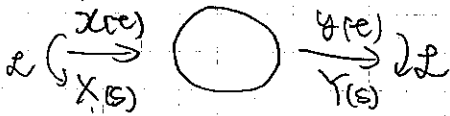


$$\tilde{F}(s) = \int_0^{\infty} e^{-st} f(t) dt$$

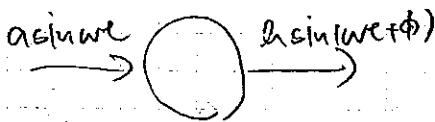
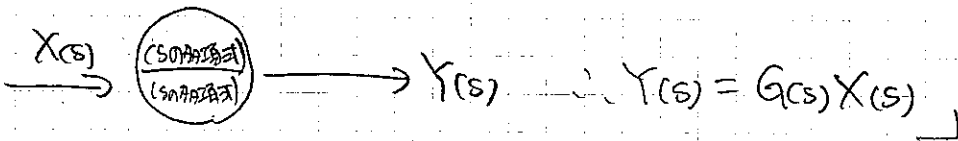
Linear

$$f(a+b) = f(a) + f(b)$$



$$\begin{aligned} & a_2 z + b_1 z + b_2 \ddot{z} + \dots + c_1 \int z dt + c_2 \int \int z dt^2 \\ & = e^z + \dots \\ & s^2 a X + b_1 s X + b_2 s^2 X + \dots + c_1 \frac{1}{s} X + c_2 \frac{1}{s^2} X \\ & = e^y + \dots \end{aligned}$$

$$\frac{Y}{X} = \frac{(s \text{ の分子式})}{(s \text{ の分母式})} \equiv G(s)$$

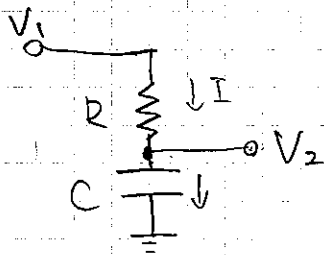


$$\frac{b}{a} = |G|, \phi \text{ phase}$$

$$s = j\omega \text{ とき}$$

$$|G(j\omega)| = \frac{b}{a} (gain), \angle G(j\omega) = \phi \text{ (phase)}$$

とき



$$I = \frac{dQ}{dt} \quad Q = CV \quad V = \frac{Q}{C} = \frac{1}{C} \int I dt$$

$$V_2 - V_1 = RI$$

$$V_2 = \frac{1}{C} \int I dt \quad \therefore I = C \frac{dV_2}{dt}$$

$$V_1 = V_2 + RC \frac{dV_2}{dt}$$

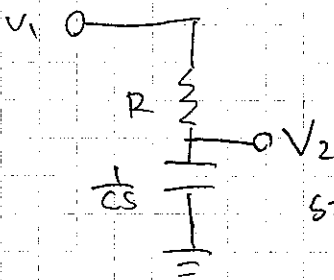
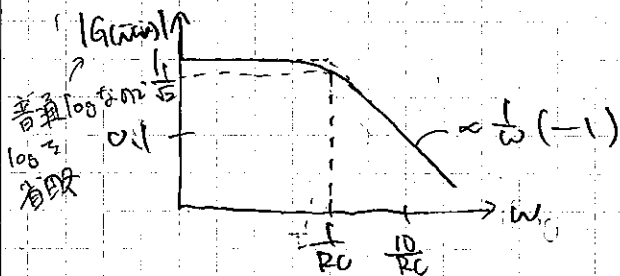
$$V_1(s) = V_2(s) + RCs V_2(s)$$

$$\therefore \frac{V_2(s)}{V_1(s)} = \frac{1}{1 + RCs} = \frac{1}{1 + \frac{s}{\omega_c}}$$

$$RC \equiv \frac{1}{\omega_c} \quad \omega_c \neq \omega_c$$

$$\frac{V_2(\omega)}{V_1(\omega)} = \frac{1}{1 + j(\frac{\omega}{\omega_c})} \equiv G(\omega)$$

$$\therefore |G(\omega)| = \frac{1}{\sqrt{1 + (\frac{\omega}{\omega_c})^2}}, \quad \angle G(\omega) = \arctan\left(-\frac{\omega/\omega_c}{1}\right) = -\arctan\left(\frac{\omega}{\omega_c}\right)$$



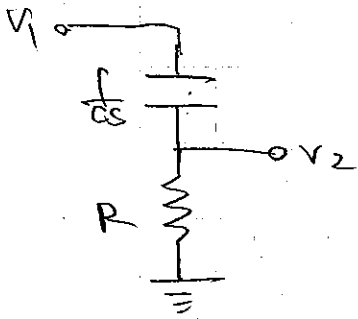
$$\frac{V_2}{V_1} = \frac{R}{R + \frac{1}{Cs}} = \frac{1}{1 + \frac{1}{RCs}}$$

$$s = j\omega \quad \therefore \frac{V_2}{V_1} = \frac{1}{1 + \frac{1}{j\omega RC}}$$

$$s = -\frac{1}{RC} \text{ の } z \neq \frac{\text{分子が } 0}{\text{分母が } 0}$$

$\Rightarrow z$ は pole である。

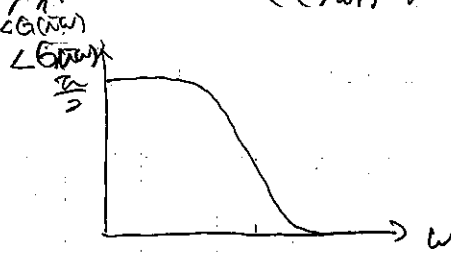
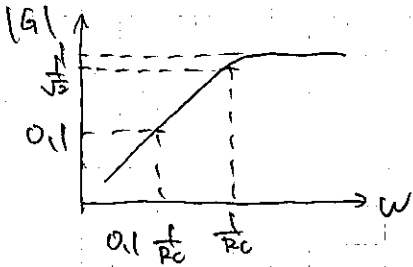
\downarrow pole が 1 個あり、 $\angle = -90^\circ$ 、 $\frac{1}{RC} = 1$ 折れ折れ、
位相は 90° 折れ折れ (pole $z = -1$ 折れ折れ)



$$= \frac{w}{w_r} (1 - \frac{w}{w_r})$$

$$\frac{V_2}{V_1} = \frac{R}{\frac{1}{Cs} + R} = \frac{RCs}{1 + RCs} \xrightarrow{s=jw} \frac{RCw}{1 + jRCw} = \frac{j\frac{w}{w_r}}{1 + j\frac{w}{w_r}} = \frac{(\frac{w}{w_r})^2 + j\frac{w}{w_r}}{1 + (\frac{w}{w_r})^2}$$

$$\therefore |G(jw)| = \sqrt{\frac{(\frac{w}{w_r})^2}{1 + (\frac{w}{w_r})^2}} \quad \phi = \arctan\left(\frac{j\frac{w}{w_r}}{1 + (\frac{w}{w_r})^2}\right) = \arctan\left(\frac{w_r}{w}\right)$$

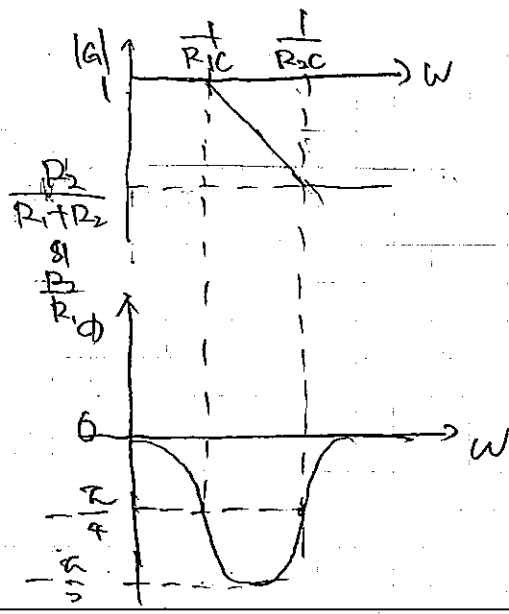
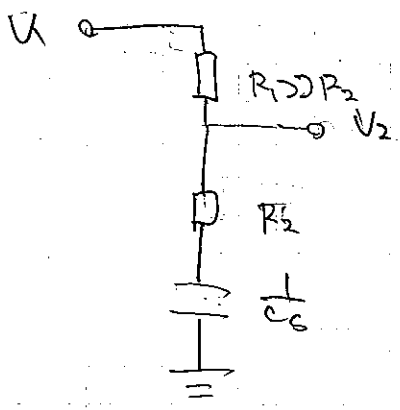


$$G(w) = \frac{RCs}{1 + RCs}$$

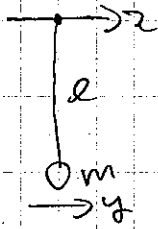
$s=0$ or $z=$ 分子が 0 になる

↓
→ 分子 s = zero になる

↓
zero が 1/RC になる。s = -1/RC になるのは
位相は 90° になる (pole は 45° になる)



4



$$m\ddot{y} = \frac{(l-x)}{l}mg$$

$$l \left(\ddot{y} + \frac{g}{l}y \right) = + \frac{g}{l}x$$

$$Ys^2 + \frac{g}{l}Y = \frac{g}{l}X$$

$$\therefore \frac{Y}{X} = \frac{g/l}{g/l + s^2}$$

$$= \frac{1}{1 + (s^2/g/l)}$$

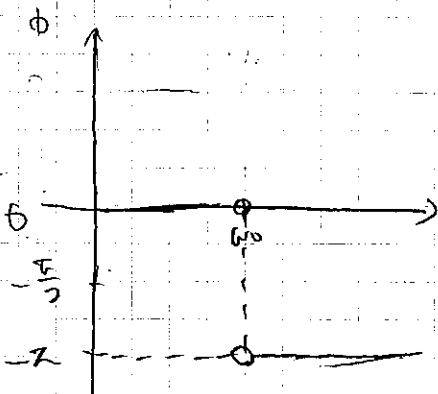
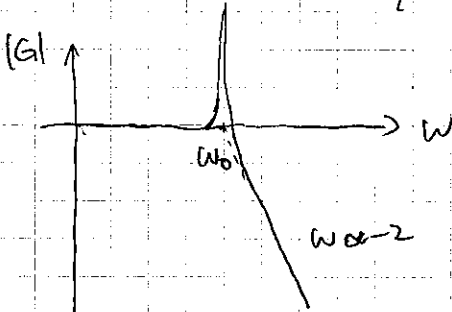
$$= \frac{1}{1 + s^2/\omega_0^2} \quad (\omega_0^2 = \frac{g}{l})$$

pole: $s = \pm i\omega_0$

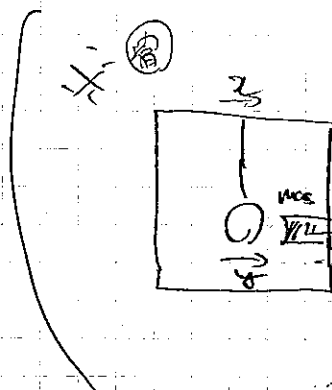
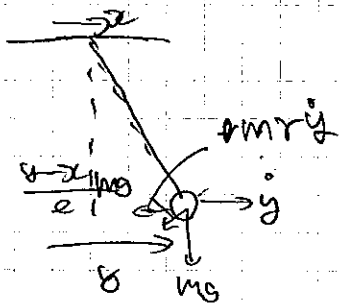
$$G(\omega) = \frac{1}{1 - \left(\frac{\omega}{\omega_0}\right)^2}$$

$$\left. \begin{array}{l} \omega \ll \omega_0 \quad G(s) \approx 1 \\ \omega \gg \omega_0 \quad G(s) \approx -\frac{\omega_0^2}{\omega^2} \end{array} \right\}$$

$$= -\frac{\omega_0^2}{\omega^2}$$



共振性が起こる場合



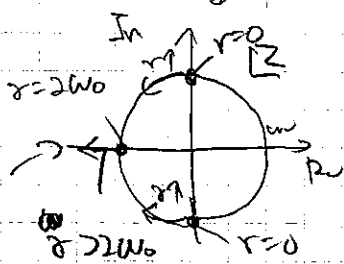
共振性が起こる場合
 共振周波数(固有周波数)
 共振振幅の2倍
 共振時の加速度

$$m\ddot{y} = -\frac{r}{e} \dot{y} - mry\dot{\theta}$$

$$\ddot{\theta} + r\dot{\theta} + \frac{g}{e}\theta = \frac{g}{e}x$$

$$\ddot{y} (\delta^2 + r\delta + \omega_0^2) = \omega_0^2 x$$

$$G(\delta) \equiv \frac{Y}{X} = \frac{\omega_0^2}{\delta^2 + r\delta + \omega_0^2} = \frac{1}{(\delta + \frac{r}{2})^2 + \omega_0^2 - \frac{r^2}{4}}$$

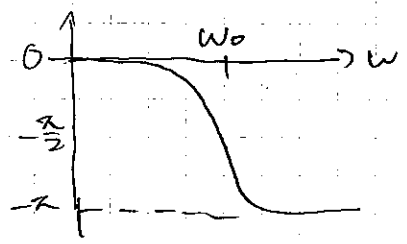


$r < 2\omega_0$ のとき

pole $s = \frac{-r \pm \sqrt{r^2 - 4\omega_0^2}}{2} = -\frac{r}{2} \pm \sqrt{\omega_0^2 - \frac{r^2}{4}}$

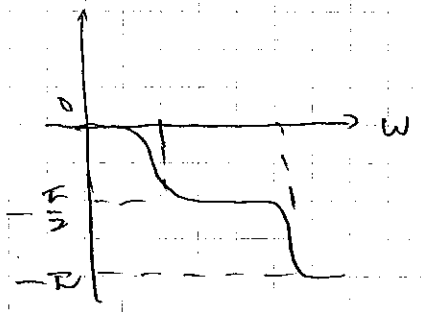
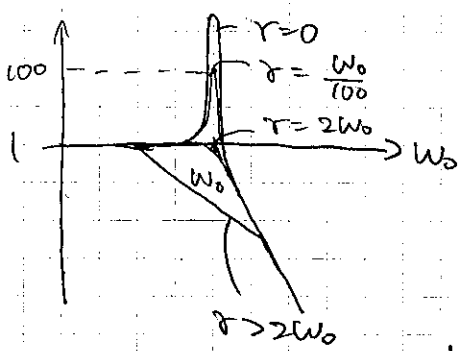
$$G(j\omega) = \frac{\omega_0^2}{-(\omega^2 - \omega_0^2) + jr\omega}$$

$$\angle G(j\omega) = \begin{cases} -\frac{\pi}{2} & \text{① } \omega = \omega_0 \\ > -\frac{\pi}{2} & \text{② } \omega < \omega_0 \\ < -\frac{\pi}{2} & \text{③ } \omega > \omega_0 \end{cases}$$



$$|G(j\omega)| = \sqrt{\frac{\omega_0^4}{(\omega^2 - \omega_0^2)^2 + r^2\omega^2}}$$

$$\omega = \omega_0 \text{ のとき } |G(j\omega)| = \sqrt{\frac{\omega_0^4}{r^2\omega_0^2}} = \frac{\omega_0}{r}$$

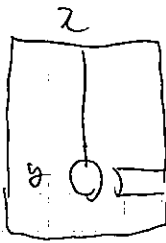


$r > 2\omega_0$ のとき

pole $s = -\frac{r}{2} \pm \sqrt{\frac{r^2}{4} - \omega_0^2}$: 実部 > 0

$\angle G(j\omega)$

6
①



$$|G(j\omega)| = \left| \frac{j\gamma\omega + \omega_0^2}{(\omega_0^2 - \omega^2) + j\gamma\omega} \right|$$

$$\therefore |G(j\omega_0)| = \left| \frac{j\gamma\omega_0 + \omega_0^2}{j\gamma\omega_0} \right| \propto \frac{\omega_0}{\gamma} \quad (\gamma < \omega_0^2)$$

$$\stackrel{!!}{=} Q$$

$$m\ddot{y} = -\frac{mg}{l}(y-x) - m\gamma(\dot{y}-\dot{x})$$

$$\therefore s^2 Y = -\frac{g}{l}(Y-X) - \gamma s(Y-X)$$

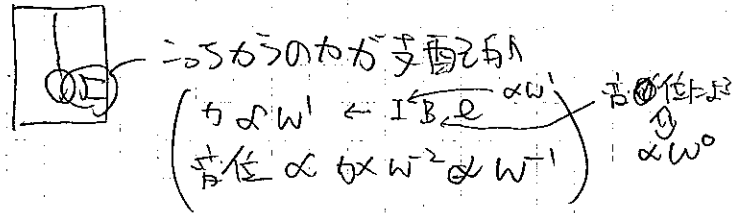
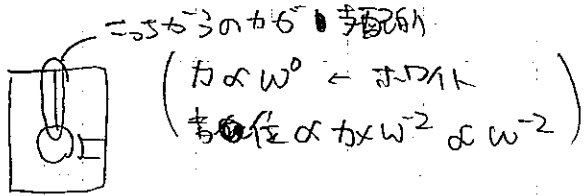
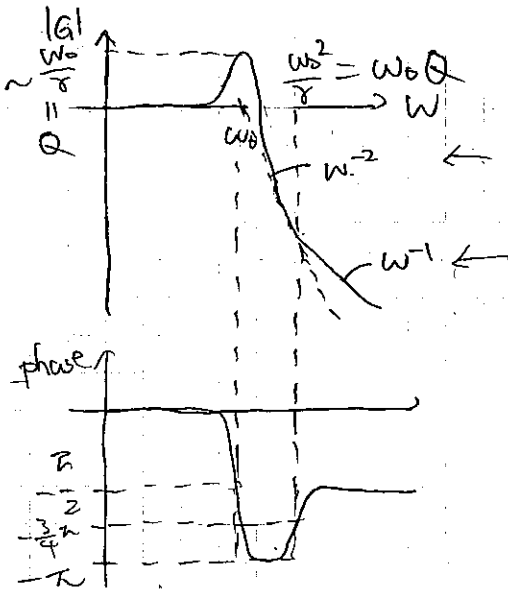
$$\therefore G(s) = \frac{Y}{X} = \frac{\gamma s + \omega_0^2}{s^2 + \gamma s + \omega_0^2} \quad (\omega_0^2 \equiv \frac{g}{l})$$

zero : $s = -\frac{\omega_0^2}{\gamma}$

pole : $\frac{-\gamma \pm \sqrt{\gamma^2 - 4\omega_0^2}}{2} = \begin{cases} -\frac{\gamma}{2} \pm \sqrt{\frac{\gamma^2}{4} - \omega_0^2} & (\gamma > 2\omega_0) \\ -\frac{\gamma}{2} \pm j\sqrt{\omega_0^2 - \frac{\gamma^2}{4}} & (\gamma < 2\omega_0) \rightarrow |s| = \omega_0 \end{cases}$

普通 (pole) < (zero) となる。この場合右向き

1) $\gamma < 2\omega_0$ のとき



$$\gamma = \frac{\omega_0}{Q}$$

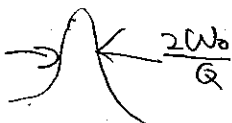
* ω_0 の幅は $\frac{1}{2Q}$

$$\frac{\omega_0}{2\gamma} = |G(j\omega_0)| \text{ になり } \gamma = \frac{\omega_0}{2Q}$$

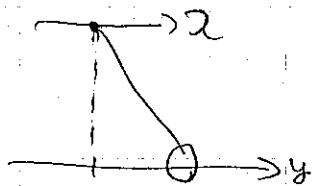
$$\left| \frac{j\gamma\omega_0 + \omega_0^2}{(\omega_0^2 - \omega_0^2) + j\gamma\omega_0} \right| = \frac{\omega_0}{2\gamma} \quad \therefore \sqrt{\frac{\gamma^2 \omega_0^2 + \omega_0^4}{(\omega_0^2 - \omega_0^2)^2 + \gamma^2 \omega_0^2}} = \frac{\omega_0}{2\gamma} = \frac{Q}{2}$$

$$\therefore \gamma^2 \omega_0^2 + \omega_0^4 = \frac{Q^2}{4} (\omega_0^4 - 2\omega_0^2 \omega_0^2 + \omega_0^4 + \frac{\omega_0^2}{Q^2} \omega_0^2) \quad \therefore \gamma = \frac{\omega_0}{2Q}$$

大体



$m\ddot{y} = -\frac{mg}{2}(y-x) - m\tau\dot{y}$ α 22 時間空間 2つ2つあり



$(\text{条件 } x=0)$

初期条件 $\dot{x}=0, y=y_0, \dot{y}=0$

$\ddot{y} + \tau\dot{y} + \omega_0^2 y = \omega_0^2 x(t)$

$x(t)=0$ α $t \geq 0$

$y = A e^{\lambda t}$ $\lambda \neq \pm i\omega_0$

$-\omega^2 y + \tau\omega y + \omega_0^2 y = 0 \quad \therefore \omega^2 - \tau\omega - \omega_0^2 = 0$

$\therefore \omega = \frac{\tau \pm \sqrt{\tau^2 + 4\omega_0^2}}{2}$

i) $\tau < 2\omega_0$ α $t \geq 0$ $\omega = \omega_1, \omega_2$ $\lambda \neq \pm i\omega_0$

$\omega_1 - \omega_2 = \sqrt{-\tau^2 + 4\omega_0^2}$

$y = A e^{\omega_1 t} + B e^{\omega_2 t}$

$y(0) = A + B = y_0 \quad \therefore B = y_0 - A$

$\dot{y}(0) = \omega_1 A + \omega_2 B = 0 \quad \therefore B = -\frac{\omega_1}{\omega_2} A$

$-\frac{\omega_1}{\omega_2} A = y_0 - A \quad \therefore \frac{\omega_2 - \omega_1}{\omega_2} A = y_0 \quad \therefore A = -\frac{\omega_2}{\omega_1 - \omega_2} y_0$

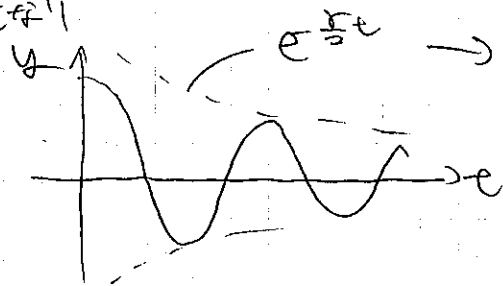
$B = \frac{\omega_1}{\omega_1 + \omega_2} y_0$

$y(t) = A e^{\omega_1 t} + B e^{\omega_2 t}$

Re(λ) $\neq 0$ $\therefore (A, B, \omega_1, \omega_2)$ が全に複素数の注意

$Re(\omega) = \frac{\tau}{2} \sin P e^{-\frac{\tau}{2} t} \quad (P = \sqrt{-\tau^2 + 4\omega_0^2})$

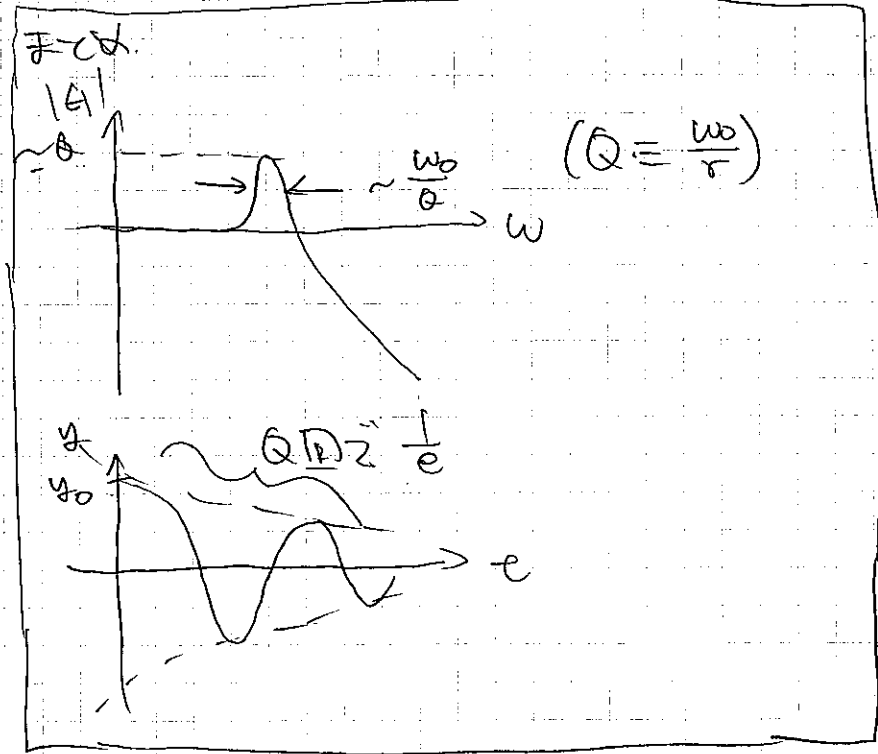
$t \geq 0$



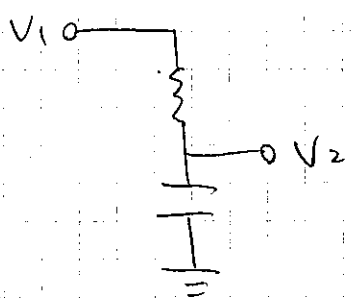
$r = \frac{\omega_0}{Q}$ α Q の逆

$\frac{\omega_0}{2Q} e = 1 \quad \therefore \omega_0 t = 2Q$

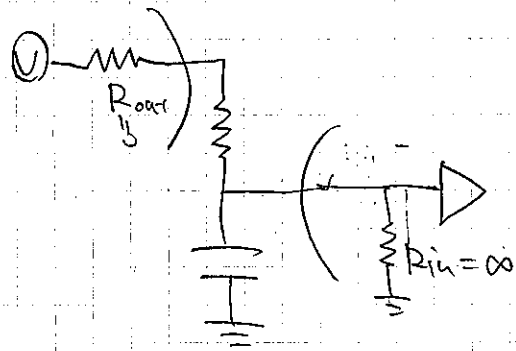
α 2 大 Q のとき $\frac{1}{e}$ になる



※



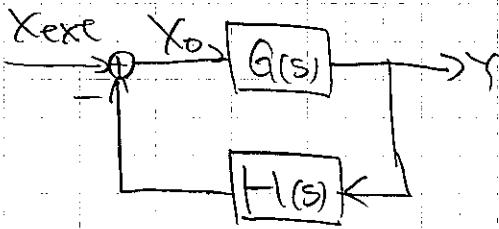
電圧の増幅



電圧の増幅

$V_1 \rightarrow V_2$ は成り立つ
 $V_2 \rightarrow V_1$ は成り立たない

井-ホ



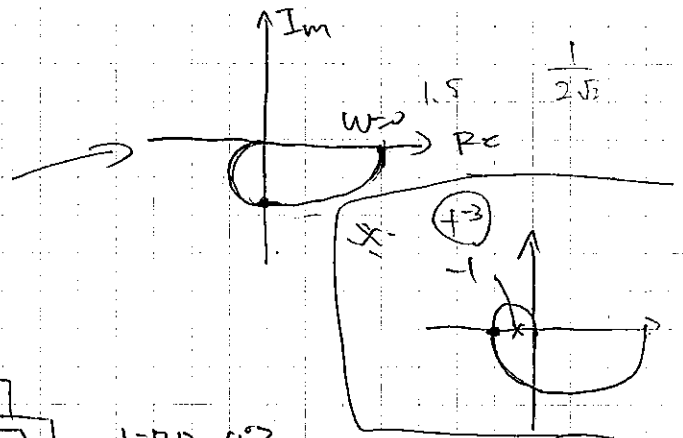
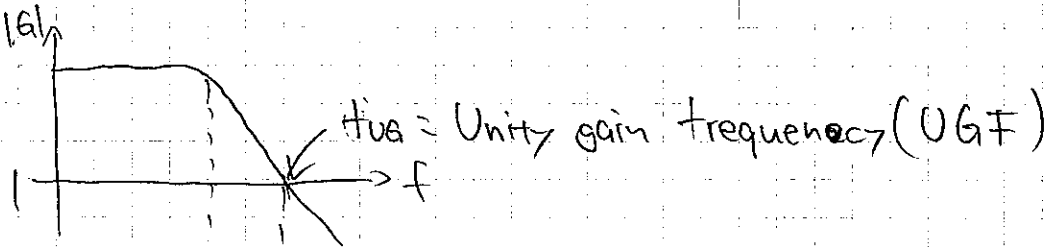
$$X_{ext} = GHX_0 = X_0$$

$$\therefore X_0 = \frac{1}{1+GH} X_{ext}$$

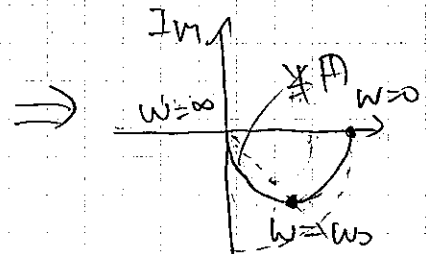
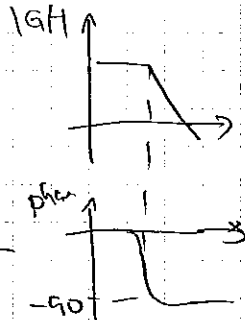
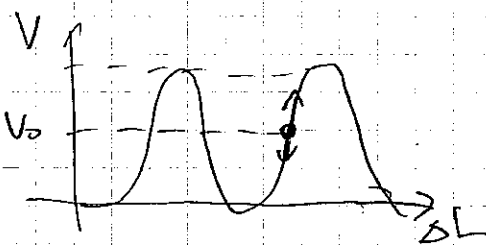
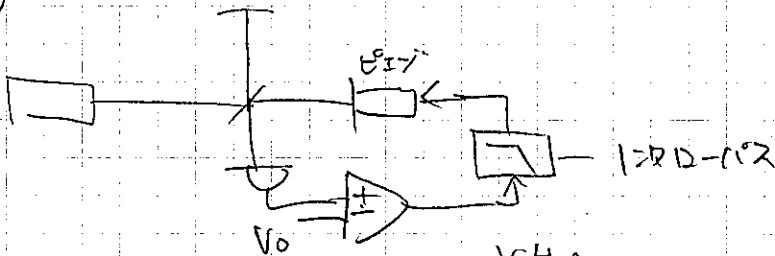
(open) loop gain

loop gain \Rightarrow poleの虚部が正だと不安定

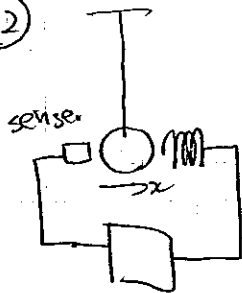
この制御はどのようにして不安定に落ちる。



例1



例1

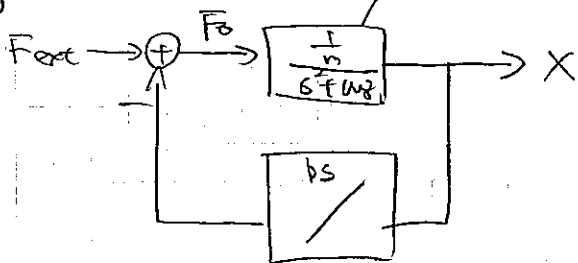


(P / s) ⇔ 微分

(P / s) ⇔ 積分

振りの伝達関数

例1



封じの振り振子系

$$F_0 = F_{ext} - \frac{1}{m} bs F_0$$

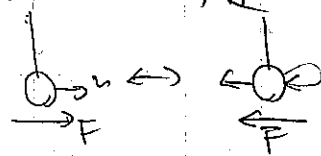
$$\frac{F_0}{F_{ext}} = \frac{1}{1 + \frac{bs/m}{s^2 + w_0^2}}$$

$$\frac{X}{F_{ext}} = \frac{\frac{Y_m}{s^2 + w_0^2}}{1 + \frac{bs/m}{s^2 + w_0^2}} = \frac{Y_m}{s^2 + w_0^2 + \frac{b}{m}s}$$

$$\frac{Y_2}{s^2 + w^2 + rs}$$

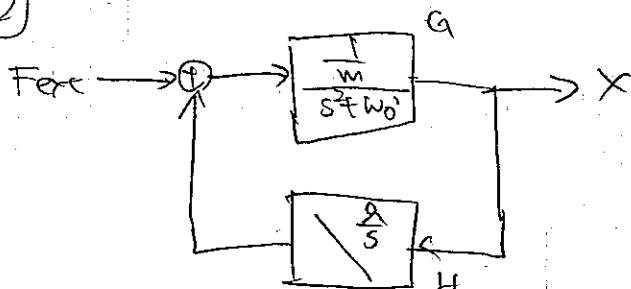
* $bs \rightarrow -bs$ とする \Leftrightarrow

$$\frac{X}{F_{ext}} = \frac{Y_m}{s^2 + w_0^2 - \frac{b}{m}s}$$



pole $s = \frac{b}{2m} \pm \lambda \sqrt{w_0^2 - \frac{b^2}{4m^2}}$ ← 実部正 = 不安定

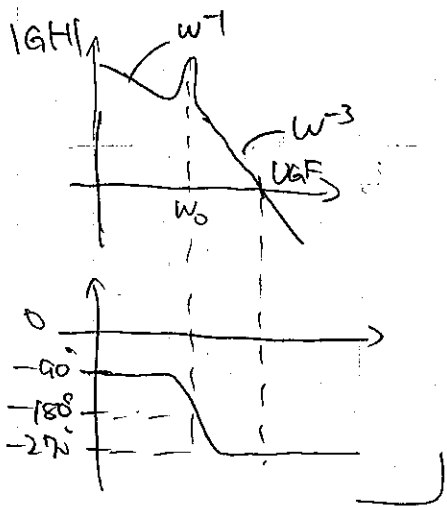
例2



(X s 解いて F=CW&3)

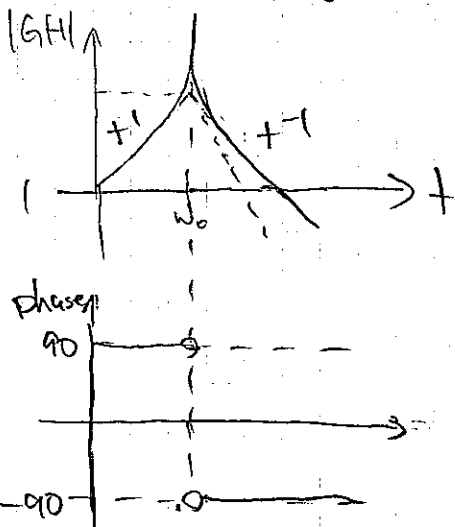
不安定

$$\frac{X}{F_{ext}} = \frac{\frac{Y_m}{s^2 + w_0^2}}{1 + \frac{b/m}{s^2 + w_0^2}} = \frac{Y_m}{s^2 + w_0^2 + \frac{b}{m}s} = \frac{s/m}{s^0 (s^2 + w_0^2) + \frac{g}{m}}$$

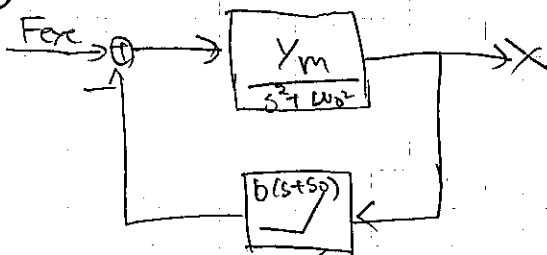


例 1 の loop gain

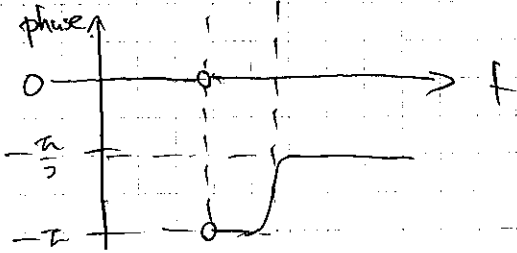
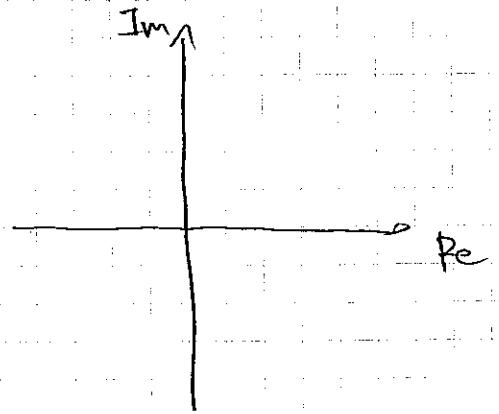
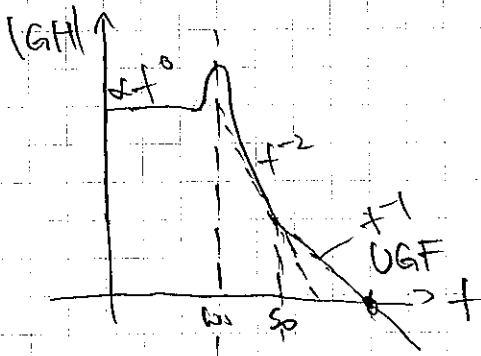
$$GH = \frac{bs}{s^2 + \omega_0^2}$$



例 3

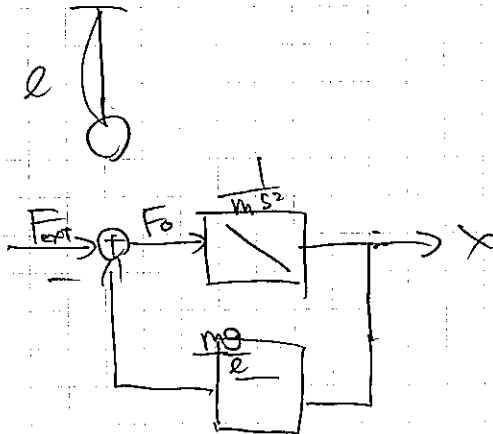


$$GH = \frac{a}{m} \frac{s + s_0}{s^2 + \omega_0^2} \quad (\text{soft 大 非 1})$$

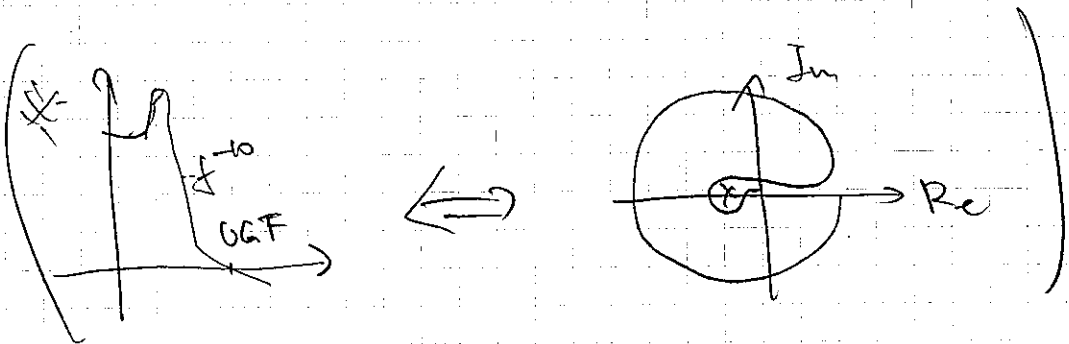


④ 二つが振りの制御の基本

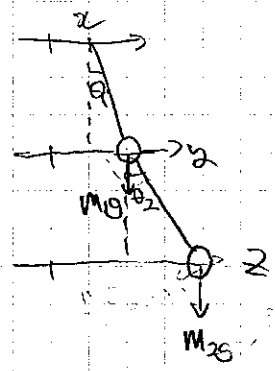
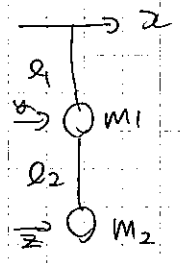
※ 普通の振りも制御を考へるか?



$$\frac{x}{F_{ext}} = \frac{1/ms^2}{1 + \frac{1}{ms^2} \frac{ms}{l}} = \frac{1}{ms^2 + \frac{g}{l}} = \frac{Y_m}{s^2 + \frac{g}{l}}$$



2重振り子



$$\begin{cases} m_2 \ddot{z} = -\frac{m_2 g}{l_2} (z - y) & (1) \\ m_1 \ddot{y} = -\frac{m_1 g}{l_1} (y - z) + \frac{m_2 g}{l_2} (z - y) & (2) \end{cases}$$

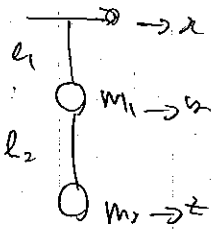
① \$x\$'
 $s^2 z = -\omega_2^2 (z - y)$ (1')

② \$x\$'
 $s^2 y = -\omega_1^2 (y - x) + \frac{m_2}{m_1} \omega_2^2 (z - y)$ (2')

①' \$x\$''
 $y = (1 + \frac{s^2}{\omega_2^2}) z$

②' \$x\$''
 $s^2 (1 + \frac{s^2}{\omega_2^2}) z = -\omega_1^2 (1 + \frac{s^2}{\omega_2^2}) z + \frac{m_2}{m_1} \omega_2^2 z - (1 + \frac{s^2}{\omega_2^2}) z$

②' \$x\$''
 $s^2 = \frac{1}{2} \left\{ -\omega_1^2 - (1 + \frac{m_2}{m_1}) \omega_2^2 \pm \sqrt{\omega_1^4 - 2(1 - \frac{m_2}{m_1}) \omega_1^2 \omega_2^2 + (1 + \frac{m_2}{m_1})^2 \omega_2^4} \right\}$



$$\begin{cases} m_1 \ddot{y} = -\frac{(m_1+m_2)g}{l_1}(y-z) + \frac{m_2 g}{l_2}(z-y) & (1) \\ m_2 \ddot{z} = -\frac{m_2}{l_2}(z-y) & (2) \end{cases}$$

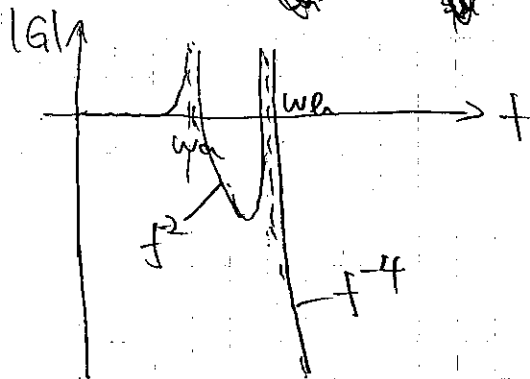
$$\frac{g}{l_1} \equiv \omega_1^2, \quad \frac{g}{l_2} \equiv \omega_2^2 \quad \text{etc}$$

$$\begin{cases} \delta^2 y = -(1+\alpha)\omega_1^2(y-x) + \alpha\omega_2^2(z-x) & (1) \\ \delta^2 z = -\omega_2^2(z-y) & (2) \end{cases}$$

$$\rightarrow \frac{z}{x} = \frac{(1+\alpha)\omega_1^2\omega_2^2}{\delta^4 + (1+\alpha)(\omega_1^2 + \omega_2^2)\delta^2 + (1+\alpha)\omega_1^2\omega_2^2} = \frac{(1+\alpha)\omega_1^2\omega_2^2}{(\delta^2 + \omega_1^2)(\delta^2 + \omega_2^2)}$$

$$\text{pole: } s^0 = \pm i\sqrt{\frac{1}{2} \left\{ (1+\alpha)(\omega_1^2 + \omega_2^2) \pm \sqrt{(1+\alpha)^2(\omega_1^2 + \omega_2^2)^2 - 4(1+\alpha)\omega_1^2\omega_2^2} \right\}}$$

$$\equiv \pm i\omega_a, \quad \pm i\omega_b \quad (\omega_a < \omega_b)$$



(1)

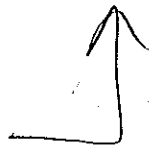
① $\alpha \rightarrow 0$ ($m_1 \gg m_2$ の場合)

$$\begin{aligned} \omega_{a,b} &= \sqrt{\frac{1}{2} \left\{ (\omega_1^2 + \omega_2^2) \pm \sqrt{(\omega_1^2 + \omega_2^2)^2 - 4\omega_1^2\omega_2^2} \right\}} = \sqrt{\frac{1}{2} \left\{ (\omega_1^2 + \omega_2^2) \pm (\omega_1^2 - \omega_2^2) \right\}} \\ &= \omega_1, \omega_2 \end{aligned}$$

$\rightarrow m_1, m_2$ はそれぞれ独立に振動する (E 振動子と C 振動子)。

ii) $\alpha \ll 1$

$$\omega_{a,b} = \sqrt{(\omega_1^2 + \omega_2^2) \pm \sqrt{\omega_1^4 + \omega_2^4}}$$



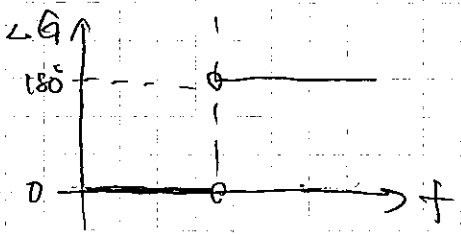
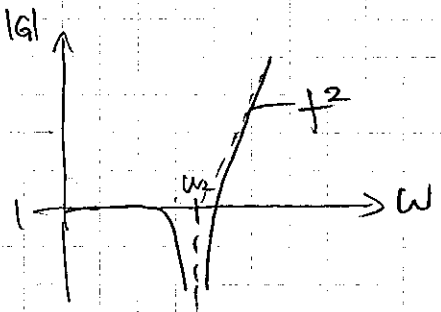
② 式1 $Y = (1 + \frac{s^2}{\omega_2^2})Z$ $\therefore Z = \frac{\omega_2^2}{s^2 + \omega_2^2} Y$

$\frac{Y}{X} = \frac{(Hd)\omega_1^2\omega_2^2}{(s^2 + \omega_a^2)(s^2 + \omega_b^2)} \cdot \frac{s^2 + \omega_2^2}{\omega_2^2}$
 $= \frac{(Hd)(s^2 + \omega_2^2)\omega_1^2}{(s^2 + \omega_a^2)(s^2 + \omega_b^2)} \leftarrow \text{zero の虚数}$

$\begin{pmatrix} \omega_a = \omega_1 \\ \omega_b = \omega_2 \end{pmatrix}$

\times $G(s) \equiv \frac{s^2 + \omega_2^2}{\omega_2^2}$ z ではない、zero の虚数の場合 ω_1, ω_2 の性質が？

$|G(j\omega)| = \left| \frac{\omega^2 + \omega_2^2}{\omega_2^2} \right|$



$\omega_a^2 = \frac{1}{2} \left\{ (Hd)(\omega_1^2\omega_2^2) \left[1 - \sqrt{1 - \frac{4\omega_2^2}{(Hd)(\omega_1^2 + \omega_2^2)}} \right] \right\}$
 $\omega_b^2 = \frac{1}{2} \left\{ (Hd)(\omega_1^2\omega_2^2) \left[1 + \sqrt{1 - \frac{4\omega_2^2}{(Hd)(\omega_1^2 + \omega_2^2)}} \right] \right\}$

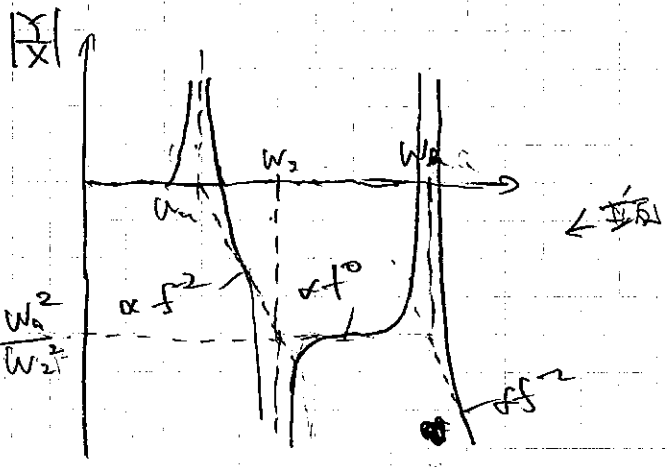
$\omega_a^2 + \omega_b^2 = (Hd)(\omega_1^2 + \omega_2^2) \approx 4\omega_2^2$

$d \approx 1, \omega_1, \omega_2 \approx 1$

$\omega_2^2 = \frac{\omega_a^2 + \omega_b^2}{4}$

$\frac{2 \cdot 1}{2} = 1$

$\rightarrow (d \approx 1.2, \omega_1 \approx \omega_2 = 1 \text{ と } \omega_2 \approx 2, \omega_a \approx \sqrt{0.6}, \omega_b \approx \sqrt{3.4} \text{ (} \omega_1 \approx 1 \text{)})$
 $(\omega_a < \omega_2 < \omega_b)$

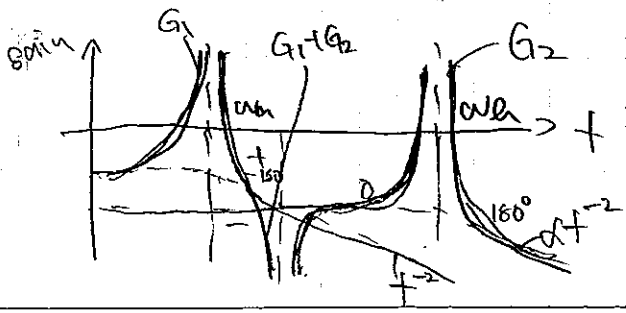


$\frac{1}{(Hd)\omega_1^2} \frac{Y}{X} = \frac{A}{s^2 + \omega_a^2} + \frac{B}{s^2 + \omega_b^2}$

$\begin{cases} A+B=1 \\ \omega_a^2 A + \omega_b^2 B = \omega_2^2 \end{cases}$

$B = 1 - A$
 $(\omega_a^2 - \omega_b^2)A + \omega_b^2 = \omega_2^2$

$A = \frac{\omega_2^2 - \omega_b^2}{\omega_a^2 - \omega_b^2}$
 $B = \frac{\omega_a^2 - \omega_2^2}{\omega_a^2 - \omega_b^2}$



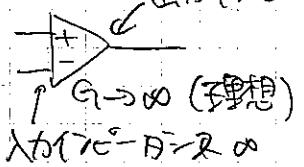
$\therefore \frac{Y}{X} \approx \underbrace{\frac{\omega_a^2 - \omega_b^2}{\omega_a^2 - \omega_b^2} \frac{\omega_2^2 - \omega_b^2}{s^2 + \omega_a^2}}_{G_1} + \underbrace{\frac{\omega_a^2 - \omega_b^2}{\omega_a^2 - \omega_b^2} \frac{\omega_a^2 - \omega_2^2}{s^2 + \omega_b^2}}_{G_2}$

16.

Y & Z mode

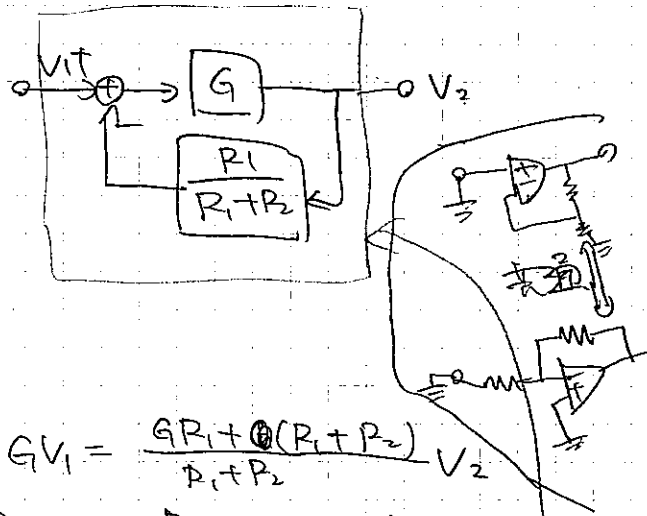
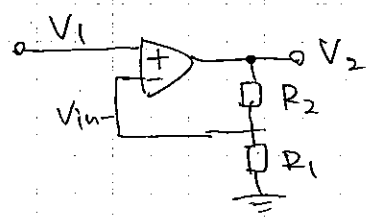
Wa \square 11

±15V 出力インピーダンス (0) ⇔ いくつでも電流流せる



$V_+ > V_- \Rightarrow +15V$
 $V_- > V_+ \Rightarrow -15V$

• 非反転増幅



$G(V_1 - V_{in-}) = V_2$
 $\therefore V_{in-} = \frac{R_1}{R_1 + R_2} V_2$ F1

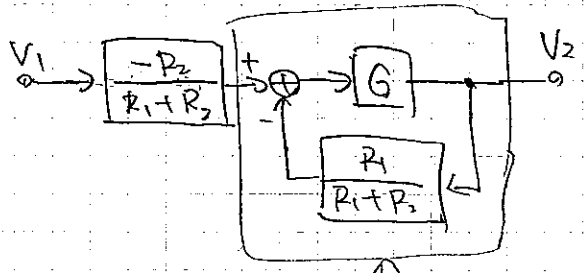
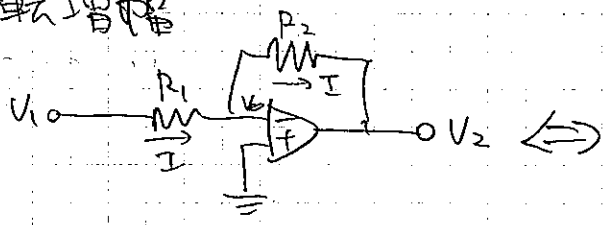
$G(V_1 - \frac{R_1}{R_1 + R_2} V_2) = V_2 \therefore G V_1 = \frac{G R_1 + (R_1 + R_2)}{R_1 + R_2} V_2$

$\therefore \frac{V_2}{V_1} = \frac{G(R_1 + R_2)}{(G+1)R_1 + R_2} \xrightarrow{G \rightarrow \infty} \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} (G \rightarrow \infty)$

16 → 17
 $G \frac{R_1}{R_1 + R_2}$

$\therefore \frac{V_2}{V_1} = \frac{G}{1 + G \frac{R_1}{R_1 + R_2}} \Rightarrow \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$

• 反転増幅



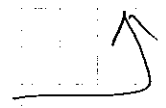
$V_2 = G(0 - V_0) = -G V_0$

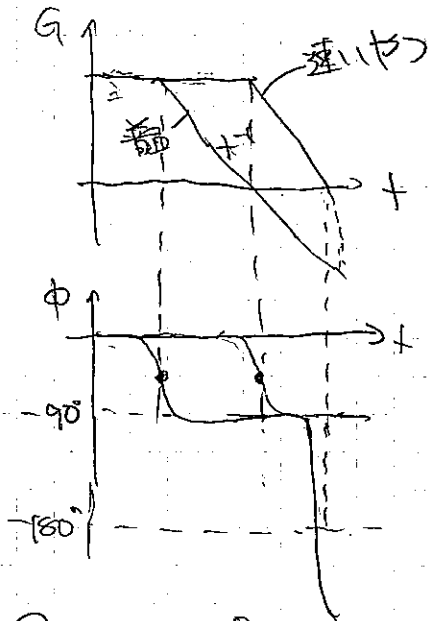
$I = \frac{V_0 - V_0}{R_1} = \frac{V_0 - V_0}{R_2} \therefore V_0 = + \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2}$

$V_2 = G(-\frac{R_2}{R_1 + R_2} V_1 - \frac{R_1}{R_1 + R_2} V_2)$

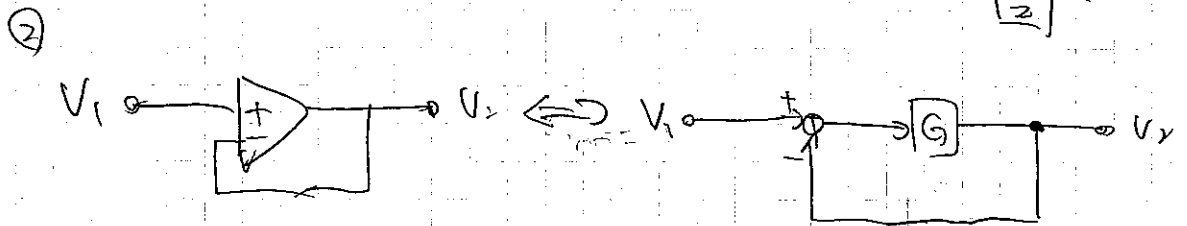
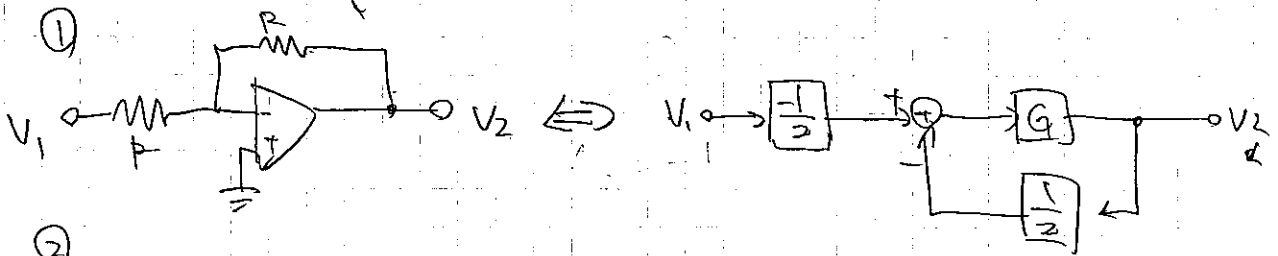
$\therefore V_2 = -G \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \therefore (R_1 + R_2) V_2 = -G (R_2 V_1 + R_1 V_2)$

$\therefore (R_1 + R_2 + G R_1) V_2 = -G R_2 V_1 \therefore \frac{V_2}{V_1} = \frac{-G R_2}{(G+1)R_1 + R_2} \xrightarrow{G \rightarrow \infty} -\frac{R_2}{R_1}$





$$\frac{1}{\frac{1}{HG}} = 1$$

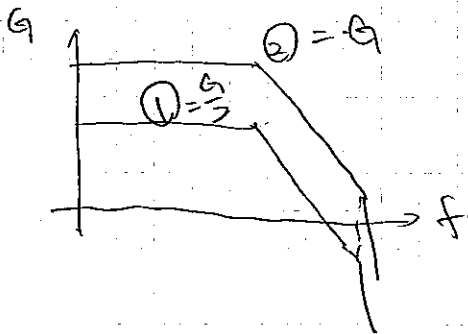


①の伝達関数

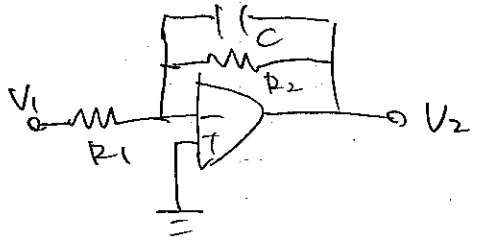
$$\frac{G}{s} \rightarrow -\frac{1}{2}$$

②の伝達関数

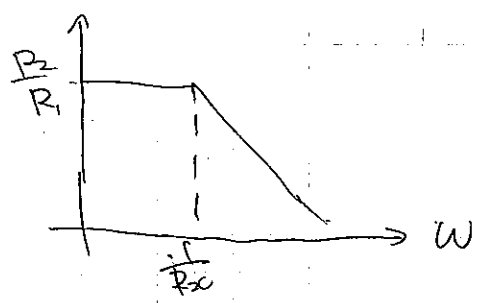
$$G \rightarrow -1$$



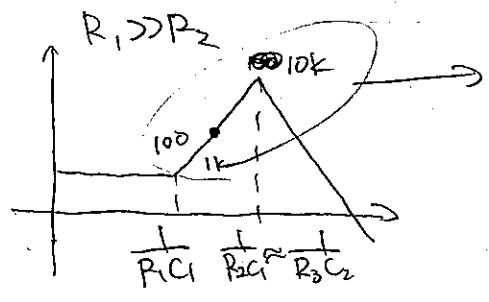
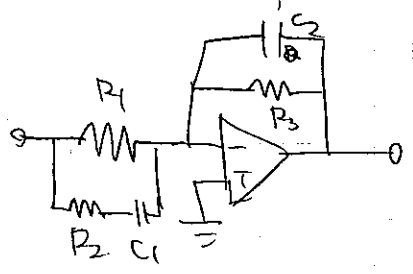
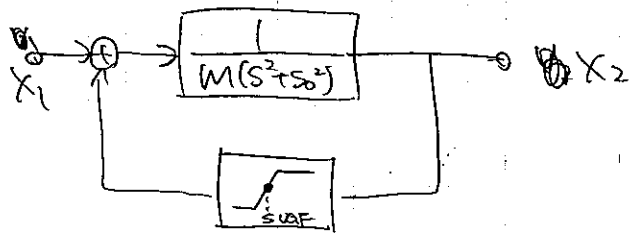
• 7kVA の設計



$$\frac{V_2}{V_1} = \frac{Z_2}{Z_1} = \frac{(\frac{1}{R_2} + Cs)^{-1}}{R_1} \rightarrow \begin{cases} -\frac{R_2}{R_1} & (s \rightarrow 0) \\ -\frac{1}{R_1Cs} & (s \rightarrow \infty) \end{cases}$$



• 振子の制御



→ 5 分 2 Suaf 2 分

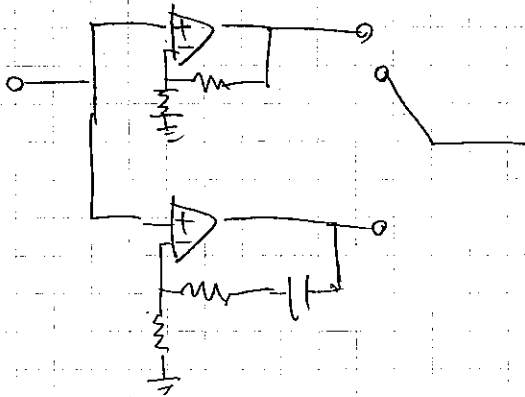
$$-90 - 6 - 6 \times 2 = -108^\circ$$

≠ 2 (≠ 3) 分, phase margin > 45°

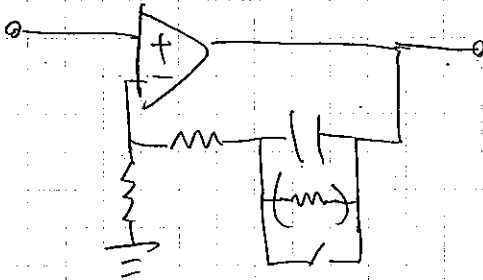
$$-180 + 108 = -72^\circ$$

X1 120k,

• D-ブースト



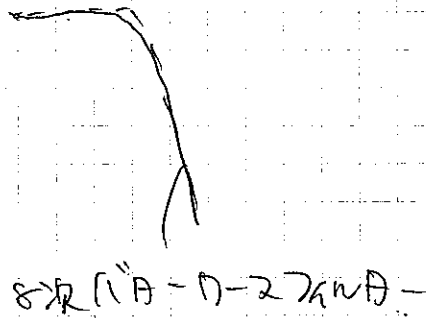
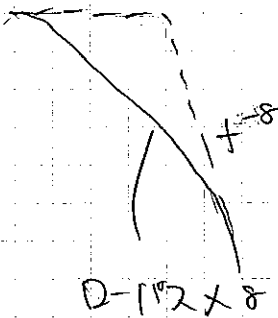
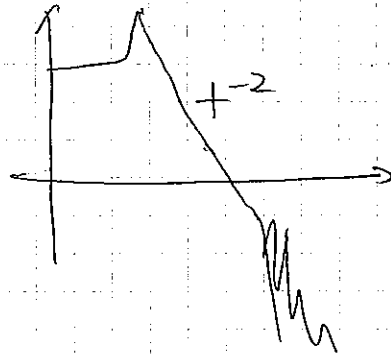
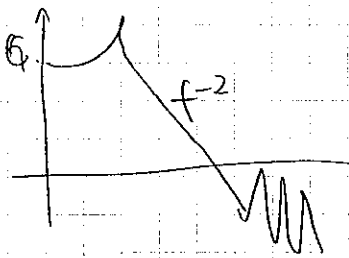
これは上巻くかな。(⊖) 下の出力は常に +15V



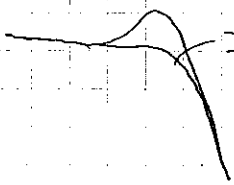
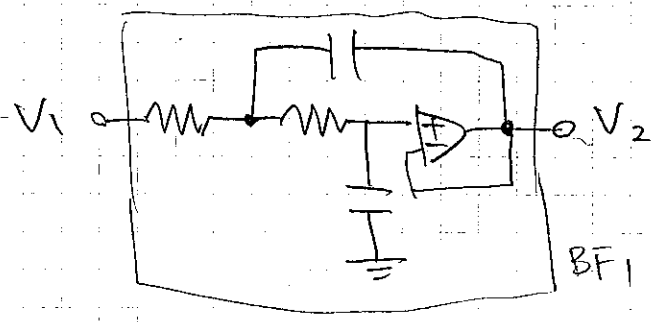
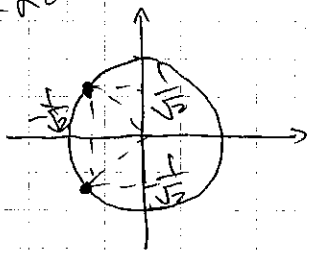
$$s^2 + as + 1$$

$$(s^2 - \frac{a}{2}) + 1 - \frac{a^2}{4}$$

• (1^A-D-2^A) D-2^A (Butter worth filter)



2次αZ

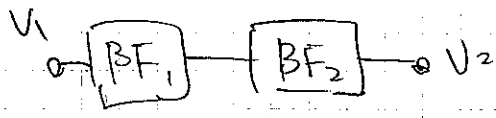
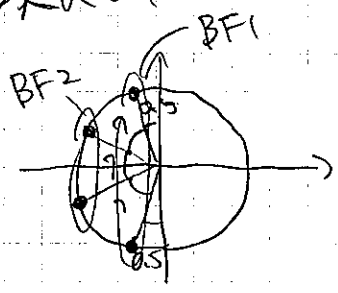


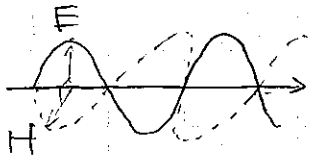
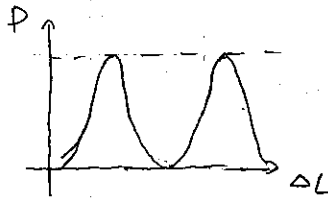
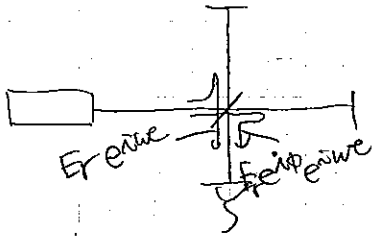
= 5dB 3dB

$$G = \frac{1}{s^2 + \sqrt{2}s + 1}$$

$$\text{pole } s = \frac{-\sqrt{2} \pm \sqrt{2-4}}{2} = \frac{-\sqrt{2} \pm \sqrt{2}j}{2} = -\frac{1}{\sqrt{2}} \pm \frac{1}{\sqrt{2}}j$$

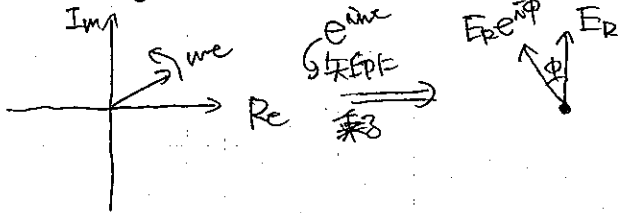
4次αZ





$10^{14} \sim 10^{15} \text{ Hz}$
 $E_0 \sin \omega t e$, $E_0 e^{i\omega t} e$ (電界)
 $E_r e^{i\omega t}$ (初期位相)
 $P = |E_r e^{i\omega t} e^{i\omega t}|^2$

Phasor diagram



$\cos 90^\circ = 2 \cos^2 \frac{\phi}{2} - 1$

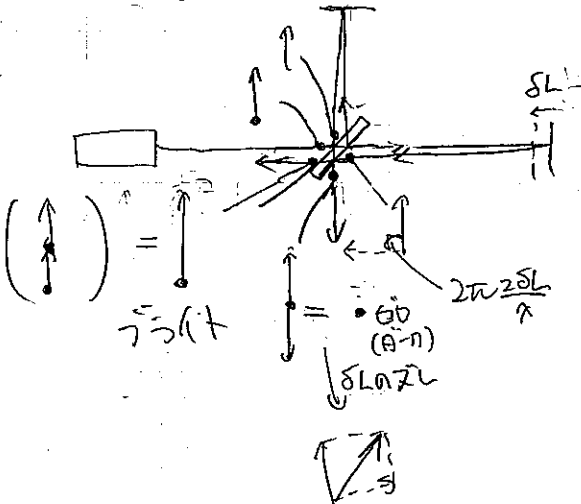
$\cos^2 \frac{\phi}{2} = \dots$

Michelson干渉計 ($E_r = 1$ とする)

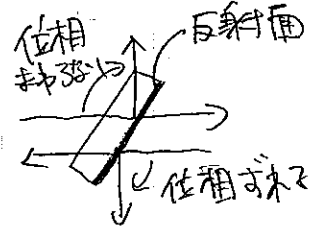
$E = e^{i\omega t} + e^{i\phi} e^{i\omega t} = e^{i\omega t} (1 + e^{i\phi})$

$\therefore P = |E|^2 = (1 + e^{i\phi})(1 + e^{-i\phi}) = 2(1 + \cos \phi) = 4 \cos^2 \frac{\phi}{2}$

(Phasor diagram を参照)

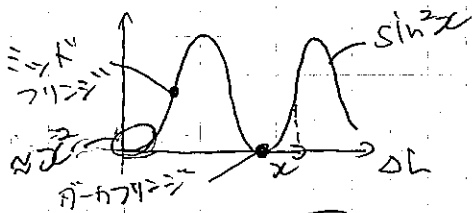


(光は屈折率の高い方に反射するとき π の位相変位)



* π の位相変位は反射の位相のズレを考慮しないと
 どのもラスタに E_0 $A - \pi$ にあたります。
 (エネルギーが保存しない)

△Lに止る光子



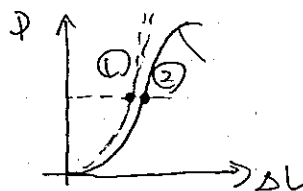
shot noise $\propto \sqrt{P}$
 $\Delta L \ll 1$ のとき
 $P \propto x^2$

shot noise $\propto \sqrt{P} \propto x$
 signal $\propto \frac{dP}{dx} \propto \frac{1}{2} x^0 \propto x$

$$S/N = \frac{\text{signal}}{\text{shot noise}} \propto x^0$$

放物線上では S/N は一定

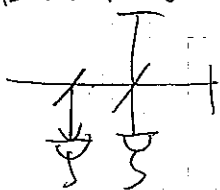
ドブリングの場合



shot noise: ① > ② の同じ
 signal: ① の方が傾きが同じ
 ↓
 signal が大きい

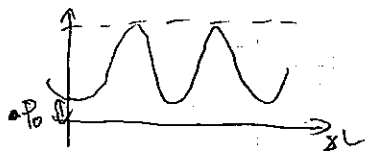
A-1 の S/N A-1 の S/N
 $S/N: ① > ②$ (正確には $S/N = \sqrt{S/N}$)
 ↓
 A-1 の光子数が大きい

左に、下の図は光子数を取り戻す回復できる



shot noise: 2倍 → $\sqrt{2}$ 下になる
 signal: 傾き2倍 → signal 2倍
 → S/N は $\frac{\sqrt{2}}{2} = \frac{1}{\sqrt{2}}$ になる

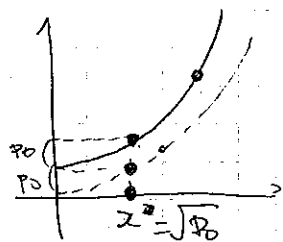
実際は A-1 は完全に A-1 に帰る



$$\text{shot noise} = \sqrt{P_0 + P} = \begin{cases} \sqrt{P_0} & (P_0 \gg P) \\ \sqrt{2P} & (P_0 \sim P) \\ x^2 & \end{cases}$$

signal: 傾き小さい

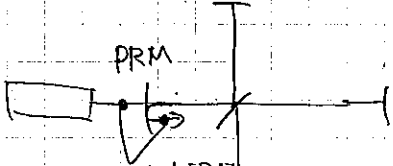
∴ S/N は $x < \sqrt{P_0}$ に近づくと悪くなる



Cはミントフリンジの幅がよいのか？

→ 実はCはP1 A-D フリンジの幅がよい = 1°D-1°Aイカリ>D

Signalの大きさが小さくなる

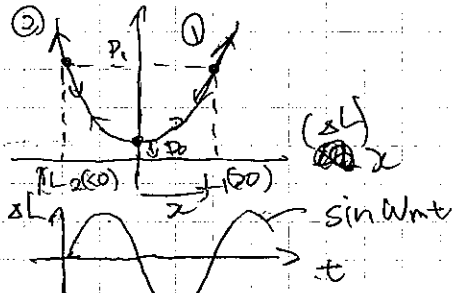


フェーズ (位相) が変化する
 大きさが変わる
 * 位相

→ PRMはM1が共振器の中心に作る

→ Shot noiseを小さくしたい (反射率を上げる)

→ 音調すればよい



① $c + a\Delta L = c + a\sin\omega mt$ → $\frac{c\sin\omega mt + a\sin^2\omega mt}{\sin\omega mt} = \frac{1}{2}a$ (∵ $c\sin\omega mt = 0$)

② $c + (-a)\Delta L = c - a\sin\omega mt$ → $\frac{c\sin\omega mt - a\sin\omega mt}{\sin\omega mt} = -\frac{1}{2}a$

(式2を使う)

$P = P_0 + \Delta^2$ とおす.

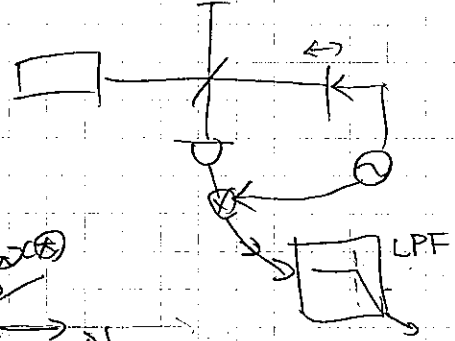
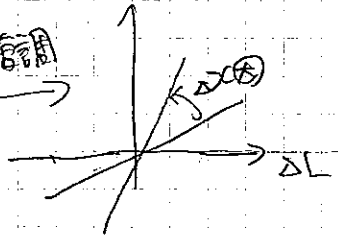
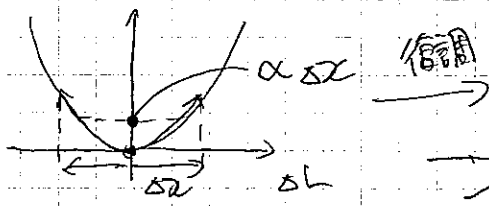
$\Delta \Rightarrow \Delta C + \Delta L \sin\omega mt$ とおす.

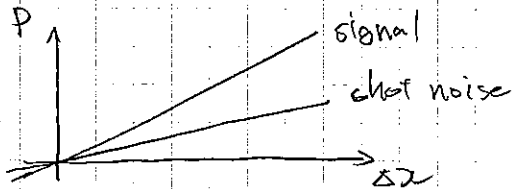
$P = P_0 + \Delta C^2 + 2\Delta C \Delta L \sin\omega mt = P_1 + 2\Delta C \Delta L \sin\omega mt$

$\frac{\Delta C \sin\omega mt}{\sin\omega mt} (\frac{1}{2}a) = \Delta C \Delta L^2$

となくするぶんはよい

・ 完璧な場合

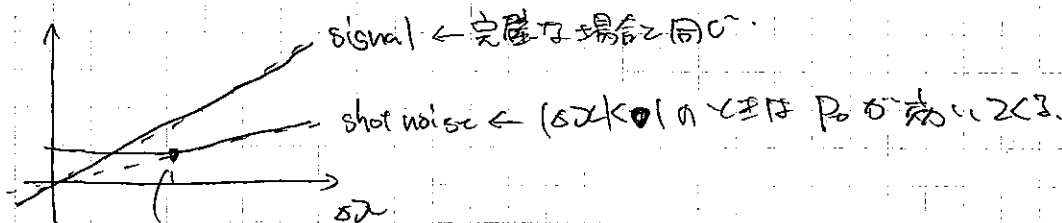




完璧な場合

shot noise $\propto \sqrt{P_0 + \Delta\Sigma^2}$

signal: 音が大きい



$P_0 \sim \Delta\Sigma^2$

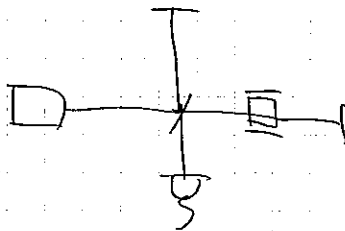
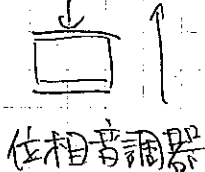
→ ∴ $\Delta\Sigma \sim \sqrt{P_0}$ になるくらいはいいから。

(大きい音はよいか) 限度はある

・ 2.5.3.6

鏡の2つを鏡の共振以下でしか信号が通らない

→ Packels cell を使う



$$\begin{pmatrix} -J_0(m) \\ \vdots \\ -J_1(m) \\ \vdots \\ -J_m(m) \end{pmatrix} \begin{matrix} \\ \\ \leftarrow -m \\ \\ \leftarrow \frac{m}{2} \end{matrix}$$

・ Phase modulation 2/F₀

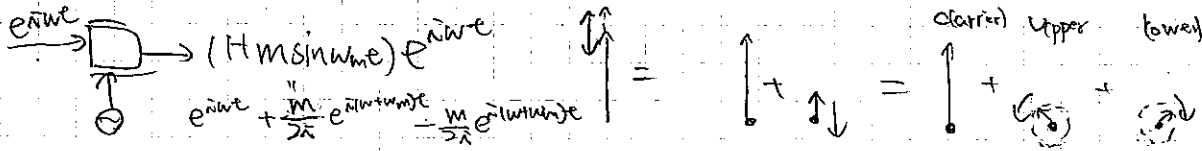
$e^{i\omega t}$ → $e^{i\omega t + m \sin \omega_c t} = J_0(m)e^{i\omega t} + J_1(m)e^{i(\omega + \omega_c)t} - J_1(m)e^{i(\omega - \omega_c)t}$

(*) $e^{im \cos \omega_c t} = \sum_{n=-\infty}^{\infty} J_n(m) e^{in\omega_c t}$

(phasor diagram 2)



(*) 強度音調



省題

phasor diagram 2次谐波

1次谐波
= gap 6倍

2次谐波 谐波 gap 3倍
實際は2倍

$$\cos 2\theta = 1 - 2\sin^2\theta$$

$$\sin^2\theta = \frac{1 - \cos 2\theta}{2}$$

$$e^{\tilde{m} \sin \omega t} = \sum_{n=-\infty}^{\infty} J_n(m) e^{jn\omega t}$$

$$e^{\tilde{m} \sin \omega t} = e^{j\omega t} + J_1(m) e^{j2\omega t} + J_2(m) e^{j3\omega t} + \dots$$

$$= e^{j\omega t} (1 + J_1(m) e^{j\omega t} + J_2(m) e^{j2\omega t} + \dots)$$

$$+ J_2(m) e^{j2\omega t} + J_2(m) e^{-j2\omega t} + J_2(m)$$

$$\begin{aligned} \frac{1}{2} e^{\tilde{m} \sin \omega t} &= (1 + \tilde{m} \sin \omega t + \frac{1}{2} (\tilde{m} \sin \omega t)^2) \\ &= (1 + \tilde{m} \sin \omega t + \frac{m^2}{2} \frac{\sin^2 \omega t}{1 - \cos 2\omega t}) \\ &= (1 - \frac{m^2}{4}) + \tilde{m} \sin \omega t + \frac{m^2}{4} \cos 2\omega t \end{aligned}$$

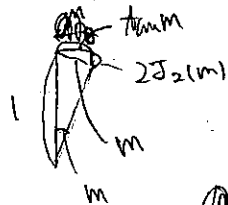
$$= e^{j\omega t} (1 + J_1(m) e^{j\omega t} - J_1(m) e^{-j\omega t} + 2J_2(m) \cos 2\omega t)$$

$$\begin{cases} 2\tilde{m} J_1(m) = \tilde{m} m \\ 2J_2(m) = \frac{m^2}{4} \end{cases}$$

$$\begin{cases} J_1 = \frac{m}{2} \\ J_2 = \frac{m^2}{8} \end{cases}$$

2次谐波 谐波
(1次谐波 + 2次谐波)
3倍谐波 谐波

ε < 1



$$\tilde{m} \sin \omega t = 2 + \frac{2\omega}{3}$$

$$\frac{1}{2} \tilde{m}^2 m = 2J_2(m) + m^2$$

$$(m + \frac{m^3}{3}) = m^2 + \frac{2}{3} m^4 + \frac{m^6}{9}$$

$$m^2 + \frac{2}{3} m^4 + \frac{1}{9} m^6 = 4J_2(m) + m^2$$

$$J_2 = \frac{m^2}{6} \Rightarrow J_2 = \frac{m}{18}$$

ε > 1
谐波

$$J_{-n} = (-1)^n J_n$$

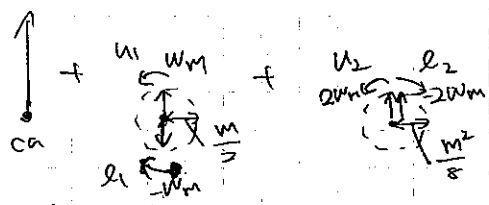
$$e^{j(\omega t + m \sin \omega t)} = e^{j\omega t} \sum_{n=0}^{\infty} J_n(m) e^{jn\omega t}$$

$$\approx e^{j\omega t} (J_0(m) + J_1(m) e^{j\omega t} + J_{-1}(m) e^{-j\omega t} + J_2(m) e^{2j\omega t} + J_{-2}(m) e^{-2j\omega t})$$

$$= e^{j\omega t} (J_0(m) + 2J_1(m) \sin \omega t + 2J_2(m) \cos 2\omega t)$$

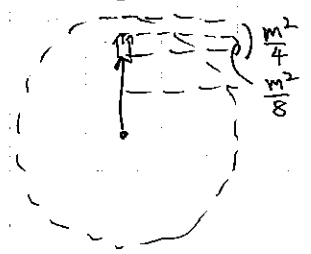
① $1 - \frac{m^2}{4}$ ② $\frac{m}{2}$

$2\omega t$ 成分は



この図は
 振幅は2回
 回る
 $\therefore 2\omega$
 ↑
 位相の
 1周期

phasor diagram 2書<2



Carrier * 5 減 24子.

光の繞幸

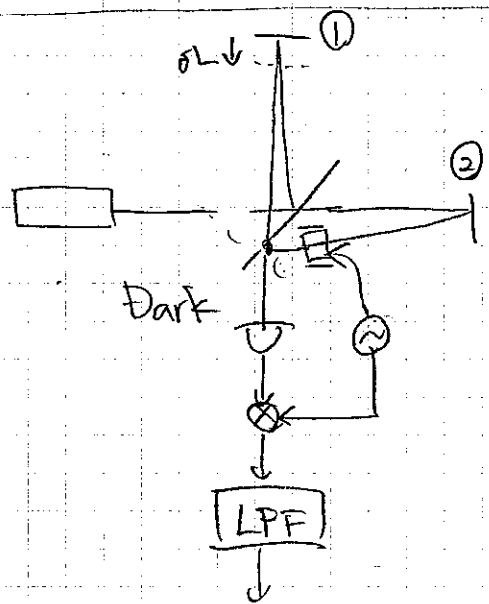
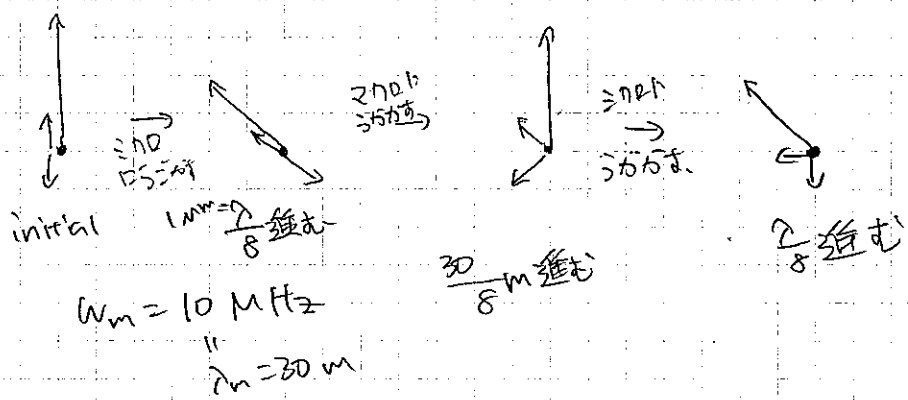
$$e^{i(\omega t + m \sin \omega_m t)} = e^{i\omega t} + \frac{m}{2} e^{i(\omega + \omega_m)t} - \frac{m}{2} e^{i(\omega - \omega_m)t}$$

$$= e^{i\omega t} \left(1 + \frac{m}{2} e^{i\omega_m t} - \frac{m}{2} e^{-i\omega_m t} \right)$$

$| \text{circle} |^2 = | 1 + i m \sin \omega_m t |^2 \approx 1$

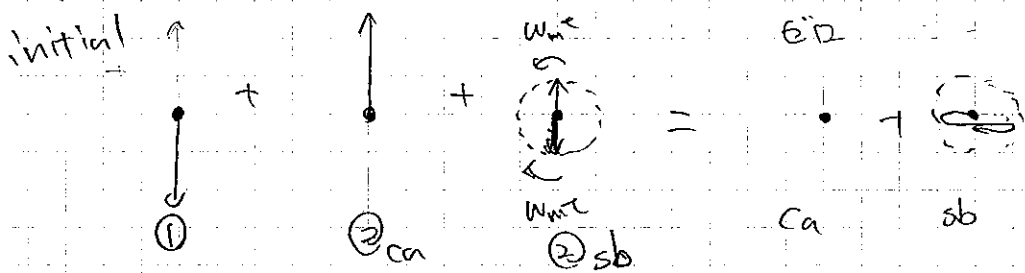
$| (1 + m \sin \omega_m t) e^{i\omega t} | = 1 + 2m \sin \omega_m t$

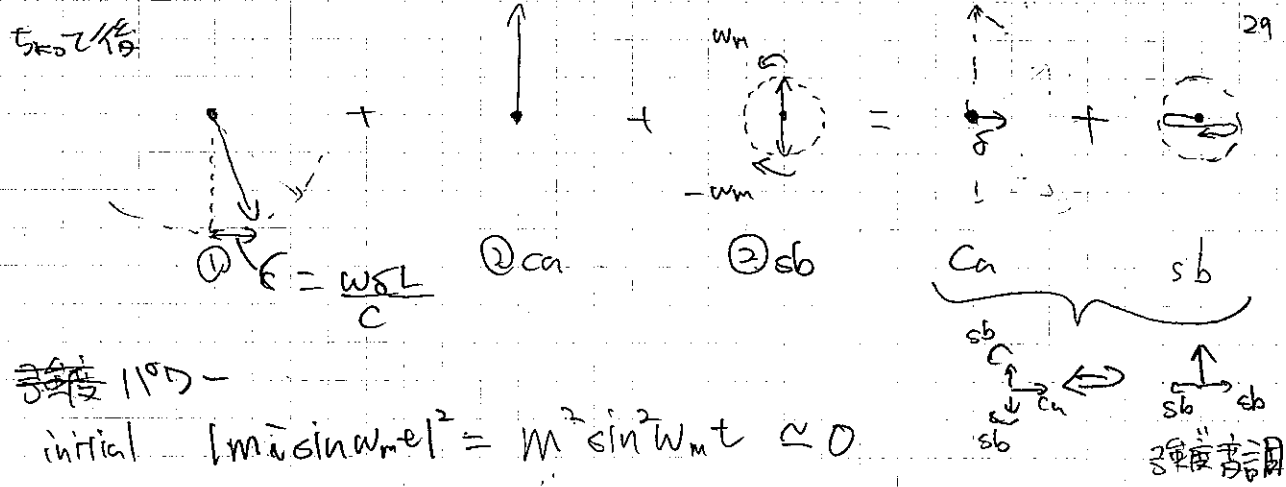
$\lambda = \frac{c}{\omega_m}$



$A (\cos \phi - \sin \phi)^2 = \cos^2 \phi + \sin^2 \phi = A^2 + B^2$

phasor diagram





強直音調 -

initial $|m \sin \omega_m t|^2 = M^2 \sin^2 \omega_m t \approx 0$

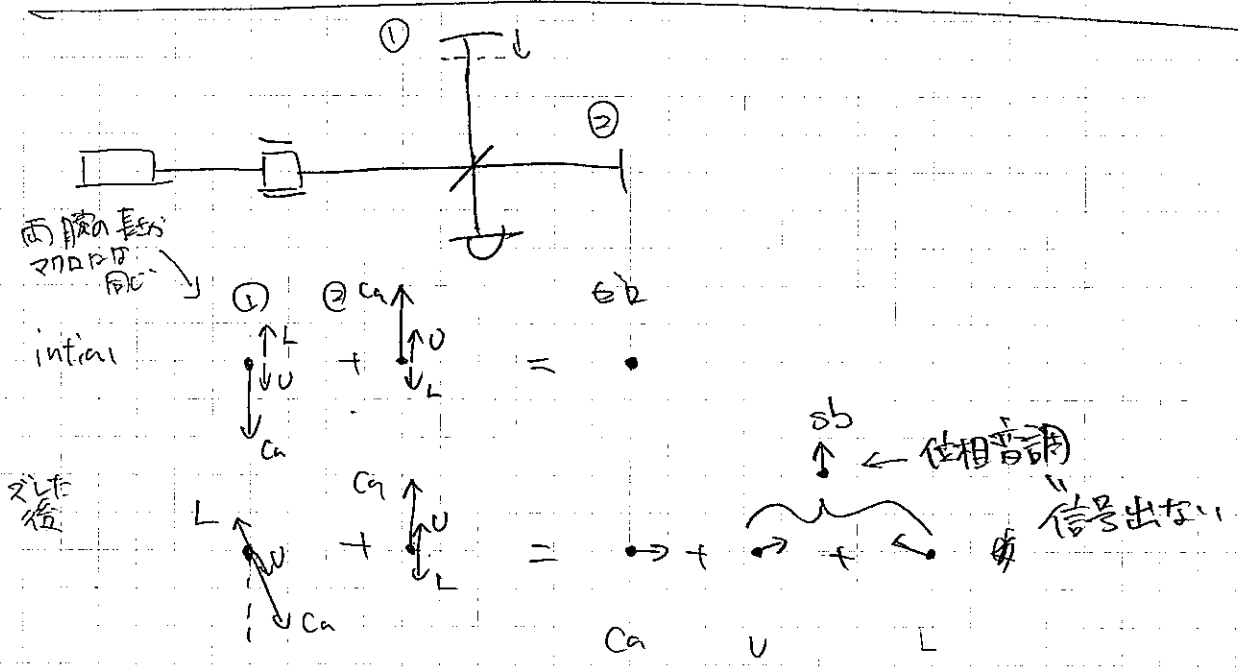
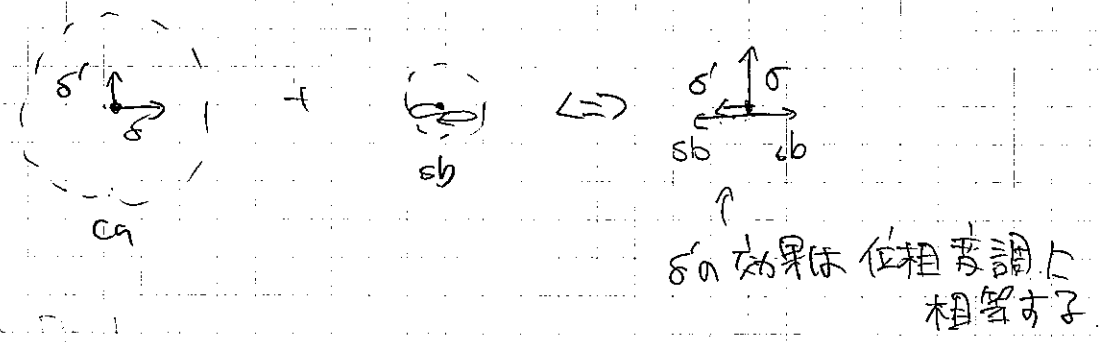
$t_{k=0}$ 後

$$|1 - (1 - \delta^2) + m \sin \omega_m t|^2 = |\delta^2 + m \sin \omega_m t|^2$$

$$\sin \omega_m t = \delta^2 + 2\delta m \sin \omega_m t + m^2 \sin^2 \omega_m t$$

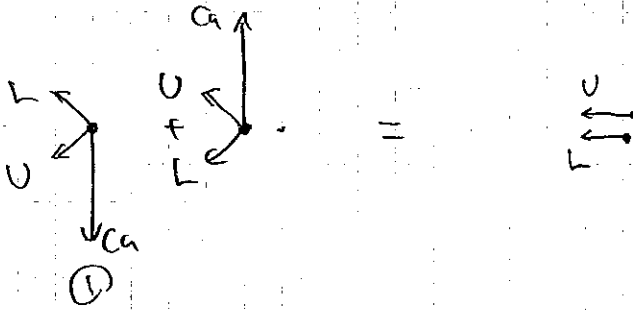
(in phase) + LPF $\Rightarrow \delta m = \frac{\omega L}{c} m$

①の鏡が「逆」の場合



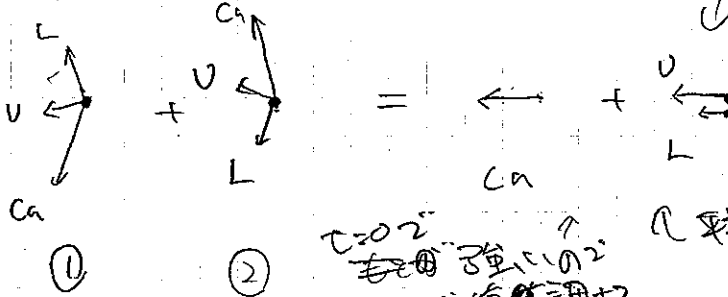
① $\frac{30}{P} m$ 長L

② $\frac{30}{P}$ 短いとす。



U は短く
 L は長くとす。

② $\frac{30}{P}$ 短いとす。



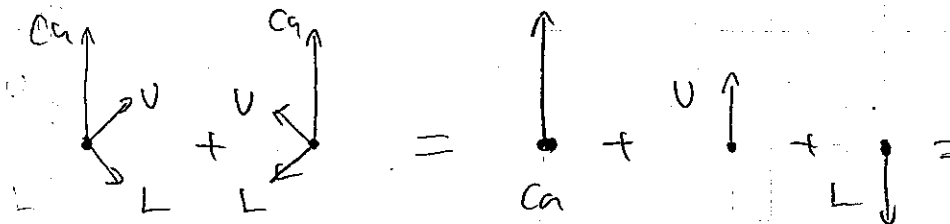
$\cos 2$
 強いの2
 $\cos 2$ 復調

1 軸長くとす
 2 強音調

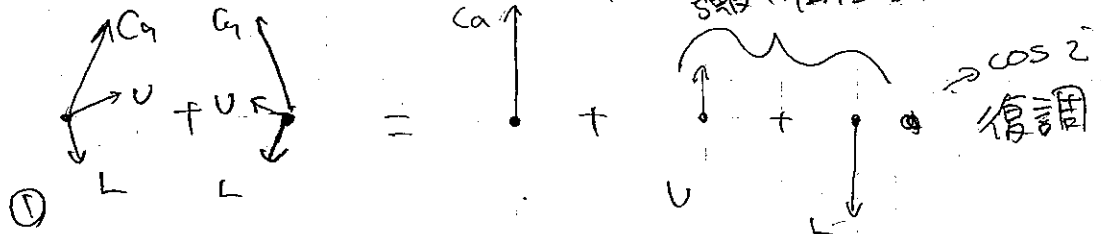
※ Upper & lower が π バランスする場合、以下の様に分解して
 位相音調の強度音調

Diagram: A vertical vector Ca is shown. It is decomposed into two vertical vectors: U_1 pointing up and U_2 pointing down. The diagram is labeled ①.

② $\frac{30}{P}$ 長くとす Bright part の信号を取。



① $\frac{30}{P}$ 短くとす

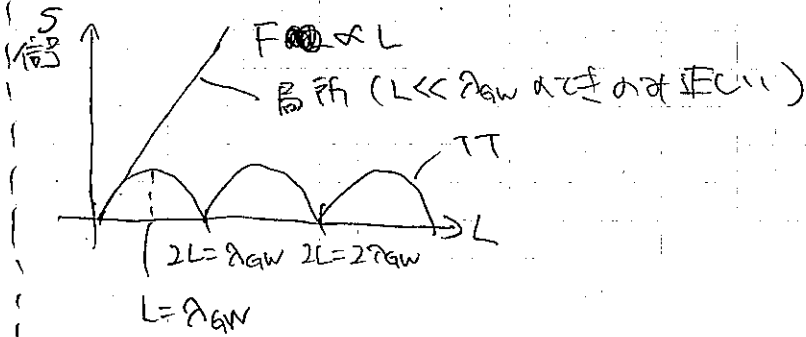


π バランス
 強音 + 位相音調

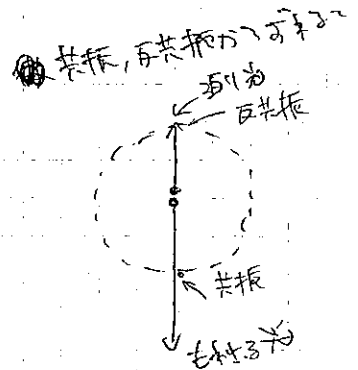
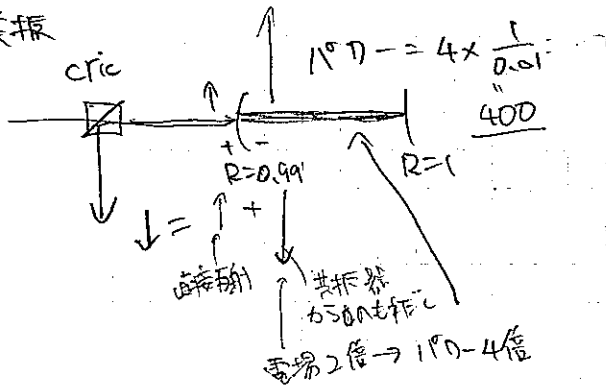
$\cos 2$
 復調

TX TT H = :

共振特性 = 共振 (共振) の場合 L に比例する



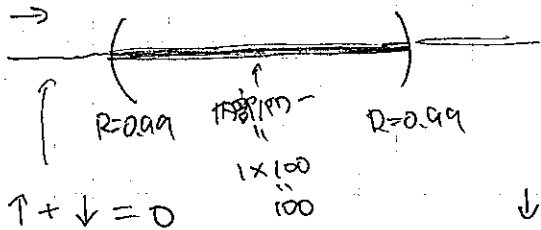
共振



共振

↑ + (0.005 x 2) 内部 1° D = (0.005)^2 x 100

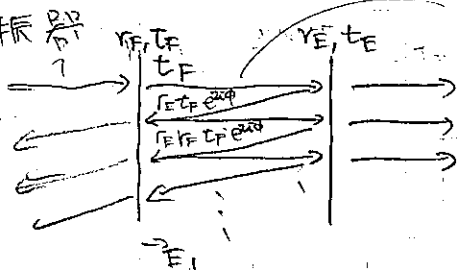
モード II - I - の場合



↓ ← 入射波と同じ大抵 (E 保存) ↑

共振器長 = 経路の逆する

共振器



$$\begin{aligned} \therefore E_1 &= t_F + V_E V_F t_F e^{2i\phi} + (V_E V_F) t_F e^{4i\phi} + \dots = t_F \sum_{n=1}^{\infty} (V_E V_F e^{2i\phi})^{n-1} \\ &= t_F \frac{1}{1 - V_E V_F e^{2i\phi}} \end{aligned}$$

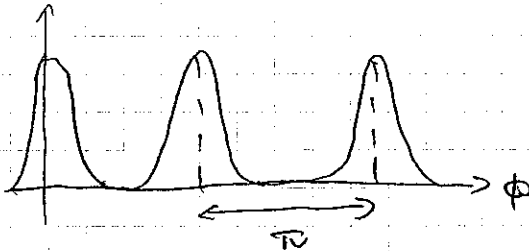
$$t_F = \sqrt{T} = 0.1, \quad r_F = \sqrt{R} = \sqrt{0.001} = 0.0316, \quad r_E = 1, \quad t_E = 0 \text{ である}$$

$$E = \frac{0.1}{1 - 0.001} = \frac{0.1}{0.999} = 0.1001 \leftarrow \pm 0.001 \text{ の } \phi \text{ である}$$

透過率は

$$E_c = E_1 \times t_E e^{i\phi} = \frac{t_F t_E e^{i\phi}}{1 - r_F r_E e^{2i\phi}}$$

$$\therefore P_c = |E_c|^2 = \frac{(t_F t_E)^2}{1 + (r_F r_E)^2 - 2 r_F r_E \cos 2\phi}$$



$$\text{① } (1/\pi) \text{ の半分の幅 } \phi_{1/2} \text{ は } P_c(\phi) = \frac{(t_F t_E)^2}{1 + (r_F r_E)^2 - 2 r_F r_E \cos 2\phi} \text{ の } 2/\pi$$

$$1 + (r_F r_E)^2 - 2 r_F r_E \cos(2\phi_{1/2}) = 2(1 - r_F r_E)^2$$

$$\therefore \cos(2\phi_{1/2}) = \frac{4 r_F r_E - 1 - (r_F r_E)^2}{2 r_F r_E}$$

$|\phi_{1/2}| \ll 1$ である

$$1 - \frac{1}{2}(2\phi_{1/2})^2 = \frac{4 r_F r_E - 1 - (r_F r_E)^2}{2 r_F r_E}$$

$$\therefore -2\phi_{1/2}^2 = \frac{2 r_F r_E - 1 - (r_F r_E)^2}{2 r_F r_E} = -\frac{(1 - r_F r_E)^2}{2 r_F r_E}$$

$$\therefore \phi_{1/2} = \frac{1}{2} \frac{1 - r_F r_E}{\sqrt{r_F r_E}}$$

$$\mathcal{F} \equiv \frac{\phi_{FSR}}{\phi_{FWHM}} = \frac{\pi / (r_F r_E)}{1 - r_F r_E} \quad \therefore \mathcal{F} \gg 1$$

$$\left(\begin{array}{ll} r_F = 0.0316, & t_F = 0.1, & r_E = 1 \text{ である} & \mathcal{F} = 200 \pi \\ r_E = 0.0316 & & & \mathcal{F} = 100 \pi \end{array} \right)$$

$$E_r = -r_F + \frac{t_F^2 r_E e^{2i\phi}}{1 - r_F r_E e^{2i\phi}} E_1 = -r_F + \frac{t_F^2 r_E e^{2i\phi}}{1 - r_F r_E e^{2i\phi}} = \frac{-r_F + r_E e^{2i\phi}}{1 - r_F r_E e^{2i\phi}}$$

$$= \frac{(-r_F + r_E e^{2i\phi})(1 - r_F r_E e^{-2i\phi})}{1 + (r_F r_E)^2 - 2 r_F r_E \cos 2\phi}$$

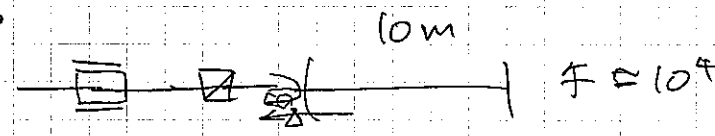
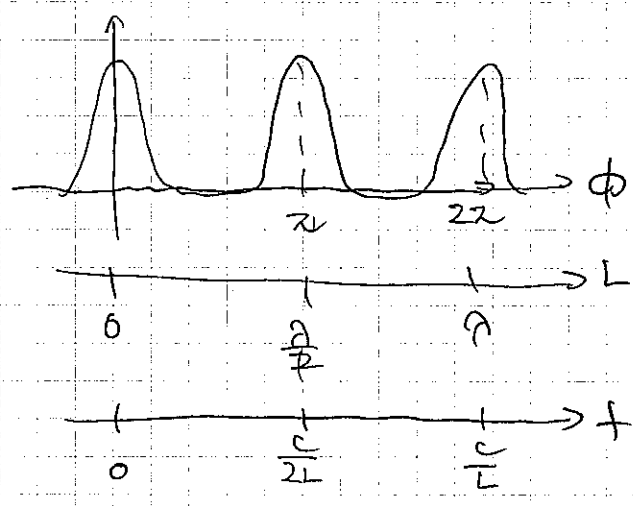
$$= \frac{-r_F - r_F r_E^2 + r_E + r_F^2 r_E e^{2i\phi} + r_F^2 r_E e^{-2i\phi}}{1 + (r_F r_E)^2 - 2 r_F r_E \cos 2\phi}$$

$$\left(\phi \ll \frac{1}{\mathcal{F}} \right) = \frac{-r_F - r_F r_E^2 + r_E + r_F^2 r_E + 2i\phi(r_E - r_F^2 r_E)}{1 + (r_F r_E)^2 - 2 r_F r_E \cos 2\phi}$$

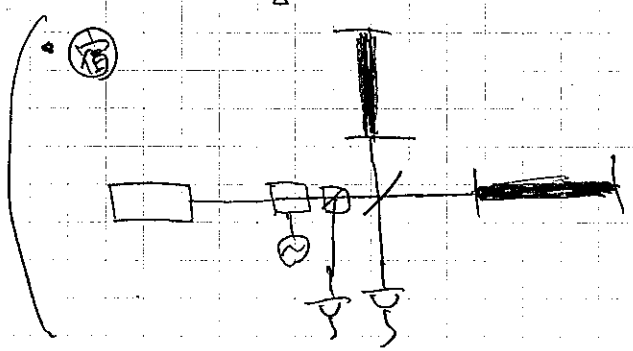
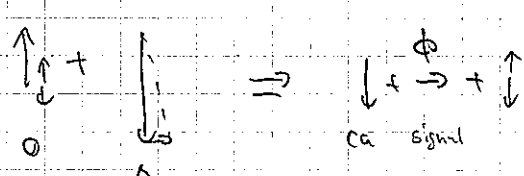
$$= \dots$$

$$\begin{aligned} \therefore \angle E_r &= \arctan \left(\frac{2V_E(1-V_F^2)\phi}{-V_F - V_E V_F^2 + V_E + V_E V_F^2} \right) \\ &= \arctan \left(\frac{2V_E(1-V_F^2)\phi}{(1-V_F V_E)(V_E - V_F)\phi} \right) \\ &= \arctan \left(\frac{2}{\pi \sqrt{V_F V_E}} \times \frac{2V_E(1-V_F^2)}{V_E - V_F} \phi \right) \\ &= \arctan \left(\frac{1}{\pi} \sqrt{\frac{V_E}{V_F}} \frac{2(1-V_F^2)}{V_E - V_F} \phi \right) \\ V_E &= 1 \Rightarrow \arctan \left(\frac{2}{\pi} \frac{1}{\sqrt{V_F}} \frac{1-V_F^2}{1-V_F} \phi \right) \\ &= \arctan \left(\frac{2}{\pi} \frac{1+V_F}{\sqrt{V_F}} \phi \right) \approx \arctan \left(\frac{2}{\pi} \phi \right) \end{aligned}$$

→ 1/V_F > 1/V_E > 2 比較
↑
N

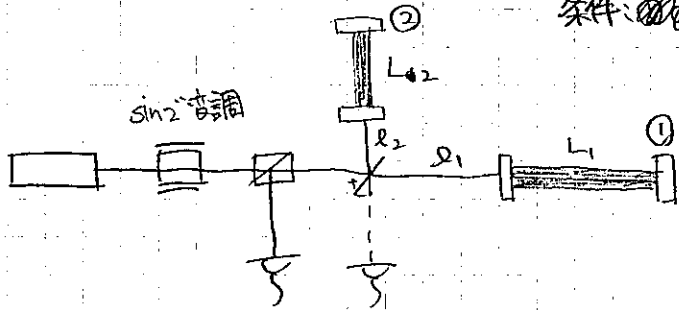


- $f_{SR} \approx 1.5 \times 10^{10}$ Hz
- $\Delta V (f_{FWHM}) = 1.5 \times 10^3$ Hz



← 共振器長 $\times 2$)
+ A = 0 時 - t)
3つの回路が必要
↓
2つのポート
3つと3つと2つと3つ

FPMIからの信号取り出し



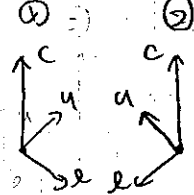
条件: $l_1 - l_2 = \frac{\lambda_m}{2} \equiv l_0$ (with $\sim 30m$ above)

$$L_{\pm} \equiv \frac{L_1 \pm L_2}{2}$$

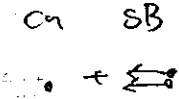
$$l_{\pm} \equiv \frac{l_1 \pm l_2}{2}$$

動作点

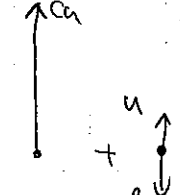
(BS 直前)



(DP)

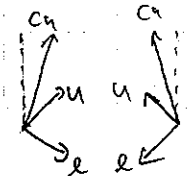


(BP)



$L \downarrow$

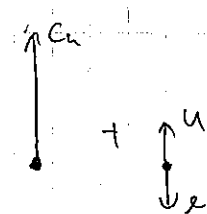
$(L_1 \rightarrow L_1 + \delta L_1)$
 $(L_2 \rightarrow L_2 - \delta L_2)$



($\pi \pm (L \times \pi/2)$)

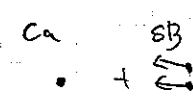
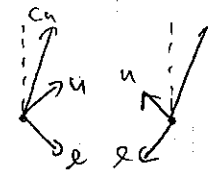
$(c_n \quad SB)$

Q-phase



$L \uparrow$

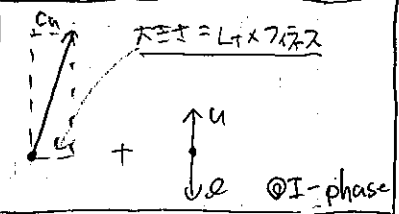
$(L_1 \rightarrow L_1 + \delta L_1)$
 $(L_2 \rightarrow L_2 + \delta L_2)$



($\pi \pm (L \times \pi/2)$)

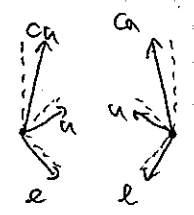
$(c_n \quad SB)$

I-phase



$l_0 \downarrow$

$(l_1 \rightarrow l_1 + \delta l_1)$
 $(l_2 \rightarrow l_2 + \delta l_2)$



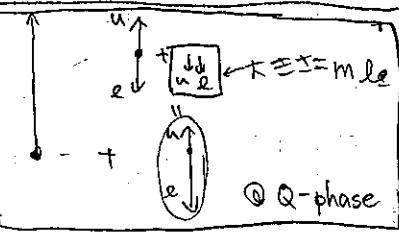
(Q-phase 2 取出し $L \pm \pi/4$ 時)

$(c_n \quad SB)$

($\pi \pm (L \times \pi/2)$)

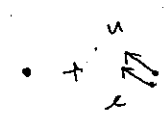
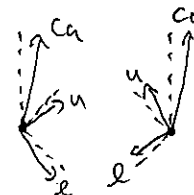
$(c_n \quad SB)$

Q-phase



$l_0 \uparrow$

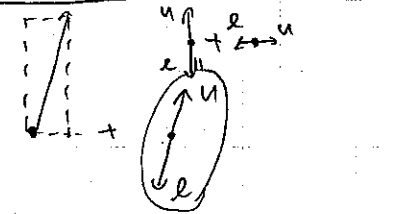
$(l_1 \rightarrow l_1 + \delta l_1)$
 $(l_2 \rightarrow l_2 + \delta l_2)$



($\pi \pm (L \times \pi/2)$)

$(c_n \quad SB)$

I-phase



2.5 Gaussian Beams in a Homogeneous Medium

If the propagation medium is homogeneous, we can, according to (2.4-5), put $k_2 = 0$, and (2.4-11) becomes

$$\frac{1}{q^2} + \left(\frac{1}{q}\right)' = 0 \tag{2.5-1}$$

Introducing the function $s(z)$ by the relation

$$\frac{1}{q} = \frac{s'}{s} \tag{2.5-2}$$

we obtain directly from (2.5-1)

$$s'' = 0$$

so that

$$s' = a \quad s = az + b$$

or, using (2.5-2),

$$\frac{1}{q(z)} = \frac{a}{az + b} \tag{2.5-3}$$

where a and b are arbitrary constants, we will find it more convenient to deal with a parameter q , so that we may rewrite (2.5-3) in the form

$$q = z + q_0 \tag{2.5-4}$$

From (2.4-11) and (2.5-4) we have

$$P' = -\frac{i}{q} = -\frac{i}{z + q_0} \tag{2.5-5}$$

so that

$$P(z) = -i \ln \left(1 + \frac{z}{q_0}\right) \tag{2.5-6}$$

where the arbitrary constant of integration is chosen as zero:⁵

Combining (2.5-5) and (2.5-6) in (2.4-9) we obtain

$$\psi = \exp \left\{ -i \left[-i \ln \left(1 + \frac{z}{q_0}\right) + \frac{k}{2(q_0 + z)} r^2 \right] \right\} \tag{2.5-7}$$

We take q_0 to be purely imaginary and reexpress it in terms of a new constant ω_0 as

$$q_0 = i \frac{\pi \omega_0^2 n}{\lambda} \quad \lambda = \frac{2\pi n}{k} \tag{2.5-8}$$

The choice of imaginary q_0 will be found to lead to physically meaningful waves whose energy density is confined near the z axis. With this last substitu-

⁵ The integration constant will merely modify the phase of the field solution (2.4-7). This is equivalent to a mere shift of the time origin.

tion, let us consider, one at a time, the two factors in (2.5-7). The first one becomes

$$\exp \left[-\ln \left(1 - i \frac{\lambda z}{\pi \omega_0^2 n}\right) \right] = \frac{1}{\sqrt{1 + (\lambda^2 z^2 / \pi^2 \omega_0^4 n^2)}} \exp \left[i \tan^{-1} \left(\frac{\lambda z}{\pi \omega_0^2 n} \right) \right] \tag{2.5-9}$$

where we used $\ln(a + ib) = \ln \sqrt{a^2 + b^2} + i \tan^{-1}(b/a)$. Substituting (2.5-8) in the second term of (2.5-7) and separating the exponent into its real and imaginary parts, we obtain

$$\exp \left[\frac{-ikr^2}{2(q_0 + z)} \right] = \exp \left\{ \frac{-r^2}{\omega_0^2 [1 + (\lambda z / \pi \omega_0^2 n)^2]} - \frac{ikr^2}{2z [1 + (\pi \omega_0^2 n / \lambda z)^2]} \right\} \tag{2.5-10}$$

If we define the following parameters

$$E^{-1} \frac{1}{\omega^2} \rightarrow \omega^2(z) = \omega_0^2 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2 n} \right)^2 \right] = \omega_0^2 \left(1 + \frac{z^2}{z_0^2} \right) \tag{2.5-11}$$

$$R = z \left[1 + \left(\frac{\pi \omega_0^2 n}{\lambda z} \right)^2 \right] = z \left(1 + \frac{z_0^2}{z^2} \right) \tag{2.5-12}$$

$$\text{Group phase} \rightarrow \eta(z) = \tan^{-1} \left(\frac{z}{z_0} \right) = \tan^{-1} \left(\frac{z}{z_0} \right) \tag{2.5-13}$$

$z_0 = \omega_0^2 n / \lambda$
 $\omega_0^2 = \lambda / z_0^2$
 $z_0 = \frac{\pi \omega_0^2 n}{\lambda}$

we can combine (2.5-9) and (2.5-10) in (2.5-7) and, recalling that $E(x, y, z) = \psi(x, y, z) \exp(-ikz)$, obtain

$$\begin{aligned} E(x, y, z) &= E_0 \frac{\omega_0}{\omega(z)} \exp \left\{ -i[kz - \eta(z)] - i \frac{k^2}{2q(z)} \right\} \\ &= E_0 \frac{\omega_0}{\omega(z)} \exp \left\{ -i[kz - \eta(z)] - r^2 \left(\frac{1}{\omega^2(z)} + \frac{ik}{2R(z)} \right) \right\} \\ k &= \frac{2\pi n}{\lambda} \end{aligned} \tag{2.5-14}$$

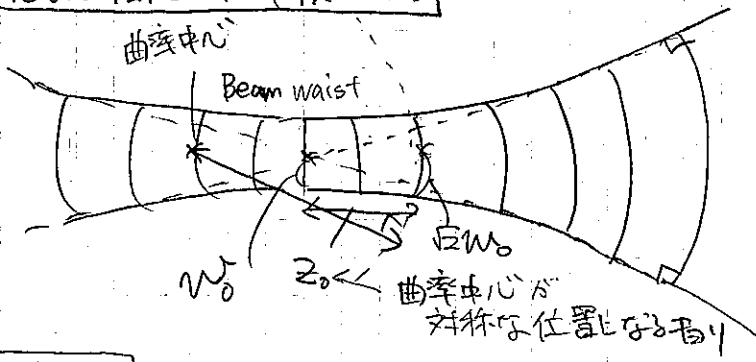
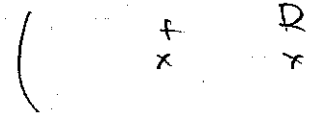
This is our basic result. We refer to it as the fundamental Gaussian-beam solution, since we have excluded the more complicated solutions of (2.4-3) (that is, those with azimuthal variation) by limiting ourselves to transverse dependence involving $r = (x^2 + y^2)^{1/2}$ only. These higher order modes will be discussed separately.

From (2.5-14) the parameter $\omega(z)$, which evolves according to (2.5-11), is the distance r at which the field amplitude is down by a factor $1/e$ compared to its value on the axis. We will consequently refer to it as the beam "spot size." The parameter ω_0 is the minimum spot size. It is the beam spot size at the plane $z = 0$. The parameter R in (2.5-14) is the radius of curvature of the very

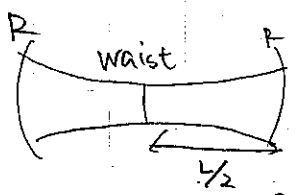
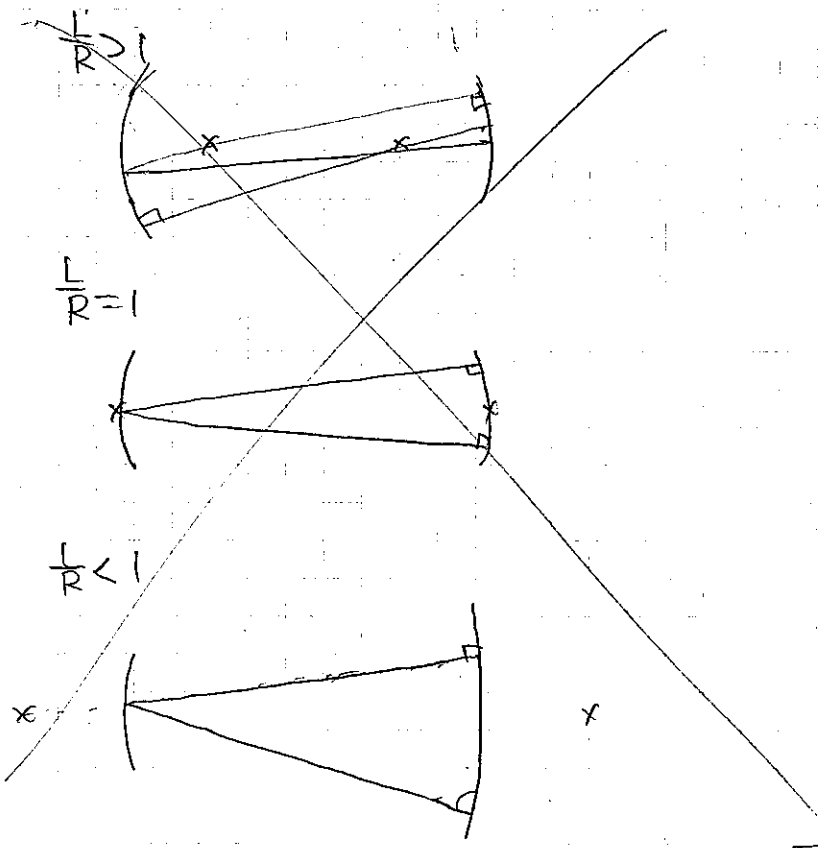
光の空間モード(横モード)

* 共振器軸は、焦点2つはなく
曲率中心を通る。

$R = 2f$



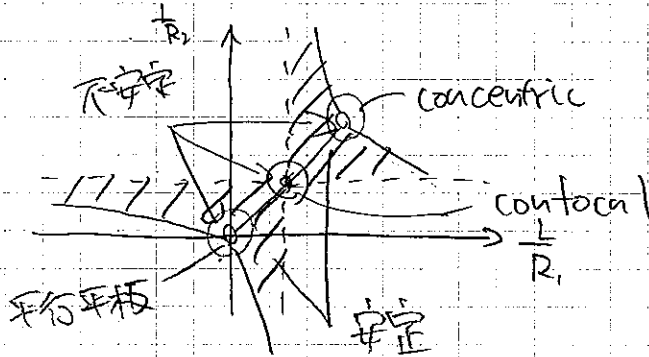
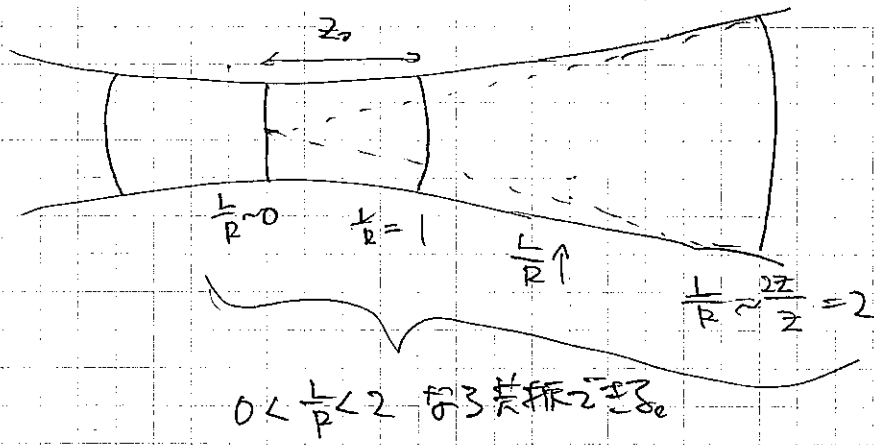
安定性



$R(z) = z \left(1 + \frac{z_0^2}{z^2} \right) \rightarrow R\left(\frac{L}{2}\right) = \frac{L}{2} \left(1 + \frac{z_0^2}{(\frac{L}{2})^2} \right)$

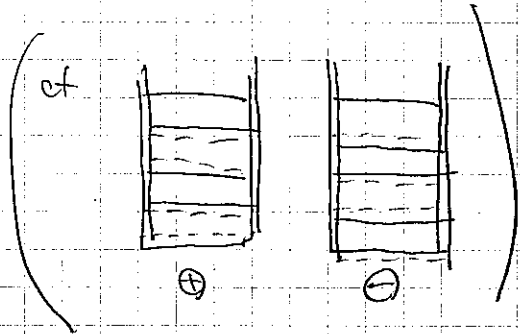
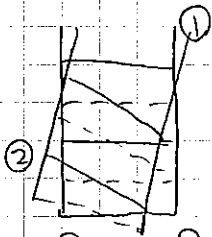
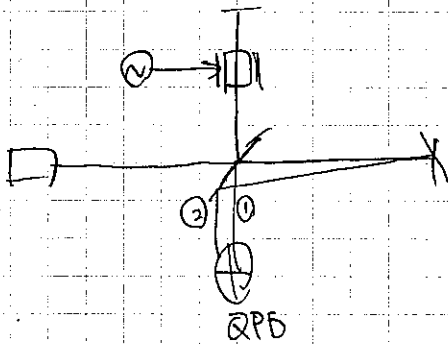
z_0 の存在は必ず

$\therefore z_0^2 = \frac{L}{2} \left(R - \frac{L}{2} \right) > 0 \quad \therefore R - \frac{L}{2} > 0 \quad \therefore (0 <) \frac{L}{R} < 2$

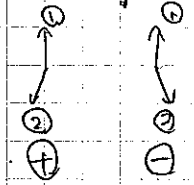


- 平行平板の concentric は全20モードが共振 = 不安定
- confocal は $00, 02, \dots$ のモードが共振 = 不安定

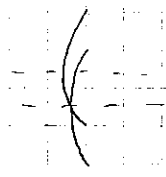
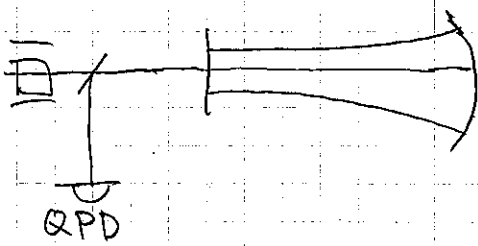
• wavefront sensing



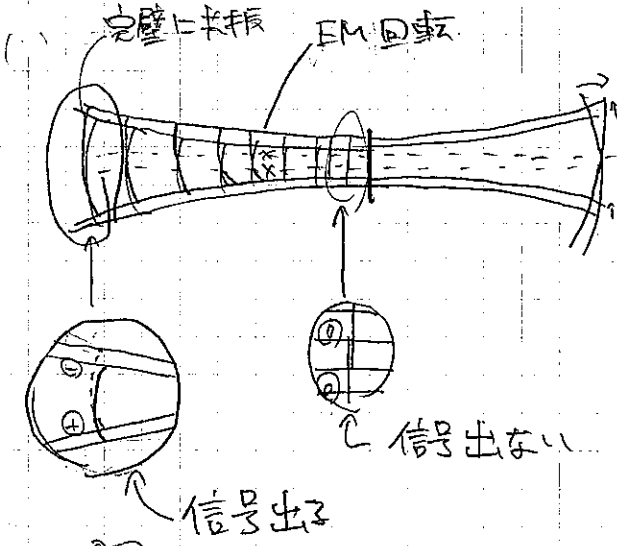
Yaw



→ Yaw 方向の情報が得られる

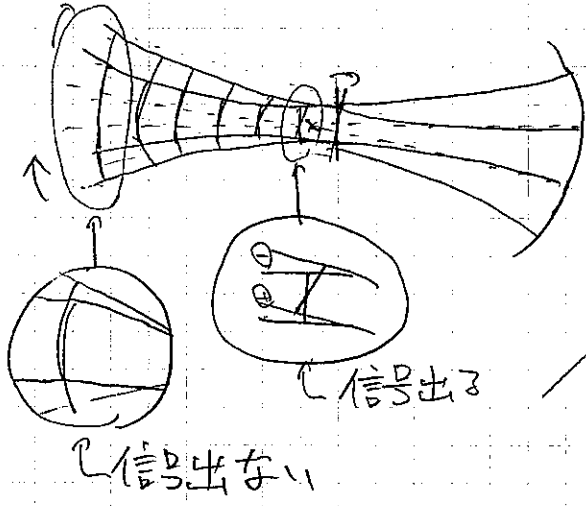


FMとEMの中心をどう区別するか



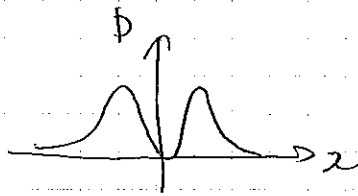
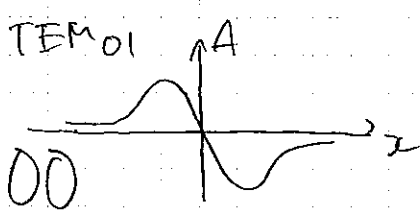
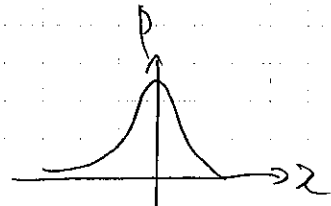
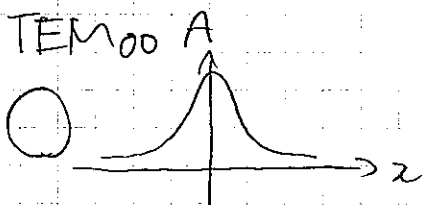
信号出ない

信号出た

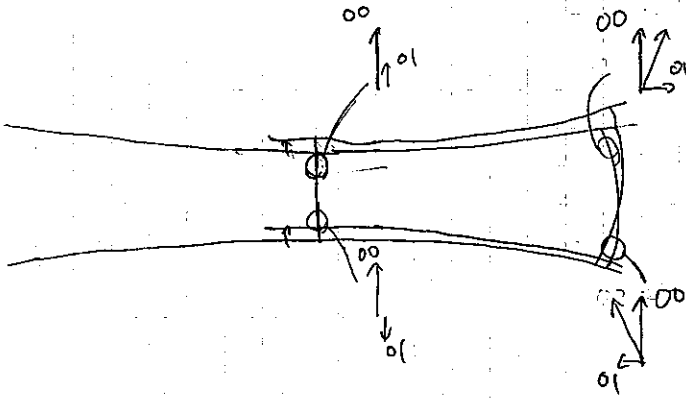
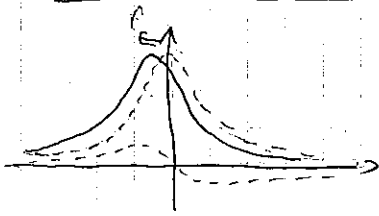


信号出ない

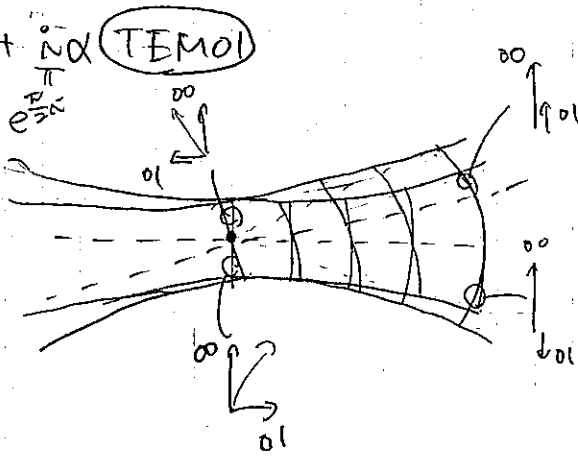
EMとFMの
中心分離
の原理



$\text{TEM}_{00} + \alpha \text{TEM}_{01}$

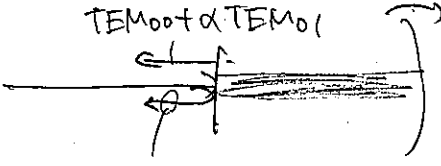


$\text{TEM}_{00} + \frac{1}{\sqrt{2}} \alpha \text{TEM}_{01}$



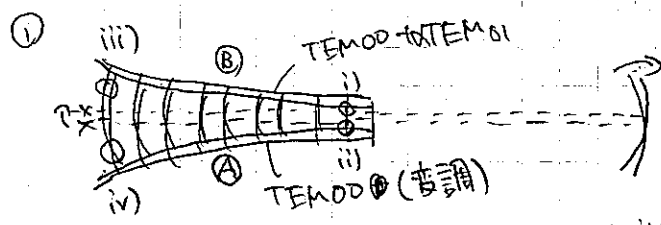
① wavefront sensing Σ TEM_{00} と TEM_{01} の混合状態の説明

$\text{TEM}_{00} + \alpha \text{TEM}_{01}$



TEM_{00}
(高利)

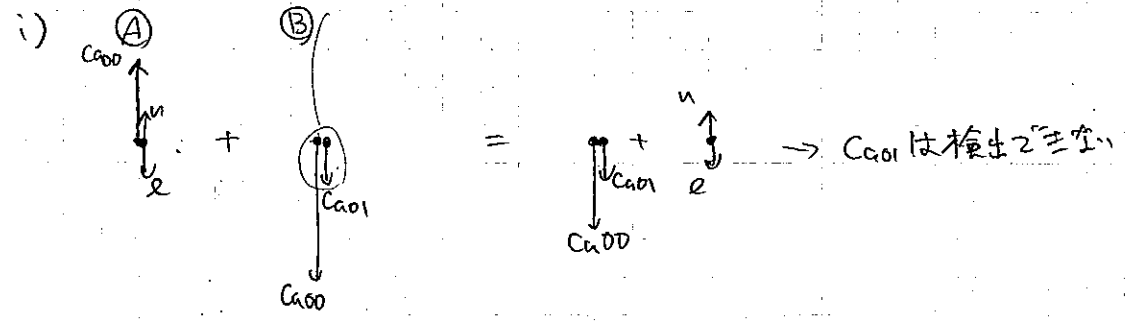
WFS Σ phasor-diagram 2 説明



- ④ FMA 反射光
- ⑤ cavity 内 30 反射光

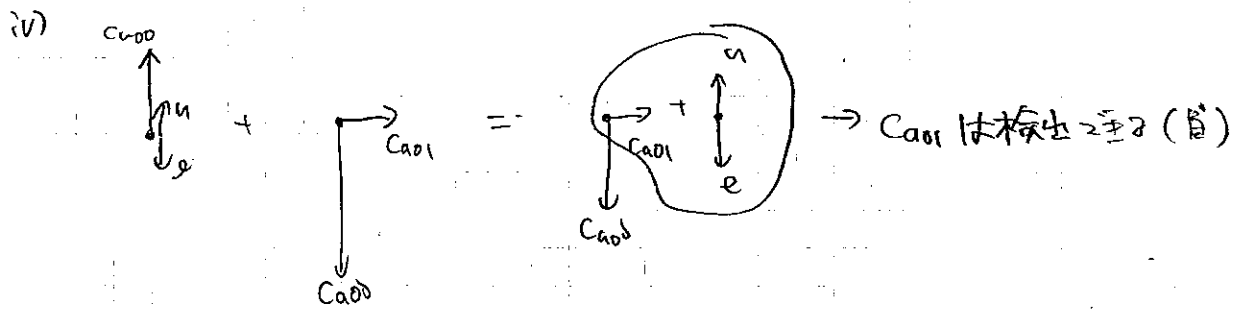
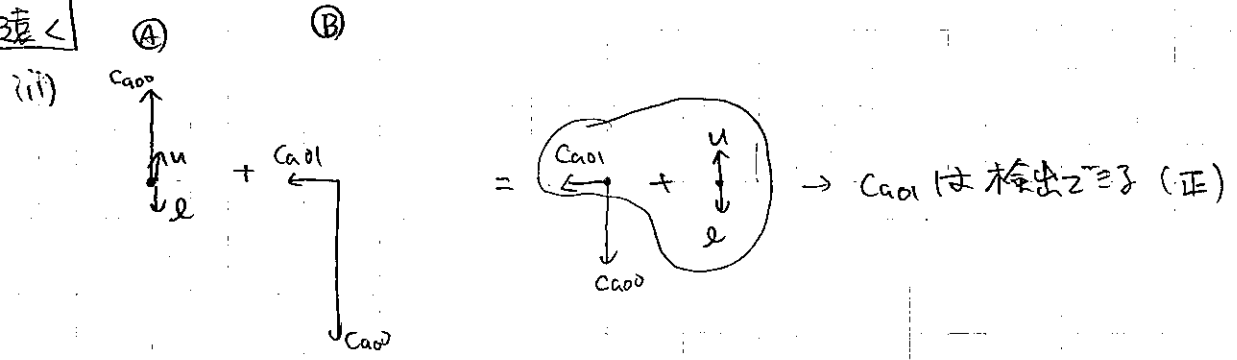
近<

00201の向きが同じなのは i) 2 は差が強いから

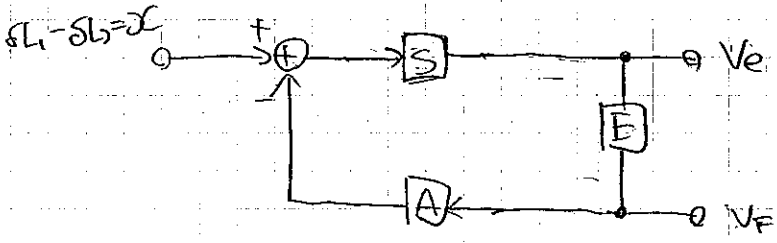
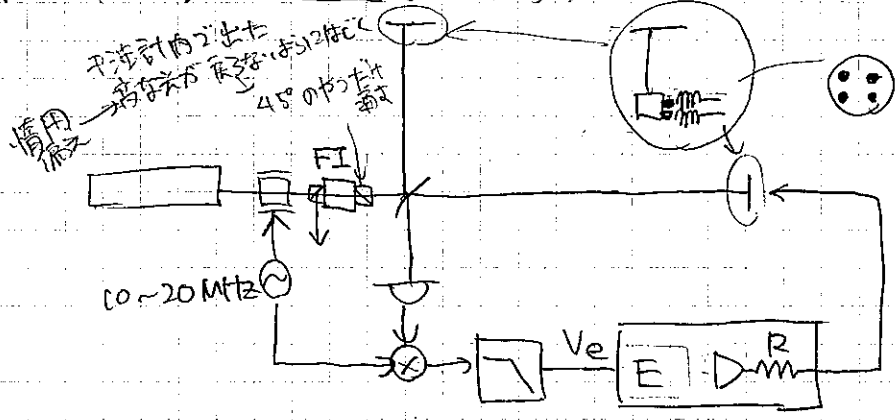


ii) も同様

遠<



③ 回転の場合も同様



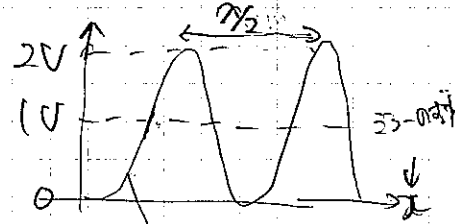
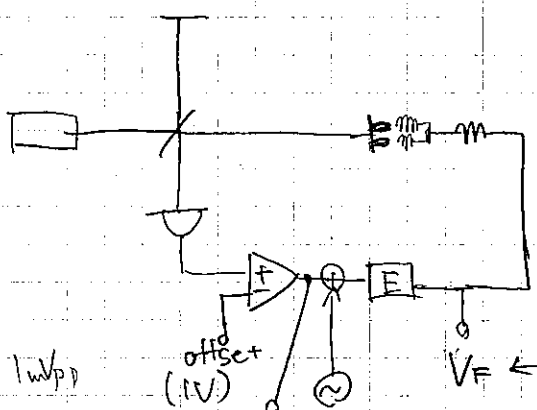
$\frac{V}{f} \propto f^{-2}$

($\frac{V}{f}$ が \rightarrow 電位)

○ E の測定
伝達関数を測る

○ A の測定 (いま、地震計の静電容量の VGF = 3 Hz <small>以下</small>。⇒ 100 Hz では 1 Vpp が
かかると仮定)

i) ミニフリンジ (E → R) の様子:



$V = 1 + \sin\left(\frac{2\pi}{T} t\right)$

→ 伝達関数 $\frac{V}{f}$ (V/m)

$2 \times \frac{2\pi V}{T} = 1 \text{ mVpp}$

$V = \frac{V_{max}}{2} \sin\left(\frac{2\pi}{T} t\right) \xrightarrow{\text{伝達}} V_{max} \frac{2\pi}{T}$

iii) $1 \text{ mVpp} \rightarrow \frac{1 \text{ mVpp} \times T}{2\pi \cdot V_{max}} \approx 10^3 \frac{10^{-6}}{20 \cdot 2} = 10^{-10} \text{ [m/V]}$

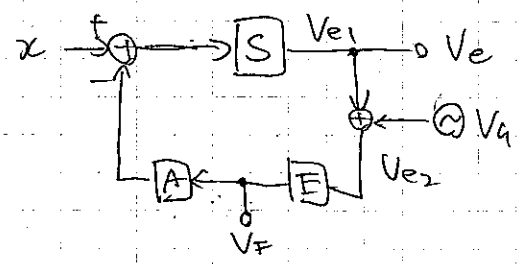
∴ $A(100 \text{ Hz}) = 10^{-10} \text{ [m/V]}$

iv) $\rightarrow A(f) = 10^{-10} (\text{高})^{-2} = 10^{-6} f^{-2} \text{ [m/V]}$

○ 問題点

- 100 Hz が 1 Vpp を 1 mVpp まで減らす
- 実際は、もとの 5 が 5 にかわると 100 Hz とかでは変わらない。(高いほど)

• おもてあてをやる。



測定が
↓
値定: S既知, E既知ない

- 表, いじりいじりな場所を見、 V_a 右の信号が支配的になるように
おまじりの V_a を入る

- $V_F \rightarrow V_{e1}$ の伝達関数を測り。

① $(V_{e2} = \frac{V_a}{1+G})$

$V_{e2} = G V_{e2} + V_a$

$V_F = \frac{E}{HG} V_a$

$V_{e1} = -\frac{G}{HG} V_a$

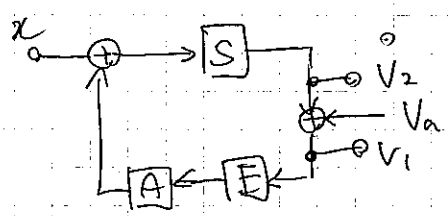
$\frac{V_{e1}}{V_F} = -\frac{E}{G} = -\frac{1}{AS}$

S既知ないから
Aが求まるから

• Sの測定 (注: Aを測るためのSとは別もの。(→ フリンジがわ))

$\frac{V_F}{V_{e1}} = -AS \leftarrow AがわかるといこのSが求まるから。$

• loop gainの測定



$V_1 = \frac{V_a}{HG}, V_2 = \frac{-G}{HG} V_a \quad \therefore \left| \frac{V_2}{V_1} \right| = |G|$

• noise

- (i) 鏡を直接やる = displacement noise
- (ii) 測定に関する = sensor noise

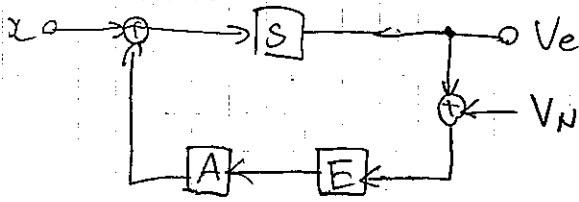
① 電圧ノイズの測定

② 光を止めて V_F を測る = V_N'

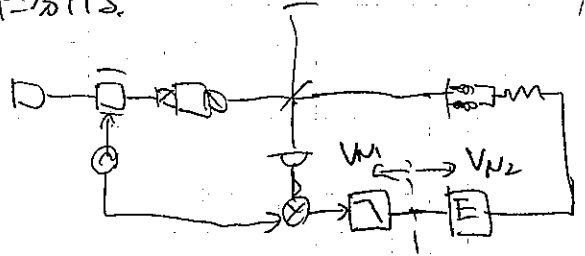
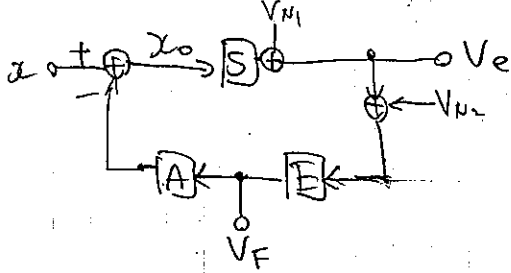
input equivalent noise: $V_N = \frac{V_N'}{E}$

↑
noiseは全部二本に押しこむ。

・ 2つの図中の noise



と書きたいが、この場合、 V_e は V_N の一部 (PDの noise とか) が含まれている。
 なので V_e の ~~部分~~ 前後に V_{N1} と V_{N2} を分ける。



今 $x = x_{sw}$ とし、 V_e と V_F の差を V_{N1} とする

① V_e の場合

$$\begin{cases} x_{sw} - (V_e + V_{N2})EA = x_0 = \\ V_e = Sx_0 + V_{N1} \end{cases} \Rightarrow x_0 = \frac{V_e - V_{N1}}{S}$$

$$\therefore x_{sw} - (V_e + V_{N2})EA = \frac{V_e - V_{N1}}{S}$$

$$\therefore Sx_{sw} - GV_e - GV_{N2} = V_e - V_{N1}$$

$$\therefore V_e = \frac{1}{1+G} (Sx_{sw} + V_{N1} - GV_{N2})$$

係数比 $x_{sw} : V_{e1} : V_{e2} = S : 1 : G$

← 計算はこれでも
 $\frac{1}{1+G}$ は
 与えられた

② V_F の場合

係数比 $x_{sw} : V_{e1} : V_{e2} = \frac{SE}{1+G} : \frac{E}{1+G} : \frac{E}{1+G} = S : 1 : 1$

③ S/N 比

S/N	V_e	V_F
signal/ V_{N1}	S	S
signal/ V_{N2}	S/G	S

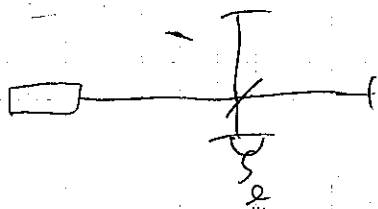
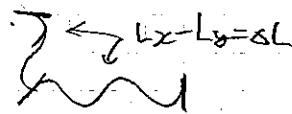
← V_F の方がよい

$$L_2 = L = \frac{c}{f}, \quad L_0 = L + \Delta L = \frac{c}{f(HM)} \text{ となる?}$$

$$\# \Rightarrow f + \Delta f \text{ となる? } \Delta L = \frac{c}{fM}$$

$$\begin{cases} L_2' = \frac{c}{f} (1 - \Delta f) = L (1 - \Delta f) \\ L_0' = \frac{c}{f} (1 - \Delta f) (1 + M) = (L + \Delta L) (1 - \Delta f) \end{cases}$$

$$\therefore \Delta L' \equiv L_2' - L_0' = -\frac{c}{f} \Delta f M = -\Delta L \Delta f$$



$$P \propto \sin \frac{2\pi \omega (l_1 - l_2)}{c} + \frac{1}{2}$$

$$\omega = \omega_0 + \delta\omega, \quad l = l_0 + \delta l \text{ となる? } \omega_0 = \frac{2\pi c}{\lambda_0}$$

$$\frac{\omega_0 + \delta\omega}{c} (l_0 + \delta l) = \frac{\omega_0 l_0}{c} + \frac{\omega_0}{c} (\delta l + l_0 \frac{\delta\omega}{\omega_0})$$

周波数雑音

× 同C長±に同じC A ⇒ D 2 粒子の同じ長±にC消滅

× 1波長おぼしいに



$$\Delta \lambda = \lambda \frac{\Delta \nu}{\nu} = \lambda \frac{\Delta \nu}{c/\lambda}$$

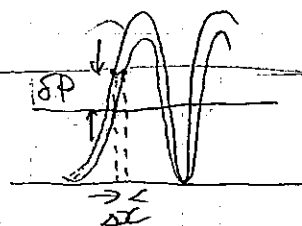
$$\therefore \frac{l_0}{\lambda} \times \Delta \lambda = l_0 \frac{\Delta \nu}{c} = \Delta \alpha$$

波の何れか

周波数雑音

② 強度雑音

$$P \approx P_0 \left[\sin \left(\frac{2\pi \omega (l_1 - l_2)}{c} \right) + \frac{1}{2} \right]$$



$$P_0 \Rightarrow P_0 + \delta P, \quad l_0 = l_0 + \delta l \text{ となる?}$$

$$P \rightarrow (P_0 + \delta P) \left\{ \sin \left[\frac{2\pi \omega (l_0 + \delta l)}{c} \right] + \frac{1}{2} \right\}$$

$$= (P_0 + \delta P) \left\{ \sin \left[\frac{2\pi \omega}{c} l_0 \right] + \cos \left[\frac{2\pi \omega}{c} l_0 \right] \frac{2\pi \omega}{c} \delta l_0 + \frac{1}{2} \right\}$$

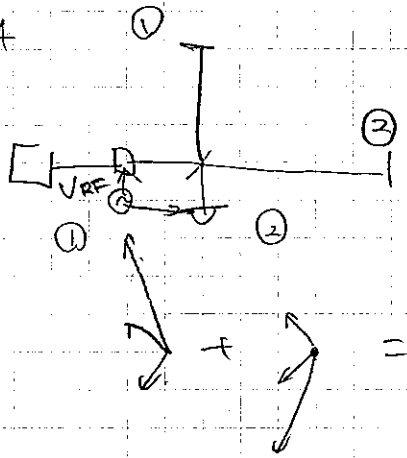
① A-1 の場合

$$P \rightarrow (P_0 + \delta P) \frac{\sqrt{2}}{2} \frac{2\pi \omega}{c} \delta l_0 \approx \frac{\sqrt{2}}{2} P_0 \frac{2\pi \omega}{c} \delta l_0$$

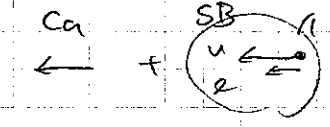
② ⇒ f の場合

$$P \rightarrow (P_0 + \delta P) \left(\frac{2\pi \omega}{c} \delta l_0 + \frac{1}{2} \right) = P_0 \frac{2\pi \omega}{c} \delta l_0 + \frac{1}{2} \delta P$$

$$= P_0 \frac{2\pi \omega}{c} \left(\delta l_0 + \frac{c}{2 \cdot 2\pi \omega} \frac{\delta P}{P_0} \right)$$



$$u = \frac{u}{l} + \frac{u}{l} = \frac{2u}{l}$$



強度が一倍になり二倍も倍 (C_a + SB 1.5倍)

$$S \propto \delta^2 I$$

$\delta^2 (I_0 + \delta I) \rightarrow$ 完全比 A=1 のときの雑音の二次

$$(\delta^2 + \Delta \delta^2)(I_0 + \delta I) = \delta^2 I_0 + \delta^2 I_0 + \Delta \delta^2 I_0 + \Delta \delta^2 I$$

完全比 A=1 のときの雑音 雑音

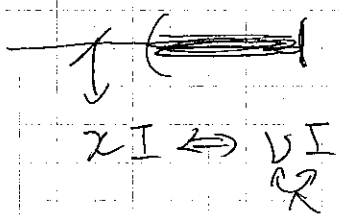
$$\begin{aligned} \therefore \delta^2 I_0 &= \Delta \delta^2 I \\ \therefore \delta^2 &= \frac{\Delta I}{I_0} \delta^2 \end{aligned}$$

※ もの言

$$S \propto \delta^2 I V_{RF}$$

と成るの V_{RF} の巾も強度巾も同じに成るから

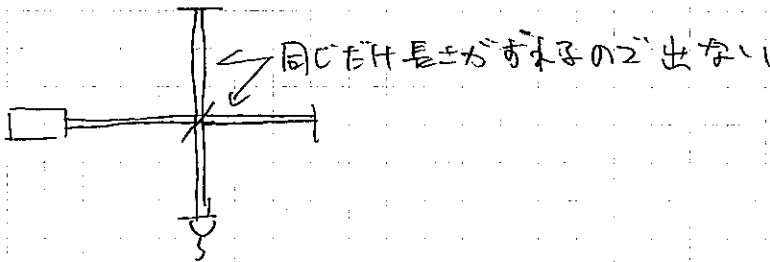
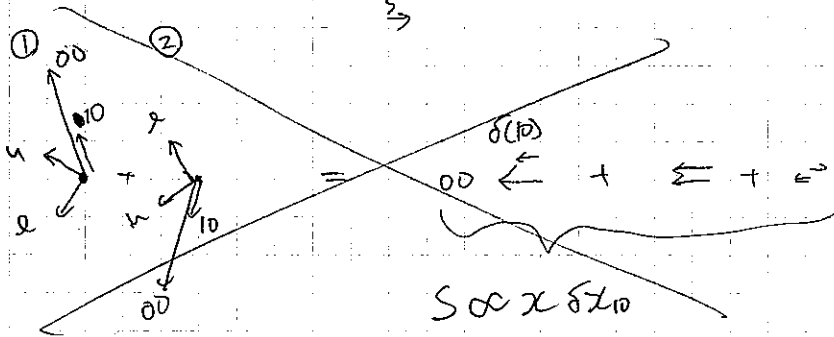
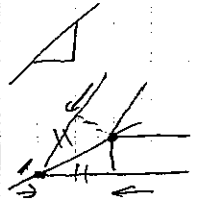
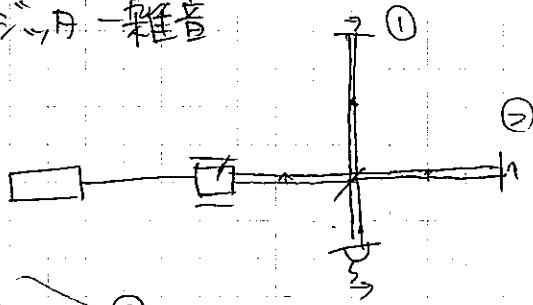
※ 共振器の場合



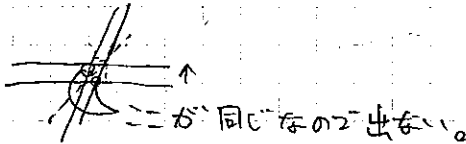
$$V = +I, I = -I_2 \text{ 成る}$$

+I, +I_2, +I, -I_2 のノイズが出る

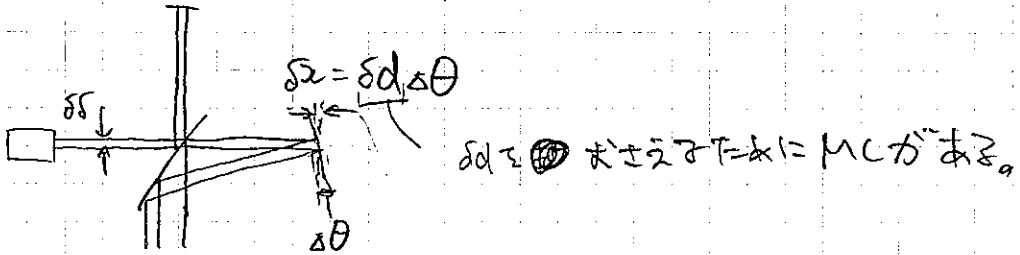
① 周波数雑音や強度雑音には 100 Hz 毎に 1 dB 減衰がある。この雑音が A のノイズポートに 100 Hz 毎に出る (H=100)



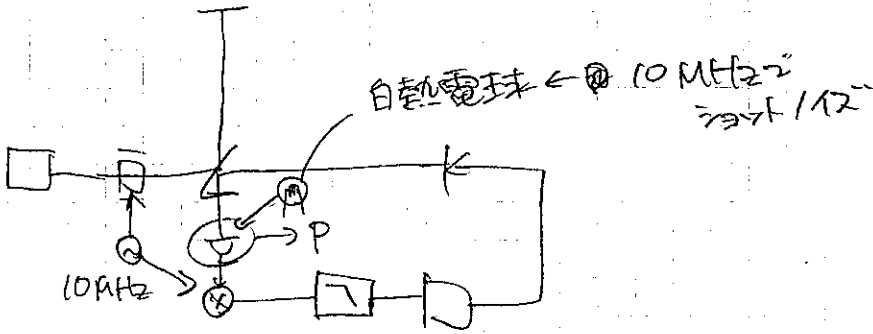
• BSが45°かると光子2つ出ない



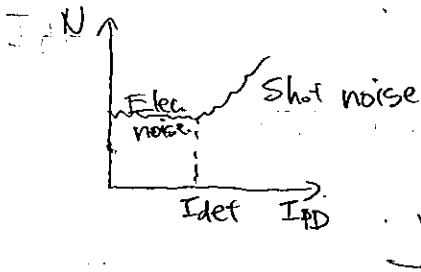
• EMが"か"をわいていって光子



① 20dB/12"



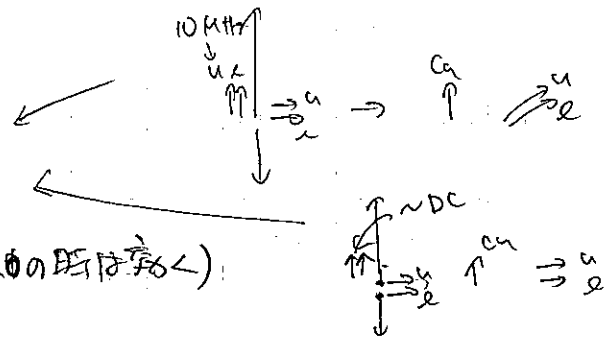
- 自熱電球を30dB/12"が増える時は、回路の設計が悪い。
- I_{def}

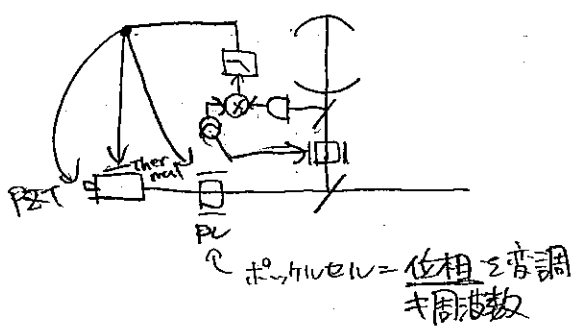
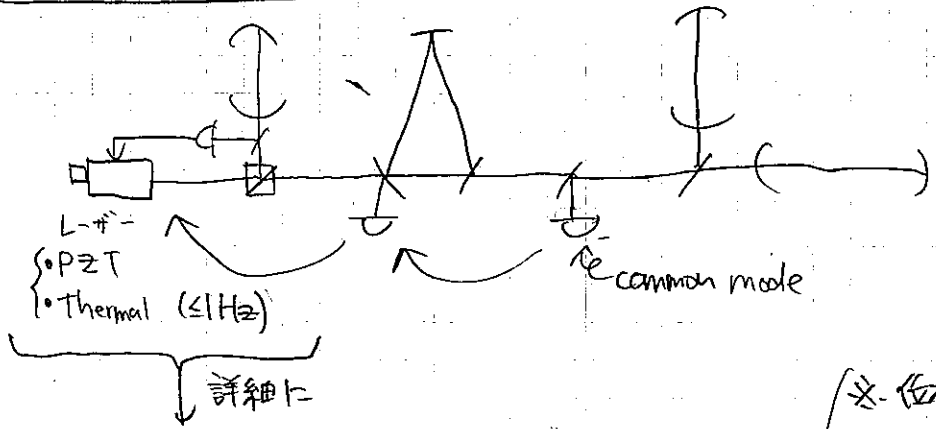


② 完全DC-DCでない子の影響

- RFの強度雑音は効く。
- DC " は効かない

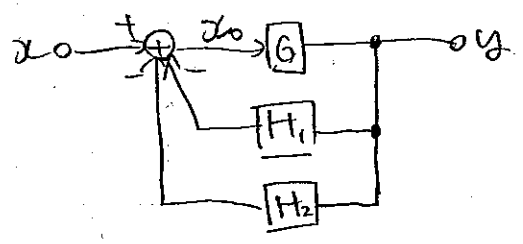
※ 1. ± 考慮した時は DC (← 2. の時は効く)





* 位相調整用共振波数
 $E = \sin \phi$
 φ = ωt + φ₀
 ∴ $\frac{d\phi}{dt} = \omega$ ∴ φ = ∫ ω dt
 $\phi(s) = \frac{1}{s} W(s)$
 ∴ $W(s) = s\phi(s)$

② 2つに返す制御



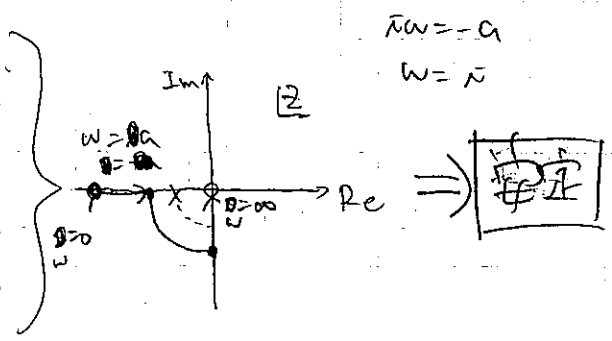
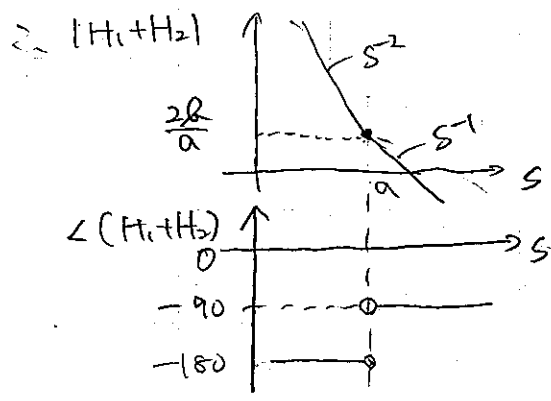
$$x_0 = x - G H_1 x_0 - G H_2 x_0 = x - G(H_1 + H_2)x_0$$

$$\therefore x_0 = \frac{1}{1 + G(H_1 + H_2)} x$$

∴ この制御はどのような時に安定か? (簡単な場合 G=1 とする)

1) $H_1 = \frac{aR}{s^2}$, $H_2 = \frac{R}{s}$ の場合

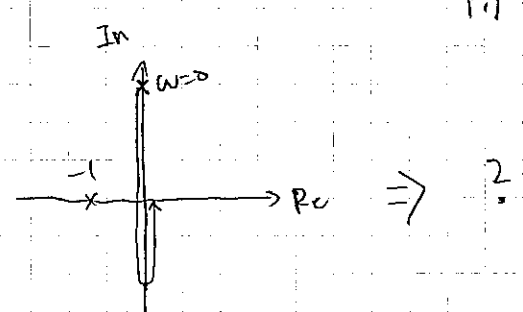
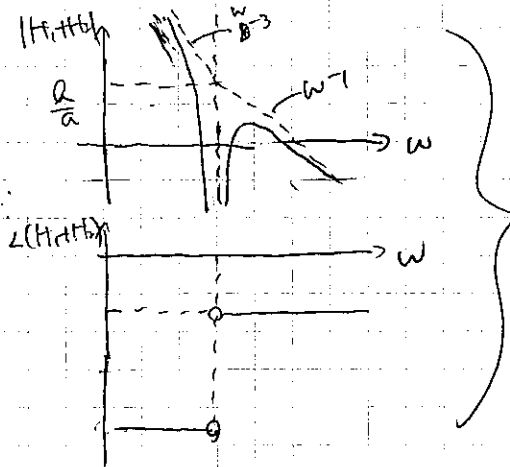
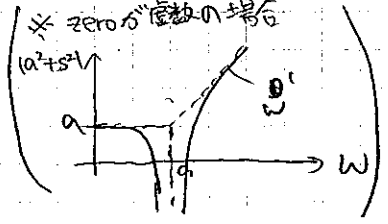
$$G(H_1 + H_2) = \frac{aR + sR}{s^2} \Rightarrow \text{pole} = 0, \text{zero} = -a$$



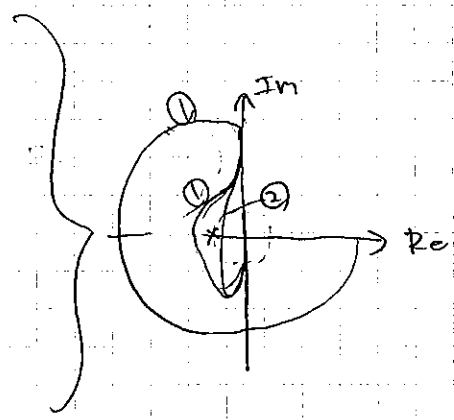
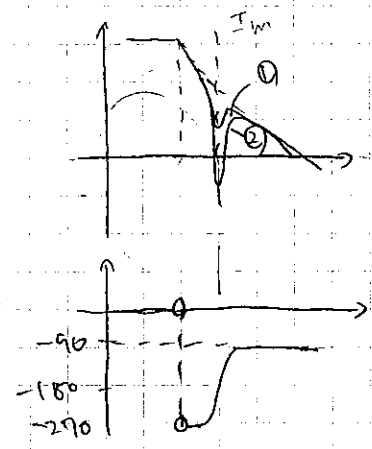
48

(i) $H_1 = \frac{a^2k}{s^3}$, $H_2 = \frac{k}{s}$ の場合

$H_1 \neq H_2 = \frac{a^2k + s^2k}{s^3} \rightarrow \text{pole} = 0, \text{zero} = \pm i\omega a$



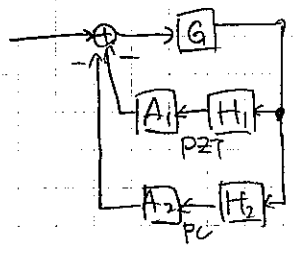
(ii) $H_1 = \frac{1}{s^3}$, $H_2 = \frac{k}{s}$ の場合



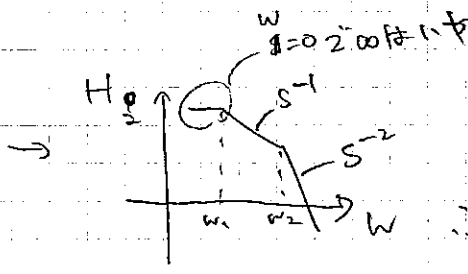
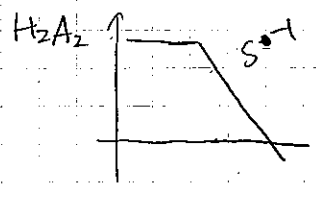
① 安定 $\Rightarrow R \rightarrow \infty$
 ② 不安定

\Rightarrow 加えることで32°位相差が90°になるようにするよ!

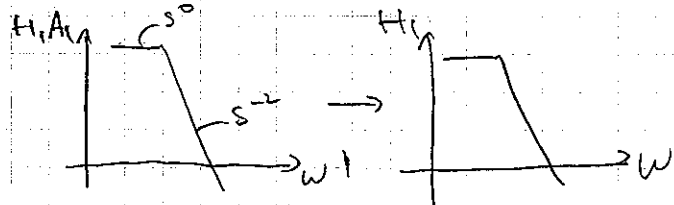
◎ 周波数安定化



$A_1 = \frac{1}{s}$
 $A_2 = \frac{1}{s}$

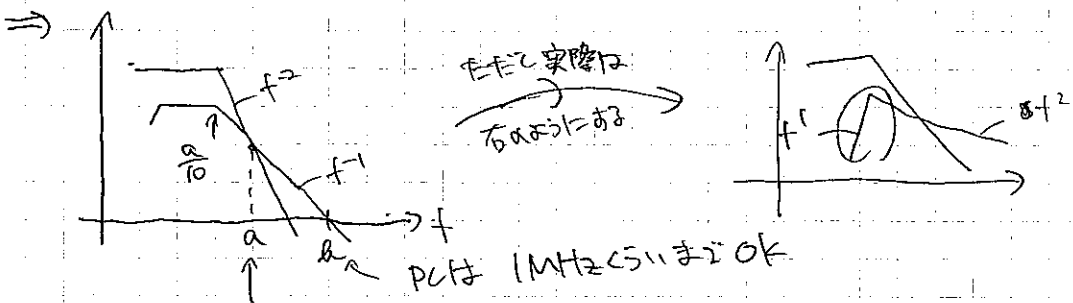


$H_0 = \frac{A_1}{(H \frac{s}{s_1})(H \frac{s}{s_2})}$
 $\therefore H_2 A_2 = \frac{AS}{(1 + \frac{s}{s_1})(1 + \frac{s}{s_2})}$

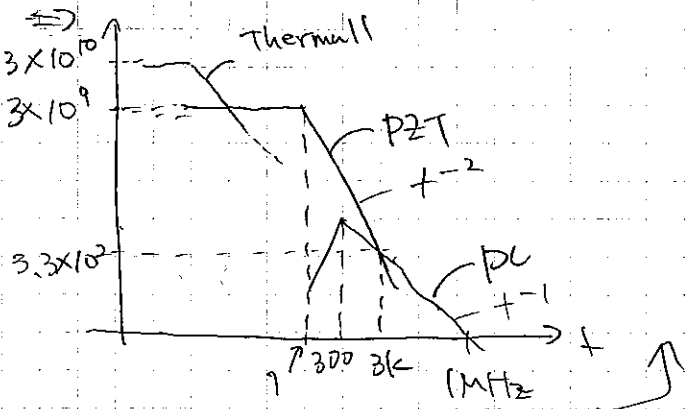


$$H_2 = \frac{1}{(1 + \frac{s}{s_1})^2}$$

$$\therefore H_1 A_1 = \frac{A_1}{(1 + \frac{s}{s_1})^2}$$



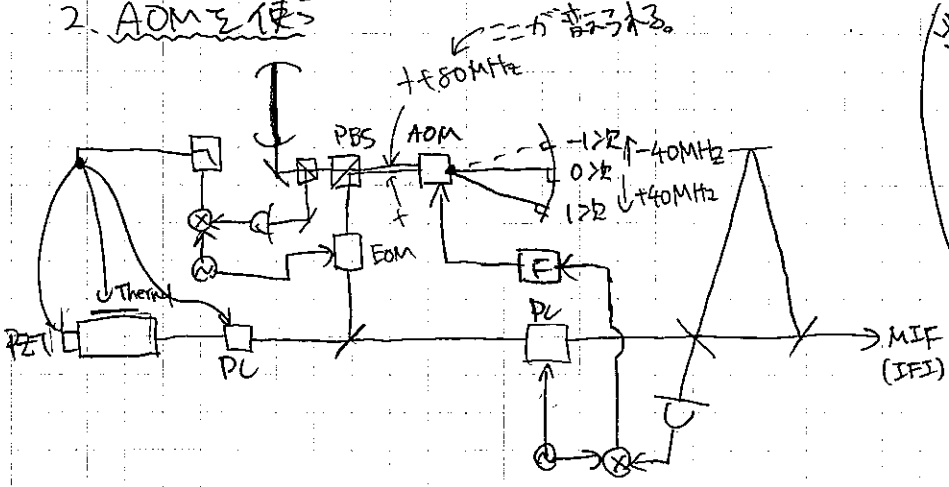
PCは 1MHz以下はOK
 PZTの共振が40kHzなので a ~ 1kHz以下はOK



◎ MCによる周波数安定化

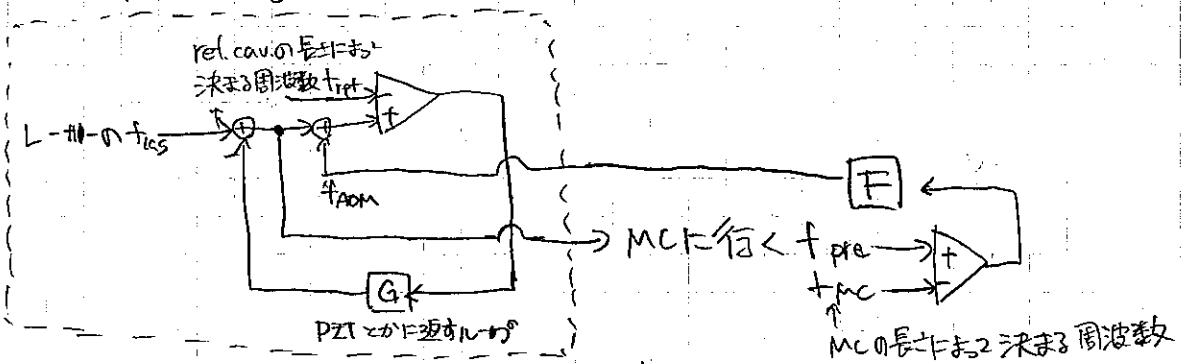
- MCの信号をどうに返すか?

1. ref. cav. の PZT。は支那はよくない。Q値が下がると ref. cav に PZT をつけたら
2. AOM を使う



* AOM: 進行波を一定波長より、2倍より2倍回折させる。
 AOMに5Vの電圧を印加する
 → AOMの周波数 f Hz
 $f \propto V$

① block diagram 2 説明



$$f_{pre} = f_{ias} - G [(f_{pre} + f_{ADM}) - f_{ret}]$$

$$\therefore f_{pre} = \frac{1}{1+G} [f_{ias} + G (f_{ret} - f_{ADM})]$$

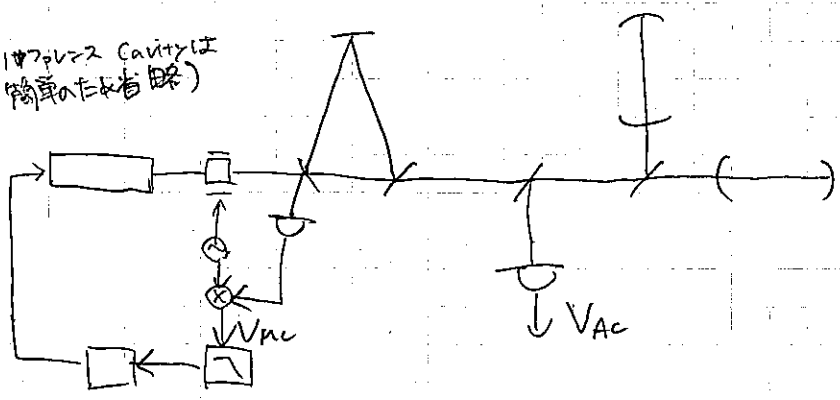
(G) \rightarrow $f_{ret} - f_{ADM}$

PC が 1MHz ほど
ADM は ~ 10kHz ほど
 \rightarrow $|G|$ は 100 ($|G| \gg 1$)
10kHz ほど

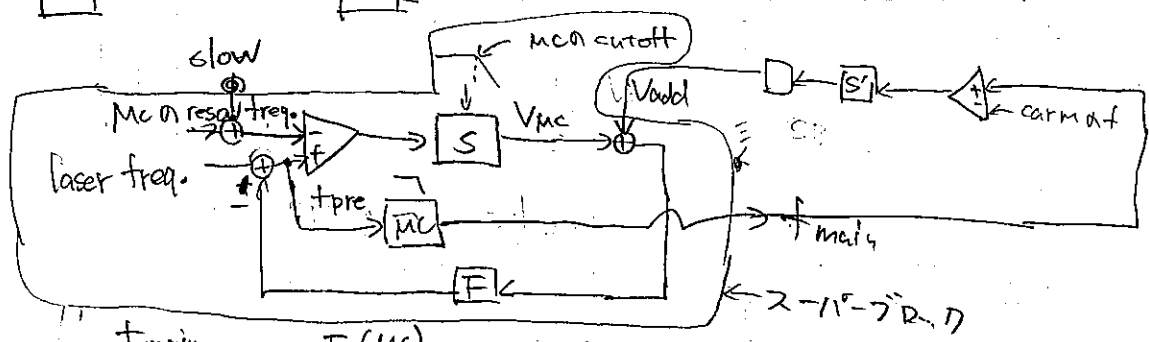
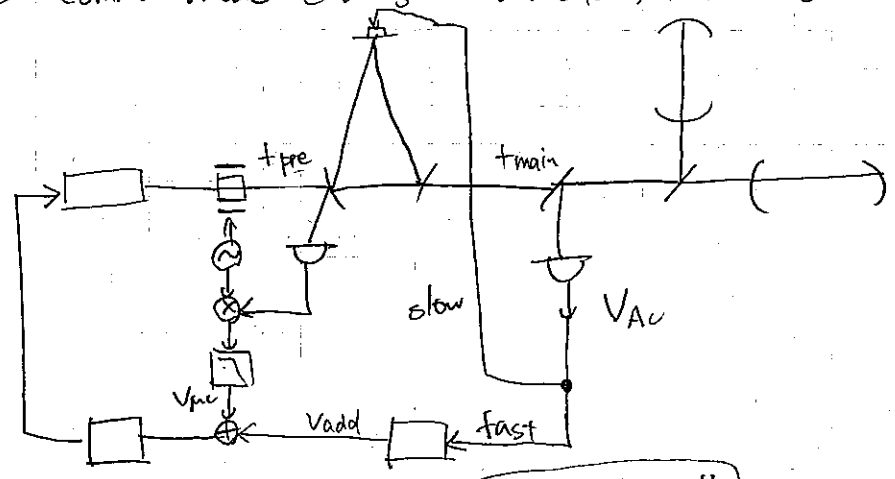
よって上の式をスルーして見ると

$$\frac{f_{pre}}{f_{ADM}} = \dots \rightarrow -1$$

(1) プレカビティは
簡単な共振器



@ common mode 2つのモードは安定化する



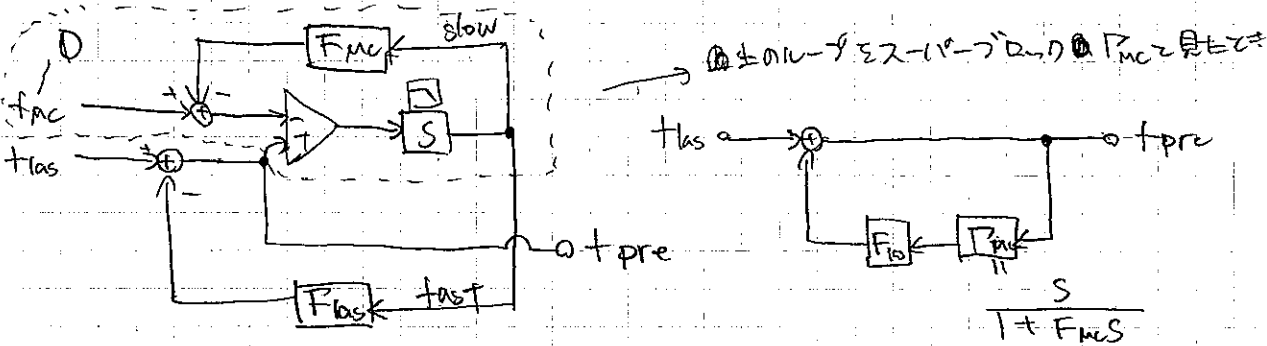
$$\frac{f_{main}}{V_{add}} = \frac{-F(MC)}{1+FS} \approx \frac{-MC}{S} \quad (FS \gg 1)$$

↑
flat

$$\text{slow } \frac{f_{main}}{V_{add}} = \frac{FS(MC)}{1+FS} \approx (MC)$$

(宿題) slowの方はMC cavity, poleが2つあるから安定しない。
何故か?

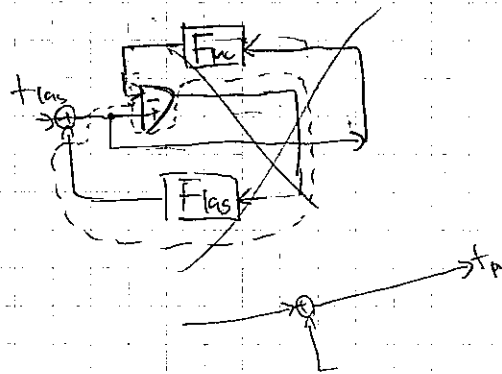
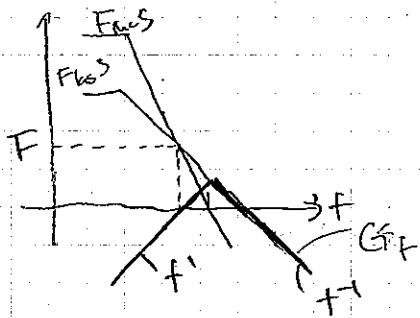
① fast & slow の 2つに区別する事は安定か。



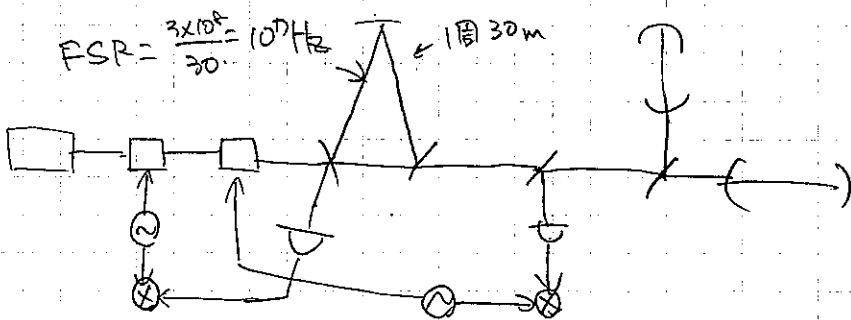
$$\frac{t_{pre}}{t_{fast}} = \frac{1}{1 + F_{fast} P_{mc}} \approx \frac{1}{1 + G_+} \quad \therefore G_+ =$$

$$\therefore G_+ = F_{fast} P_{mc} = \frac{S F_{fast}}{1 + F_{fast} S} = \begin{cases} S F_{fast} & (|F_{fast} S| \ll 1) \\ \frac{F_{fast}}{F_{mc}} & (|F_{fast} S| \gg 1) \end{cases}$$

1は抽象的に書く右の上のものは安定に制御するには下のよすにすることがある



②



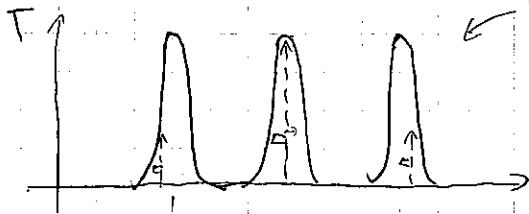
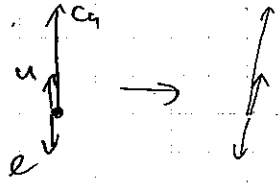
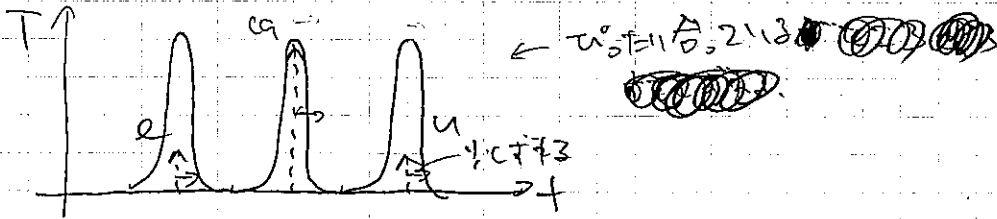
$FSR = \frac{3 \times 10^8}{30} = 10^7 \text{ Hz}$

$t_m = m \times 10^7 \text{ Hz}$ とすることがある。

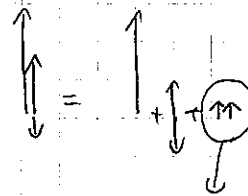
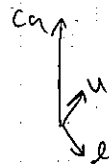
問題

- ① MC rock用の音調周波数は $10^7 \text{ Hz} = 10 \text{ MHz}$ と決まり、関係的に (9.18 MHz) とすることがある。

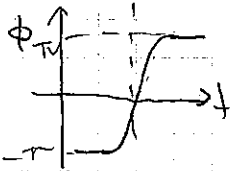
② M_c の長さを $\sim 1\text{mm}$ 程度の精度で合わせることができない



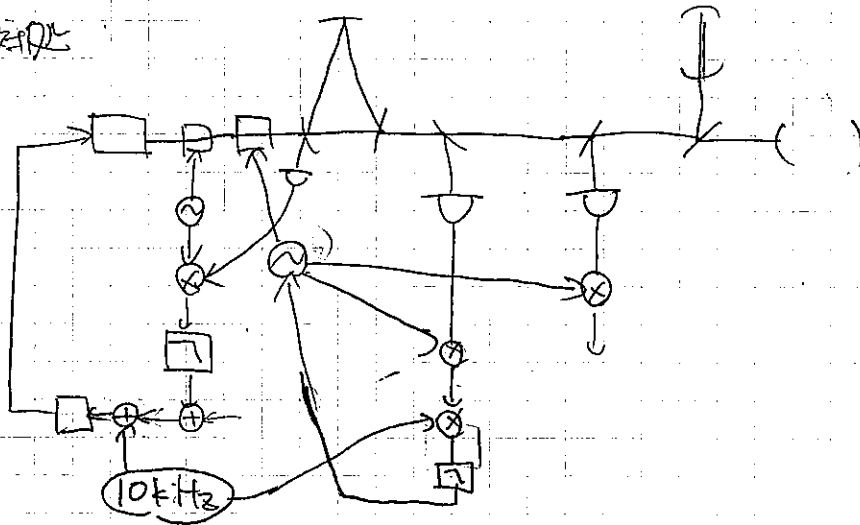
FSR = 波長が少くばあはると



これによる
周波数雑音の
出さず(注)



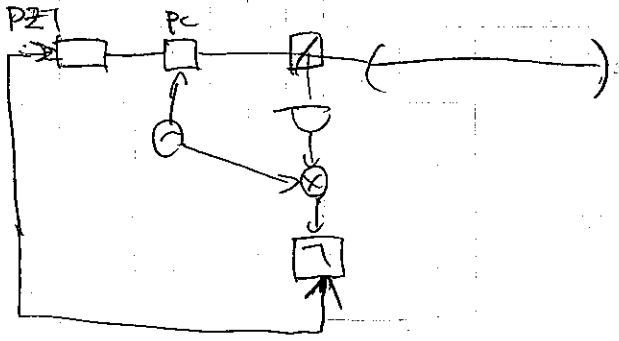
雑音



10kHzの周波数雑音を励起

これにより雑音を手で入れ制御することはよくやろ。

例は雑音

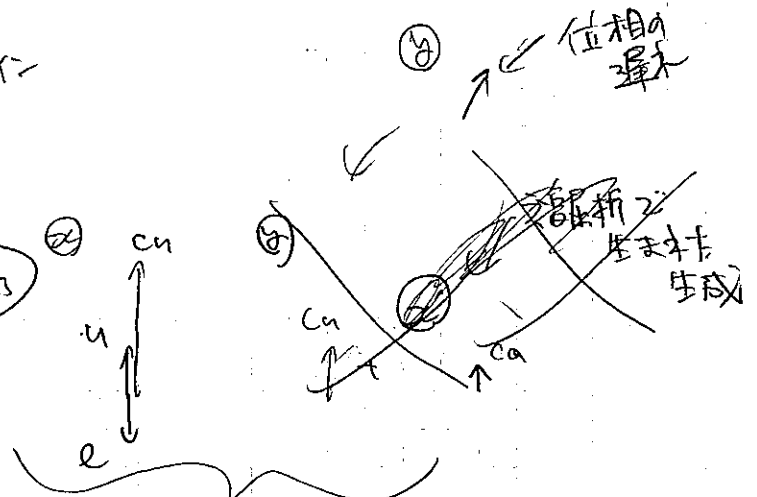
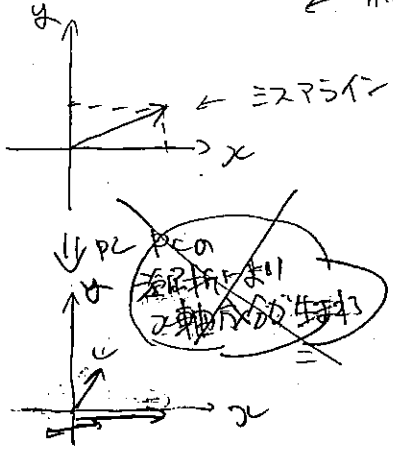


強度雑音は完全にガリになる。こゝ (= オフセット) とかが、光に出てる

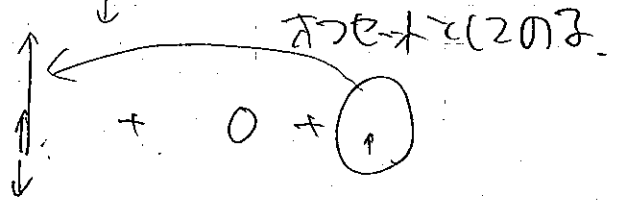
・オフセットの原因

PCのミズサイン

cavityが ω_0 を ω に
 近づけると
 ← ポラリザビルの結晶の軸



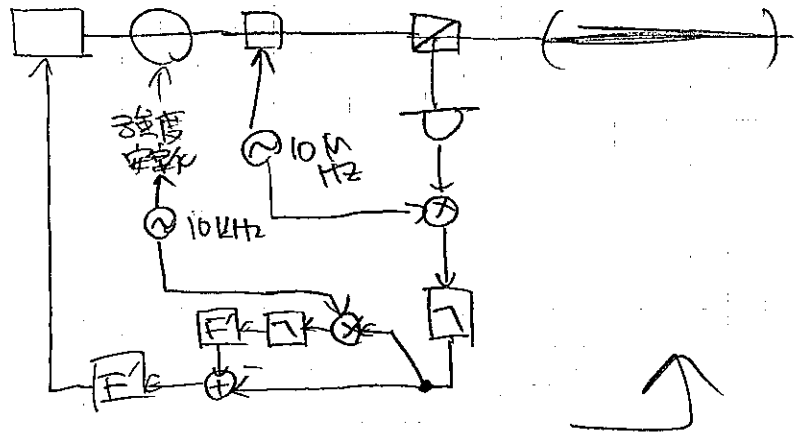
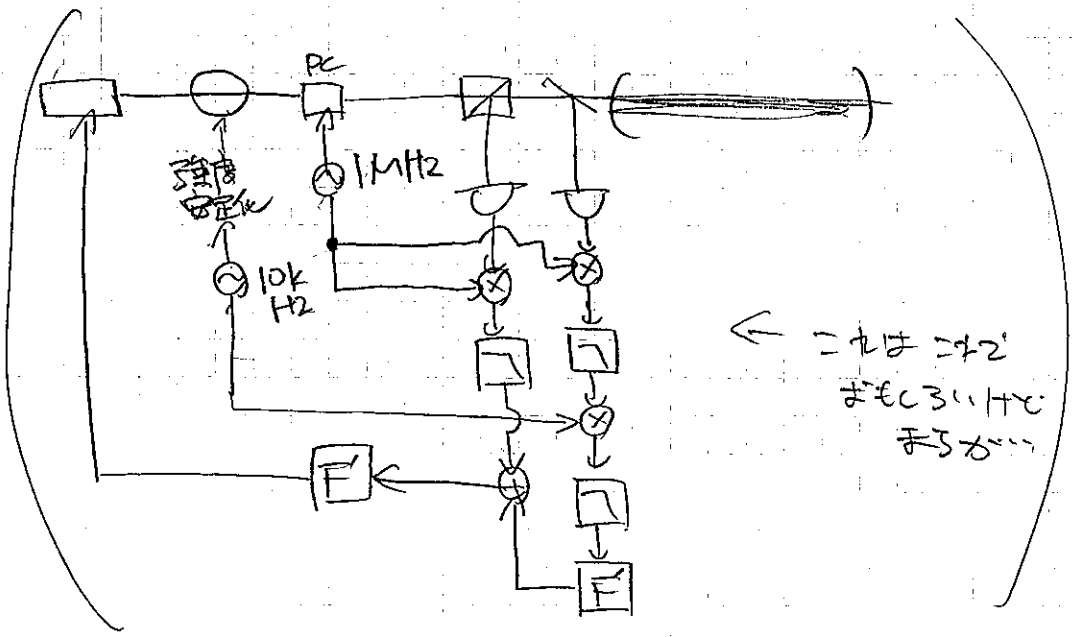
これはPBSでx軸からy軸成分を取り出す



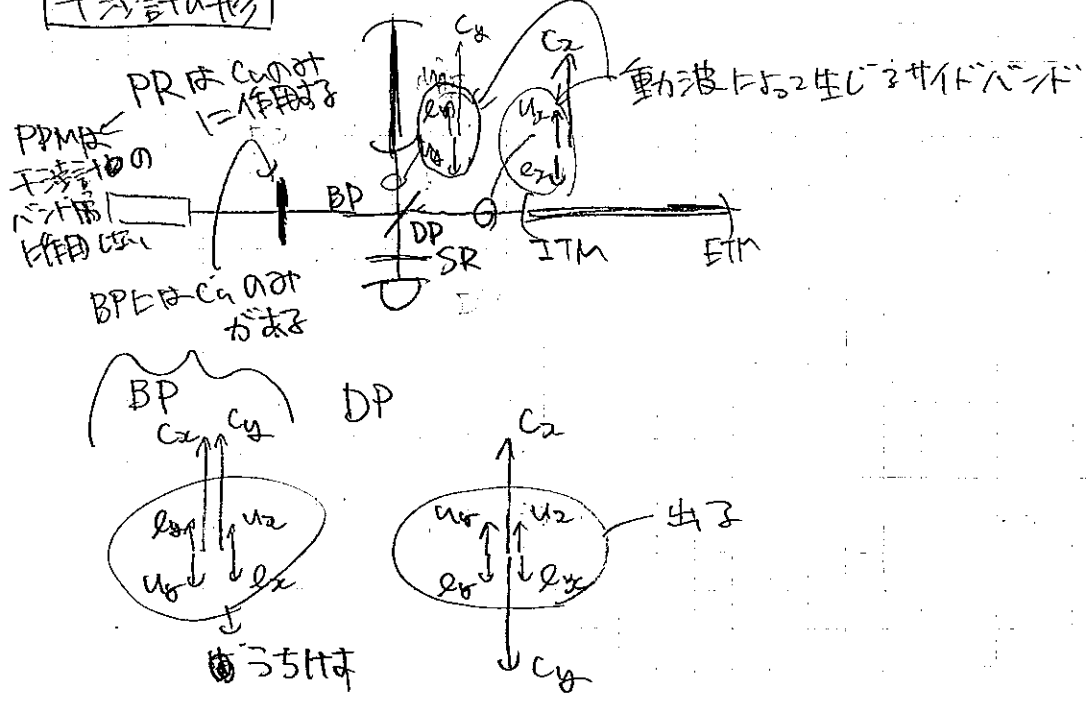
→ 強度のオフセットを削りたい

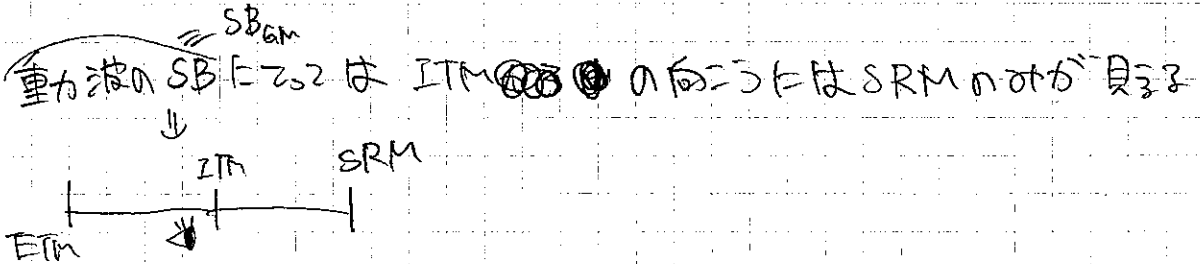
→ ~~雑音~~ 手で強度雑音を入れた方がいい

MCの場合には周波数~~雑音~~ ^{オフセット} だったのを
 周波数ループに入っていた



干渉計の形

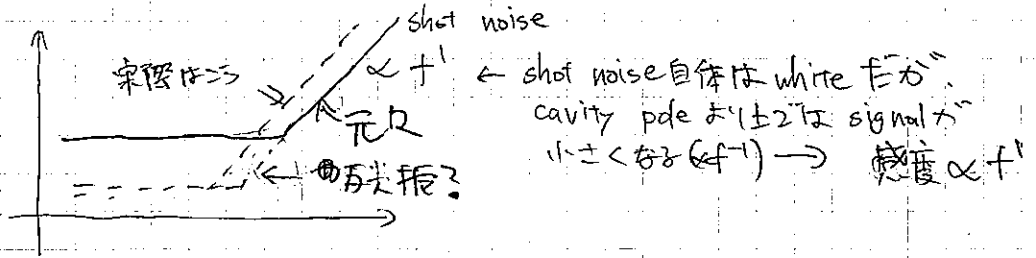




- 最初の ~~①~~ SR = ITM と ETM の間にも ~~②~~ 共振させたい
 - ITM + SRM の ~~③~~ 複合鏡の反射率を ITM 単独より大きくしたい
 - ITM + SRM を SB_{GW} に対して共振させたい

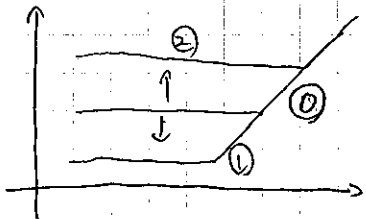
共振の位相差 $\Rightarrow \phi = 2\pi(m + \frac{1}{2})$

→ 感度が低周波ではよくなり、高周波では悪くなる



共振にするにはどうなるか

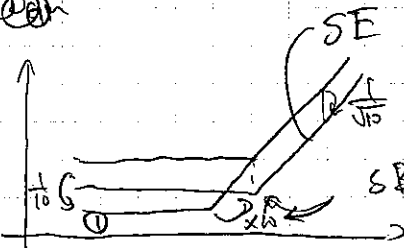
まず SRM を ~~④~~ ITM の反射率を上げると ①, 下げると ②



($\times 10$) ($\times \frac{1}{10}$)
↑ ↓
① ②

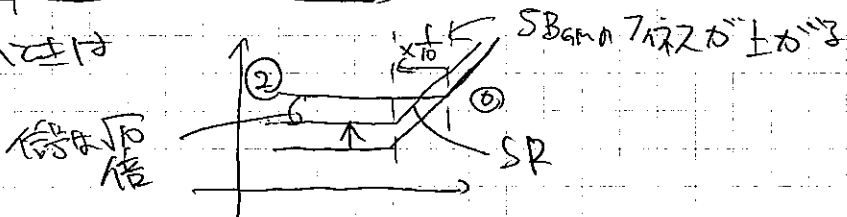
↑ 共振がよくなる

- ①の共振が SRM (SEM) を SB_{GW} に対して共振に近づける
 - Cavity 内の power は ② の 10 倍 → 電場は $\sqrt{10}$ 倍
 - 重力波信号も $\sqrt{10}$ 倍



SB_{GW} の 7/12 補償は元にも $\propto f^{-2}$ である

* SRM の変化

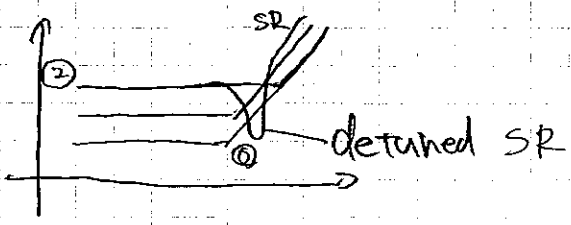


SRが良いわけではないか？

→ detune が子でよいことがあ子

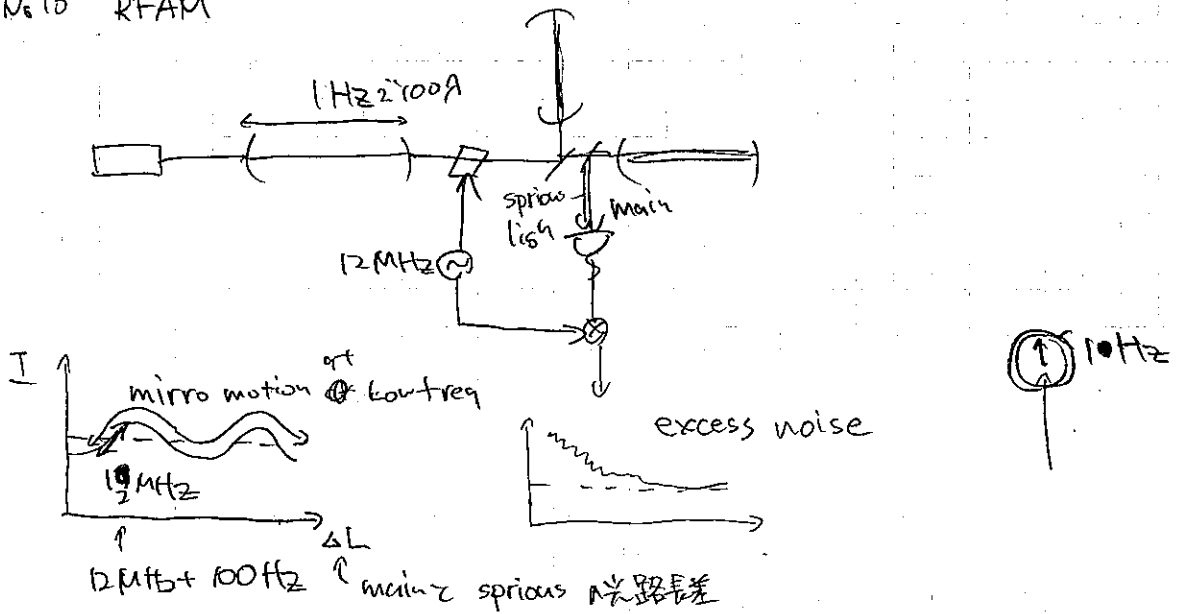
detune が子前は SBam の DC 成分 = 雑音の共振

→ detune ~~が子~~ の例は |k| に雑音の共振による



#

No. 10 RFAM

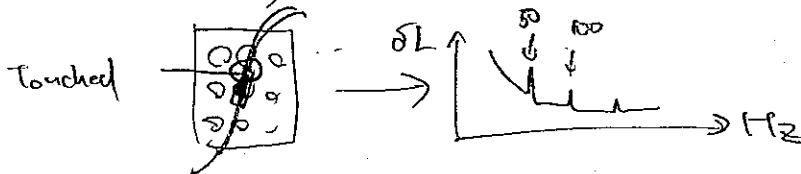


No. 9 coil ground loop duet coil driver connection

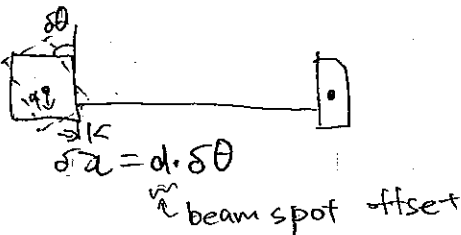
coil driver



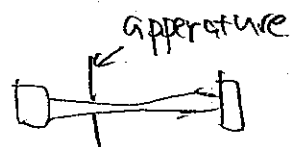
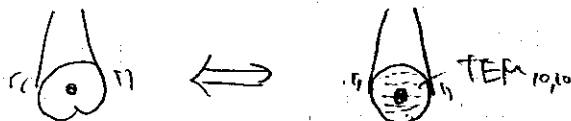
This ground should not be shorted to other ground.



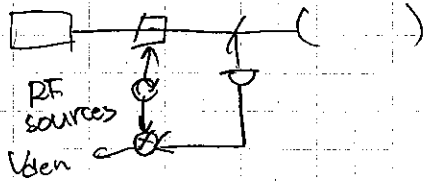
No. 8 Orientation noise



No. 11 Higher order mod flaring

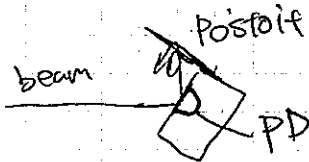


Higher order mode flaring makes burst-type noise
Corrected with angle stability of the mirror



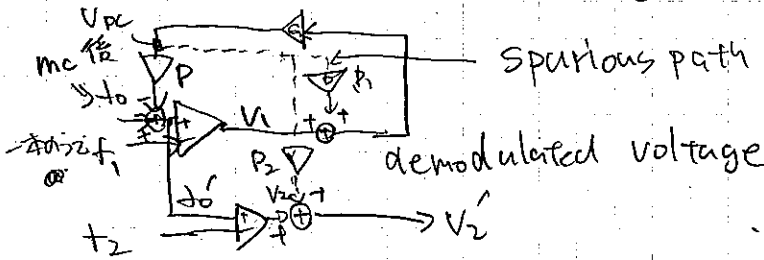
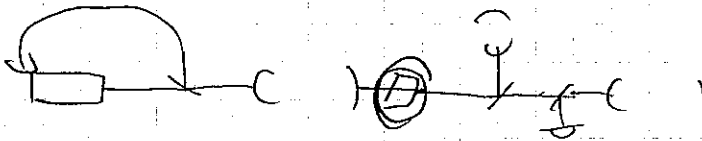
Vden is RF source $\approx 1/2$ is the ratio

No. 5 posit noise



No. 4 DC misalignment effect

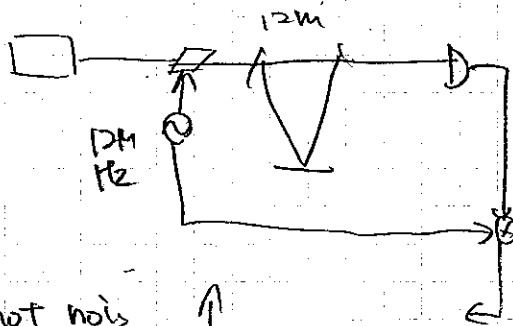
- ① 用波致雑音 (noise due to wave)
- ② ボットノイズに比べて DC 雑音の割合



$$\frac{V_{p2}}{V_1} = \frac{G_1}{1 - G_1} \rightarrow \frac{1}{D_1}$$

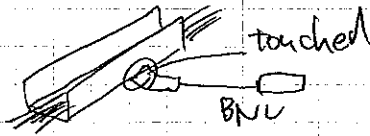
$$\frac{f_{o'}}{f_o} = \frac{1}{1 - \frac{G_1 D_1}{1 - G_1}} \rightarrow \text{gain } \frac{1}{1 - G_1 D_1}$$

No. 3 Mode cleaner transmitted light due to PC misalignment



shot noise limit? +

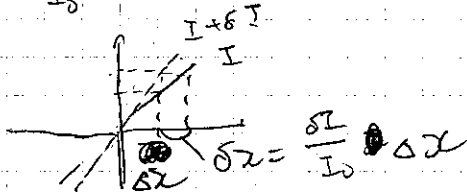
No.2. Cable Tray - BNC cable tray



No.1 Intensity - frequency down conversion noise

Intensity noise

$$\delta\lambda = \frac{\delta I}{I_0} \Delta\lambda$$

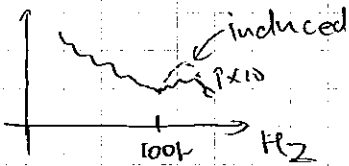


$$\delta\lambda = \frac{\delta I}{I_0} \Delta\lambda$$

↓ generalized ($\delta\lambda \rightarrow$ Frequency noise)

$$\delta\lambda = \alpha I \otimes F$$

Intensity noise



Frequency noise

