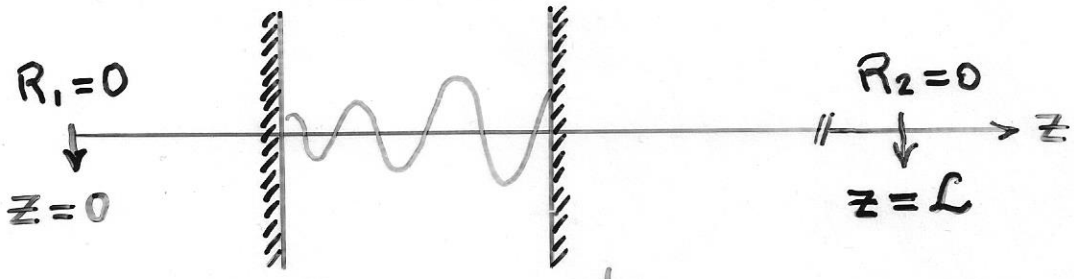
$$\langle n \rangle = \frac{P_{IN}}{hf}\,\tau \qquad\qquad \langle m \rangle = \frac{P_{OUT}}{hf}\,\tau$$

$$G_S = \frac{P_{OUT}^{\text{señal}}}{P_{IN}} = \frac{\langle m \rangle^{\text{señal}}}{\langle n \rangle} = e^{gL}$$

y, si a la entrada Poisson, ⇒ a la salida LAGUERRE

Ecuación de balance para el nº medio de fotones $\langle m(t)\rangle$

$$dz = v\,dt$$



$$t = \frac{z}{v} \qquad \frac{z+dz}{v}$$

$$\Downarrow \qquad \Downarrow$$

$$\langle m(t)\rangle \qquad \langle m(t)\rangle + d\langle m(t)\rangle$$

* $$d\langle m(t)\rangle = a\langle m(t)\rangle\,dt - b\langle m(t)\rangle\,dt + c\cdot dt$$

* $$\frac{d\langle m(t)\rangle}{dt} = (a-b)\langle m(t)\rangle + c$$

$$0 \leq t \leq \mathcal{L}/v$$

* Solución :

$$\langle m(z)\rangle = \langle m(0)\rangle\, e^{\frac{a-b}{v}z} + \frac{c}{a-b}\left\{ e^{\frac{a-b}{v}z} - 1 \right\}$$

$$0 \leq z \leq \mathcal{L}$$

(Continuación) ; para $z = \mathcal{L}^{\pm}$ tenemos :

$$\langle m(\mathcal{L}) \rangle = \langle m(0) \rangle \, e^{\frac{a-b}{v}\mathcal{L}} + \frac{c}{a-b}\left\{ e^{\frac{a-b}{v}\mathcal{L}} - 1 \right\}$$

* Definimos

$$G_s \equiv e^{\frac{a-b}{v}\mathcal{L}}$$ (Ganancia en pasada única)

* Emisión espontánea amplificada

$$m_{ASE} = \frac{c}{a-b}\left\{ G_s - 1 \right\} , \quad c = a$$ (monomodo)

* Identificación de parámetros :

  - $a = \Gamma A v N$ (A es el coef. de ganancia)
  - $b = \Gamma A v N_t + \alpha_s v = b_r + b_{nr}$

* Parámetro de emisión espontánea:

$$f \equiv \frac{a}{a-b}$$ ($= 1$ si $b_r = b_{nr} = 0$)

Resumiendo,

* $G_s = e^{\frac{a-b}{v}\mathcal{L}} = e^{g\mathcal{L}}$

* $\langle m(\mathcal{L})\rangle = \langle m(0)\rangle \cdot G_s + \langle m_{ASE}\rangle$

siendo $\langle m_{ASE}\rangle = \frac{c}{a-b}(G_s-1) = \frac{c}{a}\rho(G_s-1)$

con $\rho = \frac{a}{a-b}$ el parámetro de em. espont.

* En ampl. ópticos monomodo $c=a$,

y entonces

$$\boxed{\langle m(\mathcal{L})\rangle = \underbrace{G_s \cdot \langle m(0)\rangle}_{\text{Señal}} + \underbrace{\rho\cdot(G_s-1)}_{\text{ASE}}}$$

* $\boxed{\langle m(\mathcal{L})\rangle = G_s \frac{P_{IN}}{hf}\tau + \rho(G_s-1)} \Rightarrow$

$$\Rightarrow \boxed{\underbrace{\frac{hf}{\tau}\langle m(\mathcal{L})\rangle}_{P_{OUT}} = \underbrace{G_s P_{IN}}_{P_{OUT}^{\text{señal}}} + \underbrace{\frac{hf}{\tau}\rho(G_s-1)}_{P_{ASE}}}$$

Usualmente $\tau = 1/2B$ (tiempo de bit)

(inverso del ancho de banda óptico) $\tau = \frac{1}{\Delta f}$;