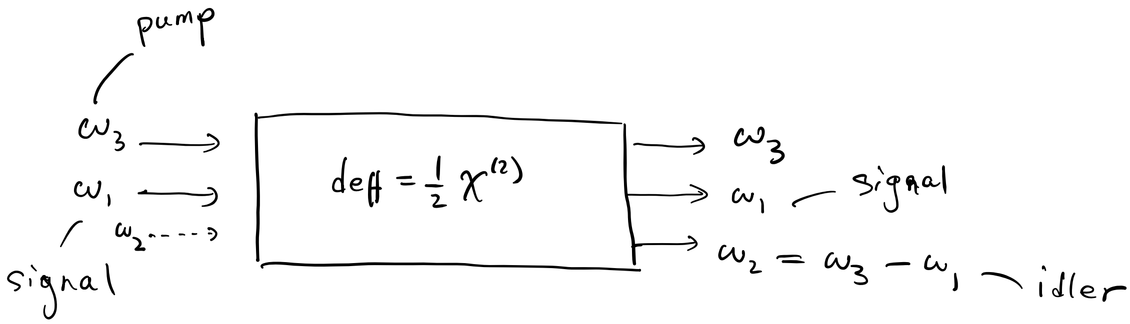
Lecture 7. Optical Parametric Oscillator (OPO)

① Recap of OPA

② OPO
- Doubly resonant OPO (DRO)
- Singly resonant OPO (SRO)

③ Frequency tuning of OPO

1. Review of OPA



$\Delta k = k_3 - k_1 - k_2$

CAEs :
$$\begin{cases} \dfrac{dA_1}{dz} = \dfrac{2i\omega_1^2 d_{eff}}{k_1 c^2} A_3 A_2^* e^{i\Delta k z} \\[2ex] \dfrac{dA_2}{dz} = \dfrac{2i\omega_2^2 d_{eff}}{k_2 c^2} A_3 A_1^* e^{i\Delta k z} \end{cases}$$

Generic solution:

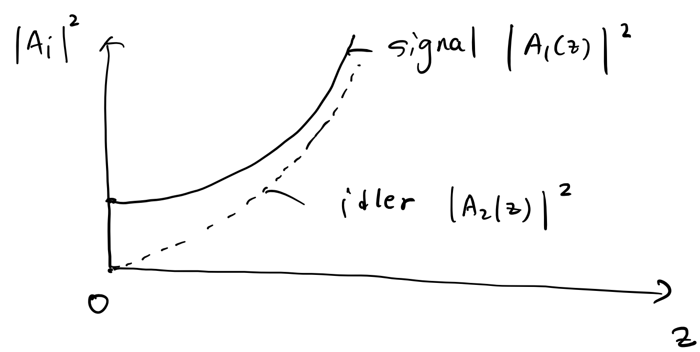
$$\begin{cases} A_1(z) = \left[A_1(0)\left(\cosh gz - \dfrac{i\Delta k}{2g}\sinh gz\right) + \dfrac{\kappa_2}{g} A_2^*(0)\sinh gz\right] e^{\frac{i\Delta k z}{2}} \\[2ex] A_2(z) = \left[A_2(0)\left(\cosh gz - \dfrac{i\Delta k}{2g}\sinh gz\right) + \dfrac{\kappa_2}{g} A_1^*(0)\sinh gz\right] e^{\frac{i\Delta k}{2}} \end{cases}$$

where $g = \sqrt{\kappa_1 \kappa_2^* - \left(\frac{\Delta k}{2}\right)}$. $\quad \kappa_i = \dfrac{2i\omega_i^2 d_{eff} A_3}{k_i c^2}$

Boundary conditions:

① Non-degenerate OPA, $A_2(0) = 0$ (no idler input) if $\Delta k = 0$

$$\begin{cases} A_1(z) = A_1(0)\cosh gz = \frac{1}{2} A_1(0)\exp(gz) \\ A_2(z) = i\left(\frac{n_1\omega_2}{n_2\omega_1}\right)^{1/2} \cdot \frac{A_3}{|A_3|} \cdot A_1^*(0)\sinh gz \sim A_1^*(0)\exp(gz) \end{cases}$$



② Degenerate OPA: signal & idler are indistinguishable

$$A_1(0) = A_{10} e^{i\phi_{10}} \neq 0$$

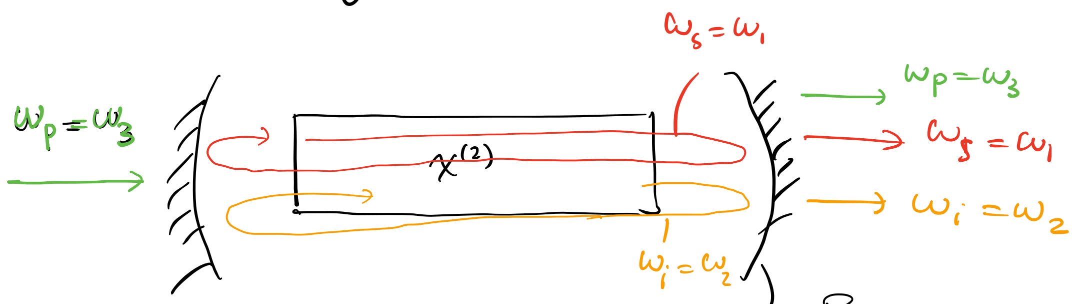
$$\Rightarrow A_2(z) = A_{10} e^{i\phi_{10}} \Big[\underbrace{\cosh(gz) + e^{i(\phi_{20} - 2\phi_{10} + \frac{\pi}{2})}}_{\text{phase-sensitive}} \sinh(gz) \Big]$$

2. Optical Parametric oscillator (OPO)

Lasers
- ① Pump → population inversion
- ② laser gain
- ③ laser cavity.

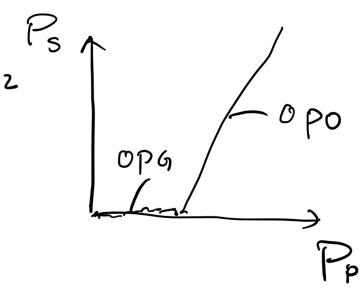
OPO
- ① pump → virtual levels
- ② Parametric gain
- ③ cavity

Problem to study:



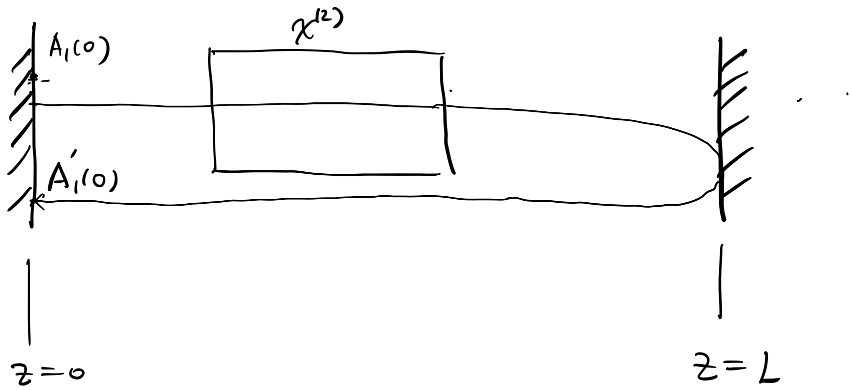
R_1 R_2 R_1 R_2

(different reflectivity to ω_1, ω_2)



① What's the threshold of an OPO?

② What's the difference between OPO and laser?



General threshold condition ($\Delta k = 0$)

$$\boxed{\text{round trip gain} = \text{round trip loss}}$$

Or $\quad A_1(0) = A_1(0)'$

$\quad\quad A_2(0) = A_2(0)'$

$$l_1 = 1 - R_1 e^{-\alpha_1 L}$$

$$\Rightarrow \underline{A_1(0)} = \left[A_1(0)\cosh gL + \frac{\kappa_1}{g} A_2^*(0)\sinh gL\right](1 - l_1) \quad ①$$

$$A_2^*(0) = \left[A_2^*(0)\cosh gL + \frac{\kappa_2^*}{g} A_1(0)\sinh gL\right](1 - l_2) \quad ②$$

$$l_2 = 1 - R_2 e^{-\alpha_2 L}$$

l_1. l_2. are "fractional" amplitude loss per pass

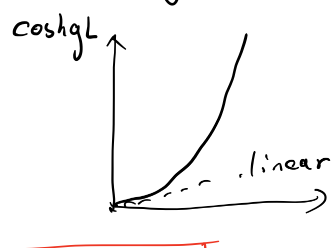
α_i is the absorption coefficient of the crystal at ω_i

Let ① and ② both satisfy.

$$\Rightarrow \boxed{\cosh gL = 1 + \frac{l_1 l_2}{2 - l_1 - l_2}}$$

① Doubly-resonant OPO (DRO):

both ω_s and ω_i are resonating in the cavity.



$\Rightarrow l_1 \ll 1, \quad l_2 \ll 1$

$$\cosh gL \simeq 1 + \frac{1}{2} g^2 L^2 = 1 + \frac{l_1 l_2}{2 - l_1 - l_2}$$

$$\Rightarrow \boxed{g^2 L^2 = l_1 l_2 = (1 - R_1 e^{-2\alpha_1 L})(1 - R_2 e^{-2\alpha_2 L})}$$

② Singly resonant OPO (SRO)

Only signal is resonating, no feedback for idler, i.e. $\underline{l_2 = 1}$

$$\cosh gL = 1 + \frac{l_1}{1 - l_1} \simeq \frac{1}{1 - l_1}$$

Assume $l_1 \ll 1$.

$$1 + \frac{1}{2} g^2 L^2 \simeq 1 + \frac{l_1}{1 - l_1} \quad 1 - l_1 \to 1$$

$$\boxed{g^2 L^2 = 2 l_1 = 2 \cdot (1 - R_1 e^{-2\alpha_1 L})}$$

Comments:

① Threshold value of gL for a SRO is larger than that of DRO by a factor of $\sqrt{\frac{2}{\ell_2}}$ → loss of idler in DRO

② There increase in threshold pumping intensity of the SRO to DRO is

$$\left[\frac{(g_t L)_{SRO}}{(g_t L)_{DRO}}\right]^2 = \frac{2}{\ell_2}$$

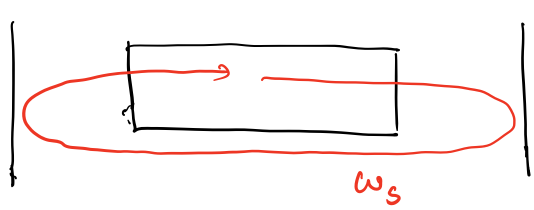
Example:

KTP: $L = 10\,mm$, $d_{eff} = 3\,pm/V$, $n_p = n_s = n_i = 1.5$

pump: $1064\,nm$, $W_0 = 20\,\mu m$, signal $\sim 2.12\,\mu m$.

idler: $2.14\,\mu m$.

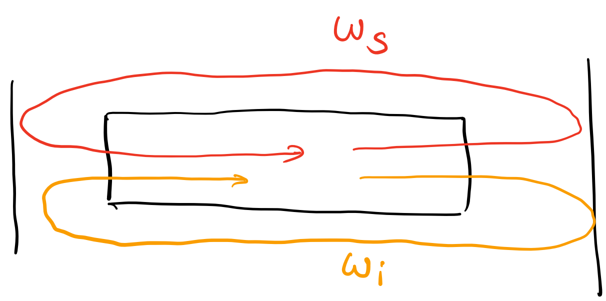
SRO:



$\alpha_s = 2\%$.

$$(P_{th})_{SRO} = 14.4\,W\ !$$

DRO:



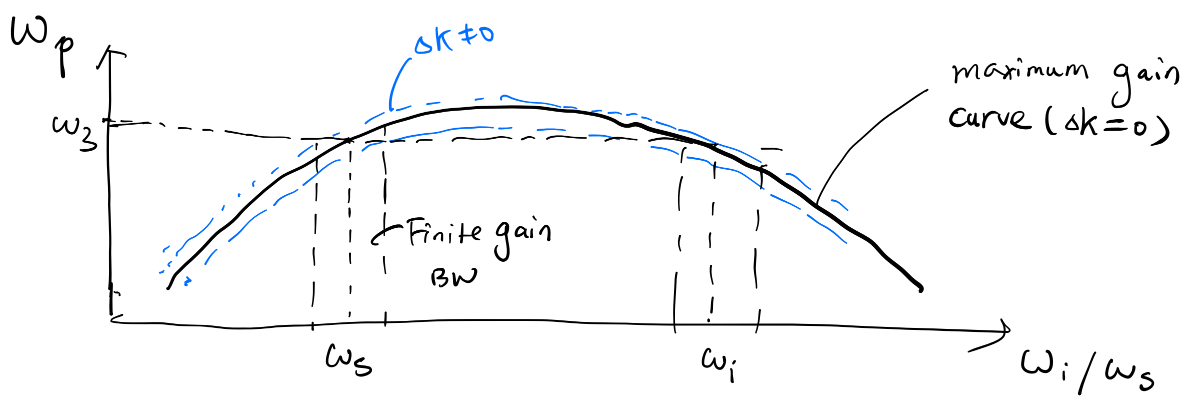
$(\alpha_s = 2\%,\ \alpha_i = 2\%)$

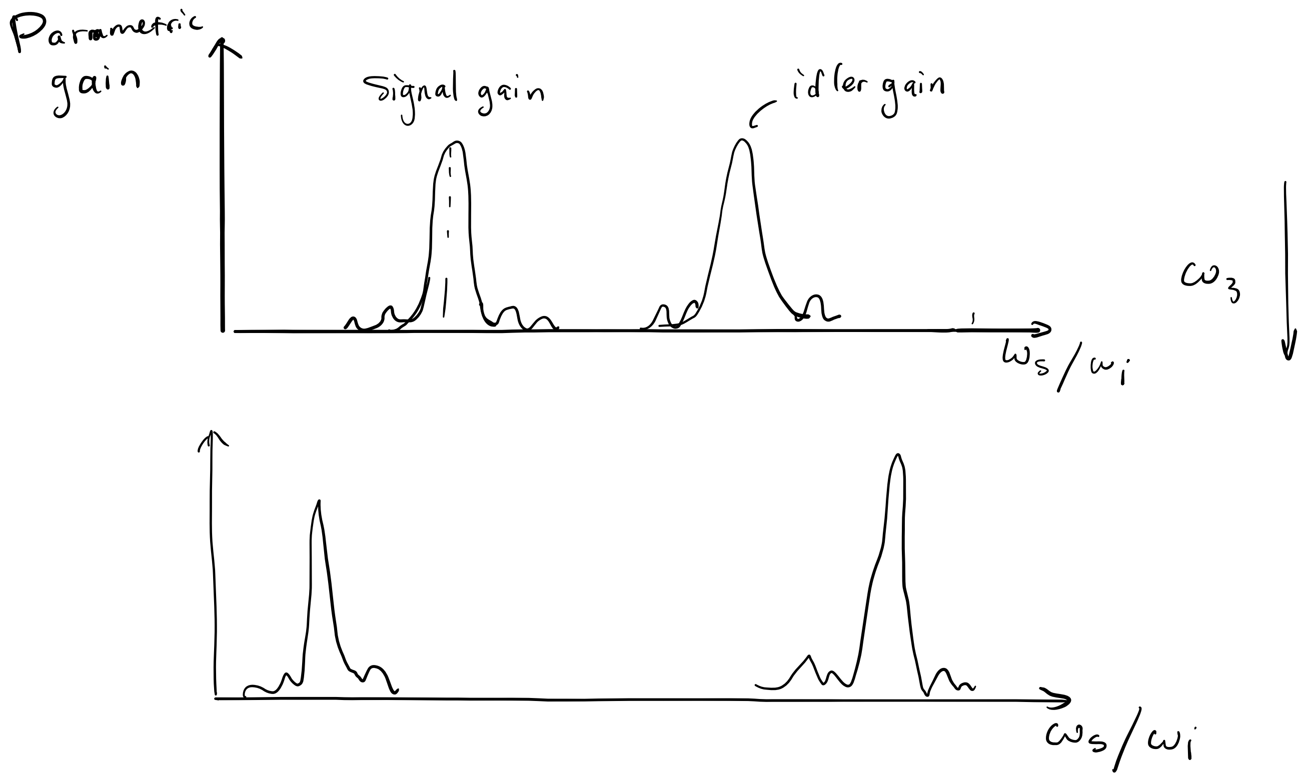
$$(P_{th})_{DRO} = 72 \text{ mW !}$$

3. Frequency tuning of OPO

$$\omega_1 + \omega_2 = \omega_3 \longrightarrow \text{energy conservation}$$

$$n_1\omega_1 + n_2\omega_2 = n_3\omega_3 \longrightarrow \text{momentum conservation}$$





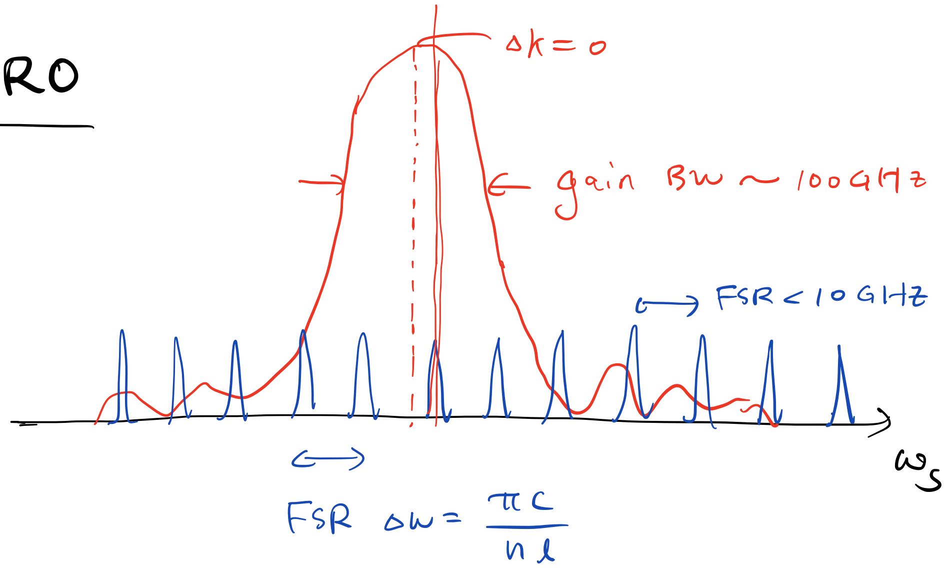
Comments:

① Lasers has a fixed gain spectrum.

② OPO has a tunable gain spectrum.
by varying the phase matching condition

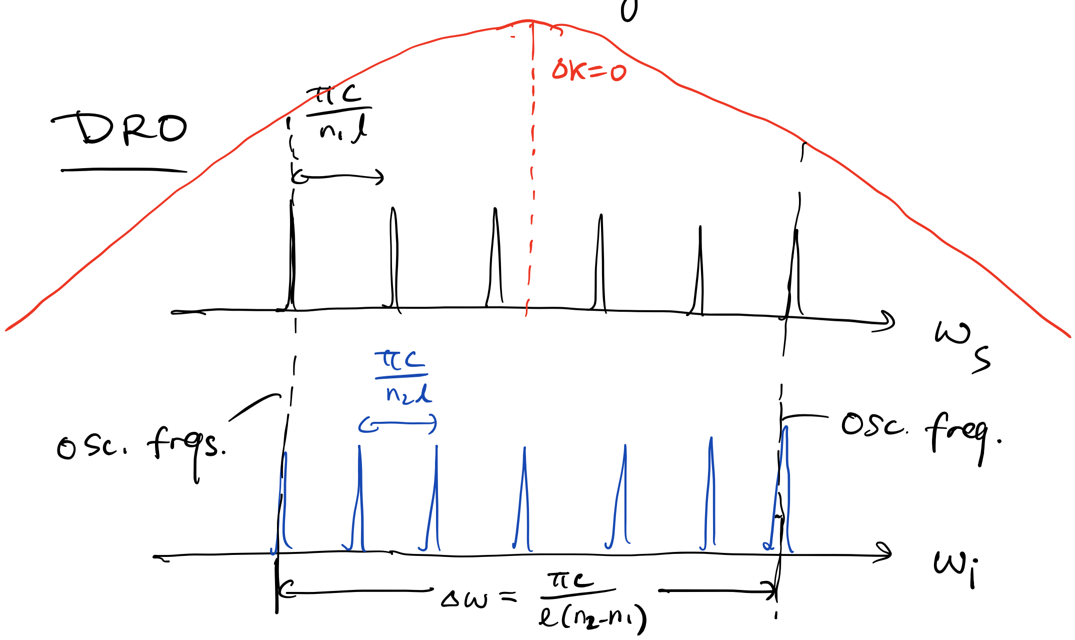
③ Reason: lasers have real energy levels
OPOs have virtual levels.

SRO



If we tune the ω_3, or phase matching condition. we can tune the oscillation frequency of the opo. the resolution can be as high as the FSR.

DRO



① For, DRO, oscillation occurs when ω_s and its corresponding ω_i can both oscillate.

② The oscillation freq. can be far from the peak gain frequency.

③ Due to these constrains, DRO cannot be tuned continously.

④ Not stable. $\Delta\omega = \dfrac{\pi c / l}{n_2 - n_1}$ $\quad n_2 - n_1 \sim 10^{-2} \sim 10^{-1}$

A small variation of cavity length, can induce a large $\Delta\omega$.

Summary:

① SRO: high threshold, smooth tuning, high stability

② DRO: low threshold, unsmmooth tuning, low stability