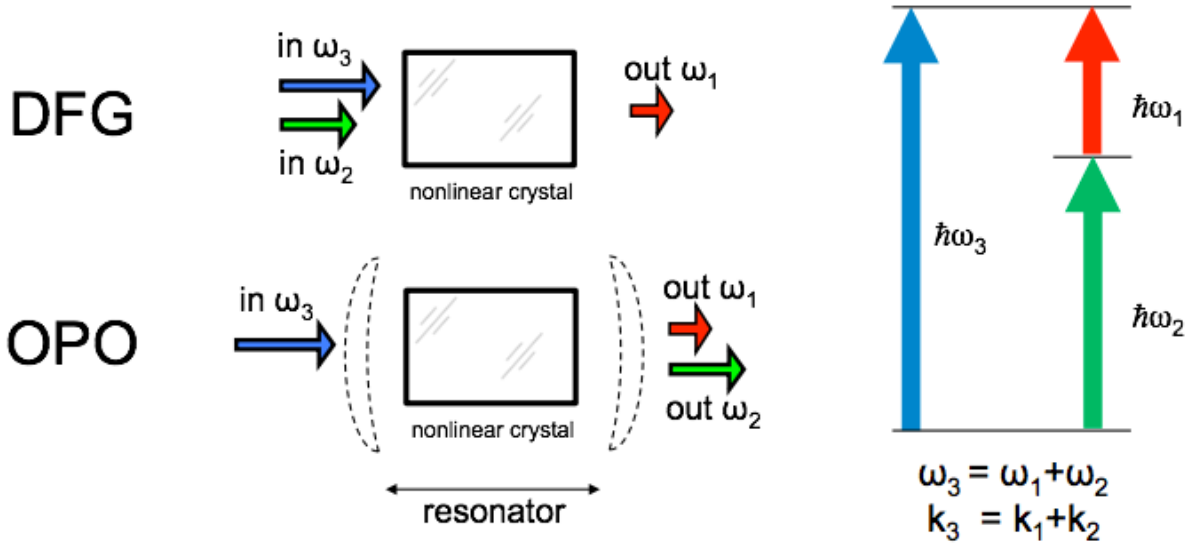
Lecture 13

Tuning curves and bandwidth in optical parametric oscillators.

OPO as a photon splitter

Only one strong input is present



Parametric frequency down-conversion in an OPO can be regarded as the inverse process of sum-frequency generation: a nonlinear optical (NLO) crystal can be viewed as a catalyst that promotes decay of the pump photon into two smaller photons.

How one tunes the OPO?

The condition of energy conservation

$$\omega_1 + \omega_2 = \omega_3$$

- usually written as:

$$\omega_i + \omega_s = \omega_p$$

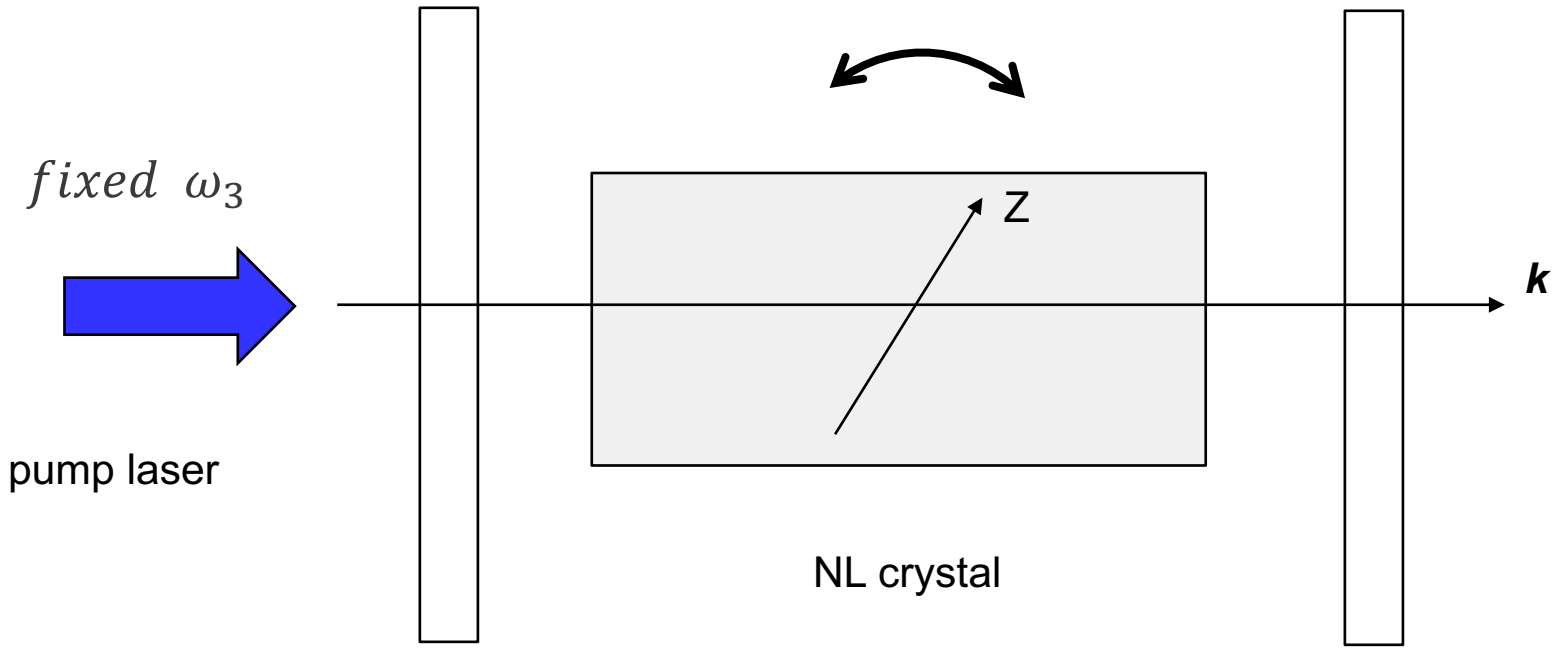
– allows frequencies smaller than that of the pump (ω_p) to be to generate by an optical parametric oscillator. The output frequency pair ω_s and ω_i can be controlled through the phase-matching condition **Δk = 0**

The phase matching (and thus frequency tuning) can be achieved by:

1. Varying the orientation of the nonlinear crystal (angle phase matching)
2. Varying the temperature of the crystal
3. Changing the inversion period for QPM crystals
4. Tuning the wavelength of the pump
5. Changing the OPO cavity length (in case of ultrafast OPOs)
6. Other methods: pressure tuning through the pholoelastic effect or electric field tuning through the electro-optic effect, etc. (result in small tuning ranges)

1. Varying the orientation of the nonlinear crystal (angle phase matching)

Angle phase matching



Angle phase matching

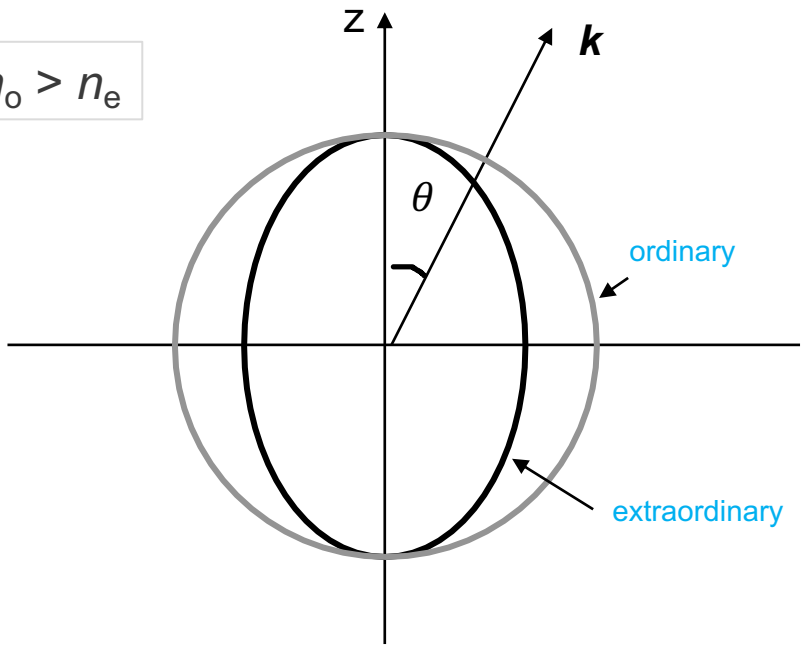
for ordinary wave

$$k = \frac{\omega n_o}{c}$$

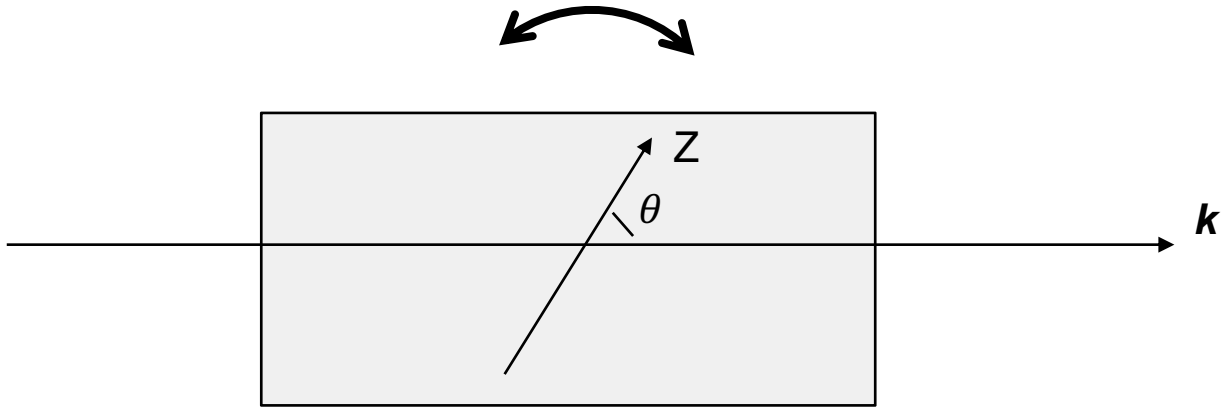
for extraordinary wave

$$k = \frac{\omega n_e(\theta)}{c}$$

$n_o > n_e$



$$\frac{1}{n_e^2(\theta)} = \frac{cos^2(\theta)}{n_o^2} + \frac{sin^2(\theta)}{n_e^2}$$



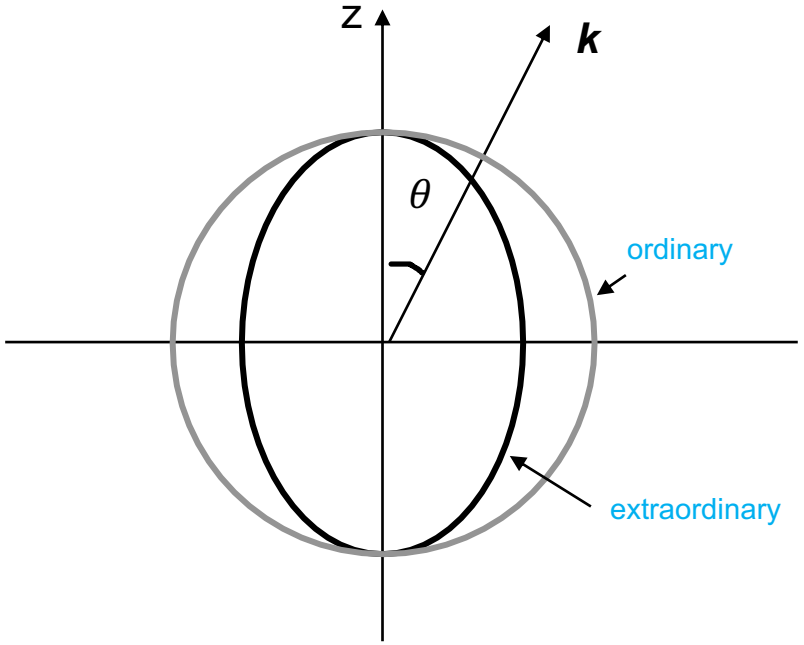
Angle phase matching

Easy case: Uniaxial crystal with $n_o > n_e$

Type I, ooe interaction $(\omega_1\ \omega_2\ \omega_3)$

– only one extraordinary wave

From desired ω_1 you find $n_e(\omega_3)$=$n_e(\theta)$ you need to get to Δk=0 condition and hence θ angle



$$\frac{1}{n_e^2(\theta)} = \frac{cos^2(\theta)}{n_o^2} + \frac{sin^2(\theta)}{n_e^2}$$

$$\frac{1}{n_e^2(\theta)} = \frac{1 - sin^2(\theta)}{n_o^2} + \frac{sin^2(\theta)}{n_e^2}$$

$$\frac{n_o^2 n_e^2}{n_e^2(\theta)} = \frac{n_e^2 n_e^2(\theta)(1 - sin^2(\theta))}{n_o^2} + \frac{n_o^2 n_e^2(\theta) sin^2(\theta)}{n_e^2}$$

$$n_o^2 n_e^2 = n_e^2 n_e^2(\theta)(1 - sin^2(\theta)) + n_o^2 n_e^2(\theta) sin^2(\theta)$$

$$sin^2(\theta) n_e^2(\theta)\ (n_o^2 - n_e^2) = n_e^2(n_o^2 - n_e^2(\theta))$$

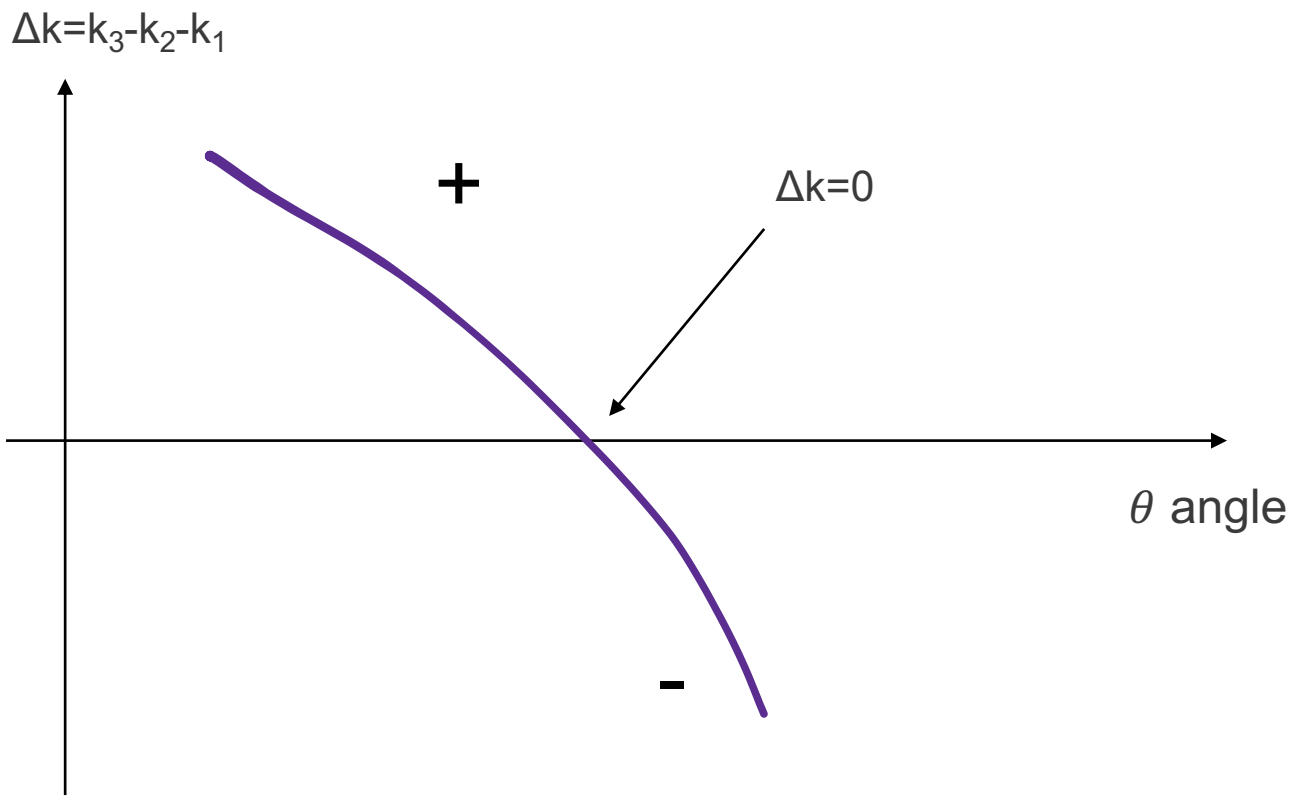
$$sin^2(\theta) = \frac{n_e^2}{n_e^2(\theta)} \frac{(n_o^2 - n_e^2(\theta))}{(n_o^2 - n_e^2)}$$

$$\theta = asin\sqrt{\frac{n_e^2}{n_e^2(\theta)} \frac{(n_o^2 - n_e^2(\theta))}{(n_o^2 - n_e^2)}}$$

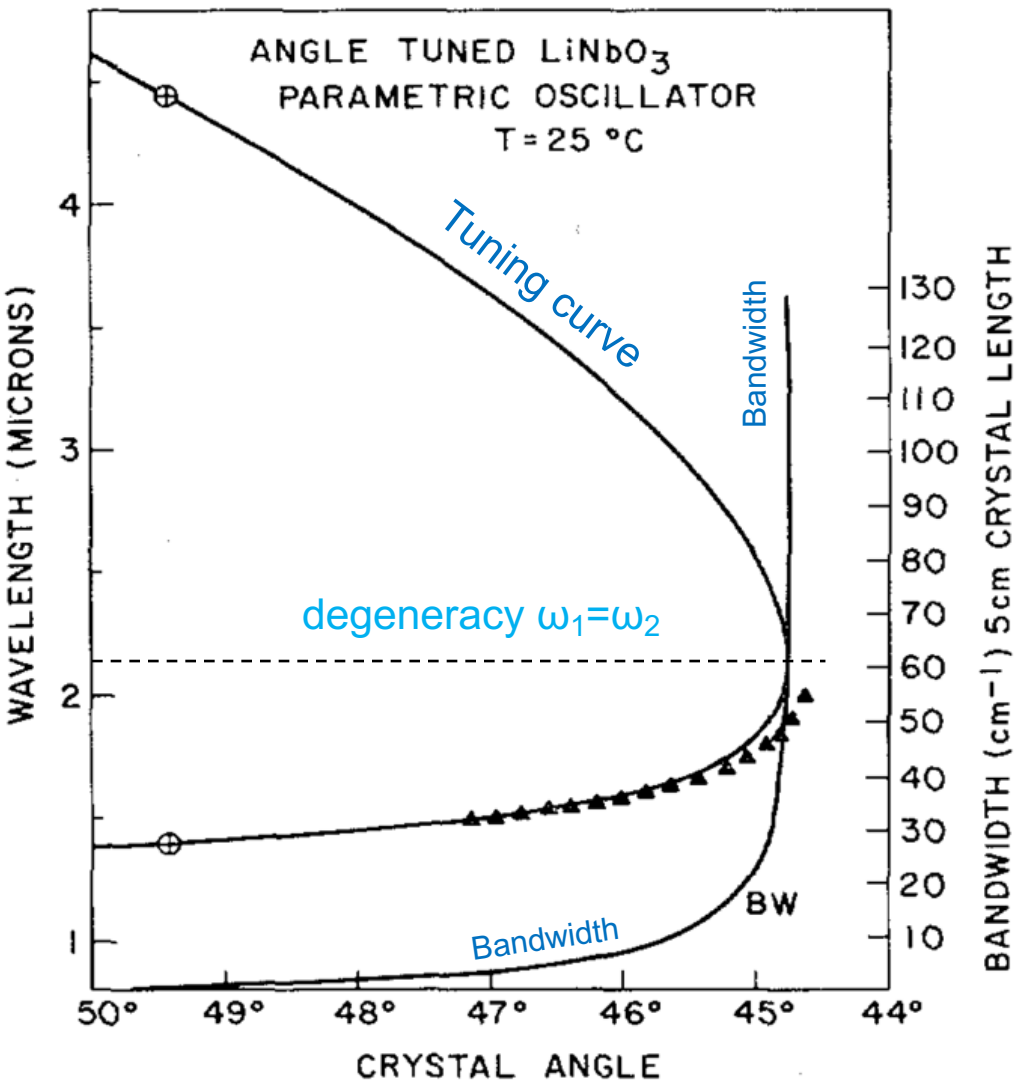
Angle phase matching

Type II, eoe interaction
– two extraordinary waves, more complicated

For a desired ω_1, find numerically the θ angle when $\Delta k=0$

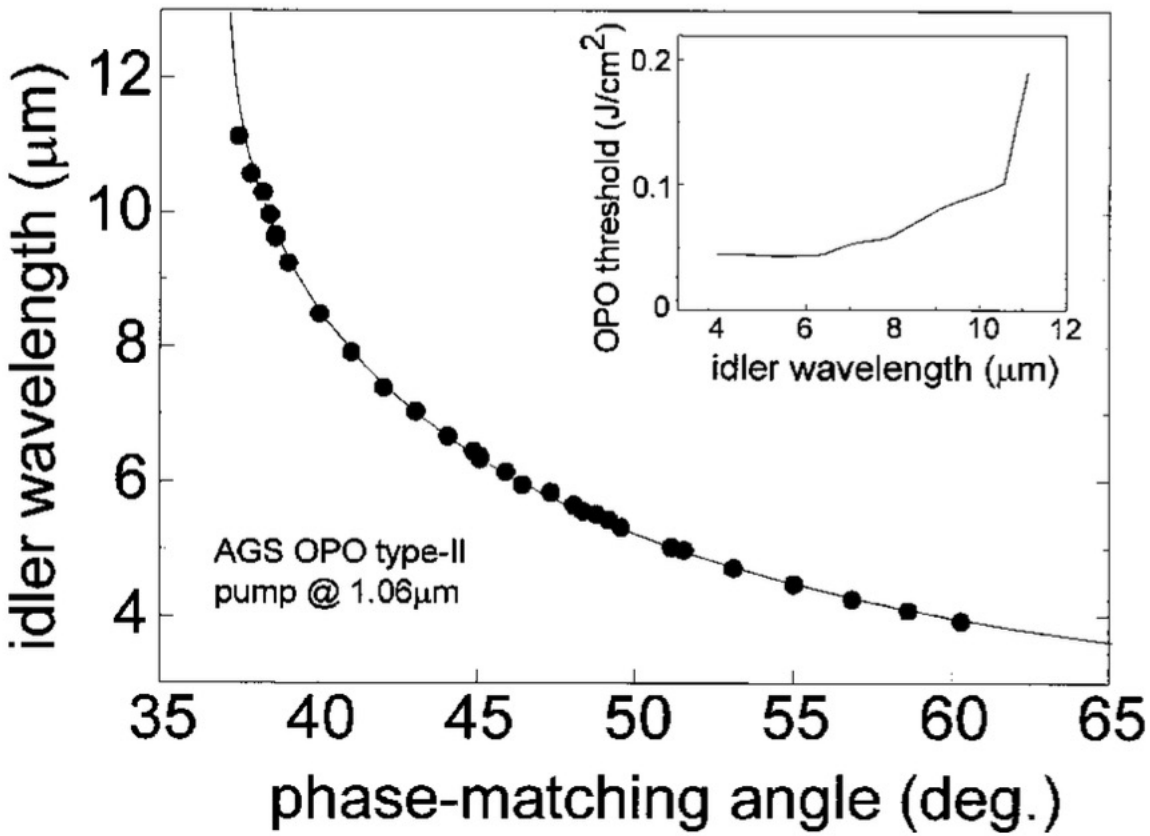


Angle phase matching and bandwidth



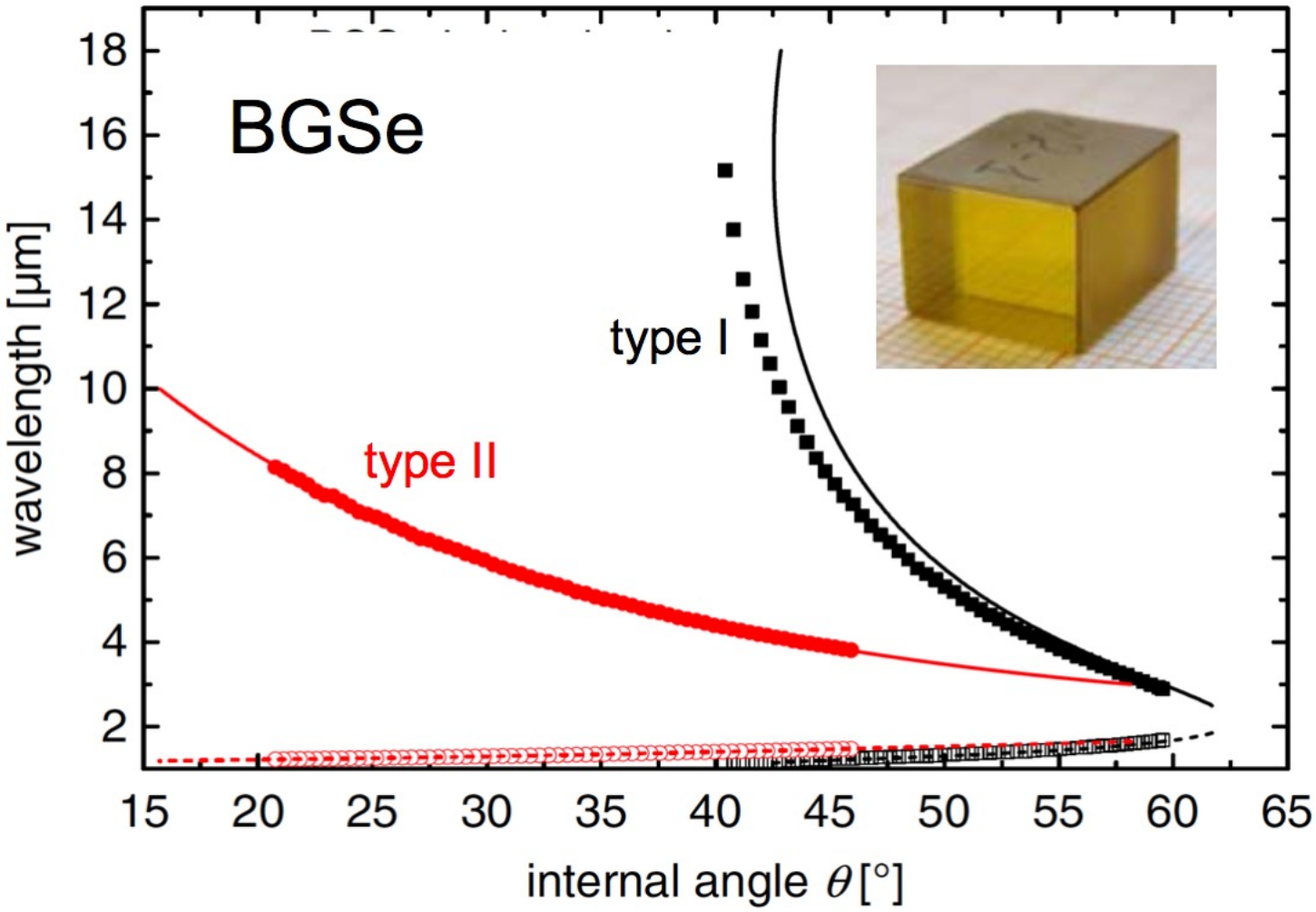
Tuning curve and bandwidth for the 1.06-μm-pumped angle-tuned $LiNb0_3$ SRO

Angle phase matching



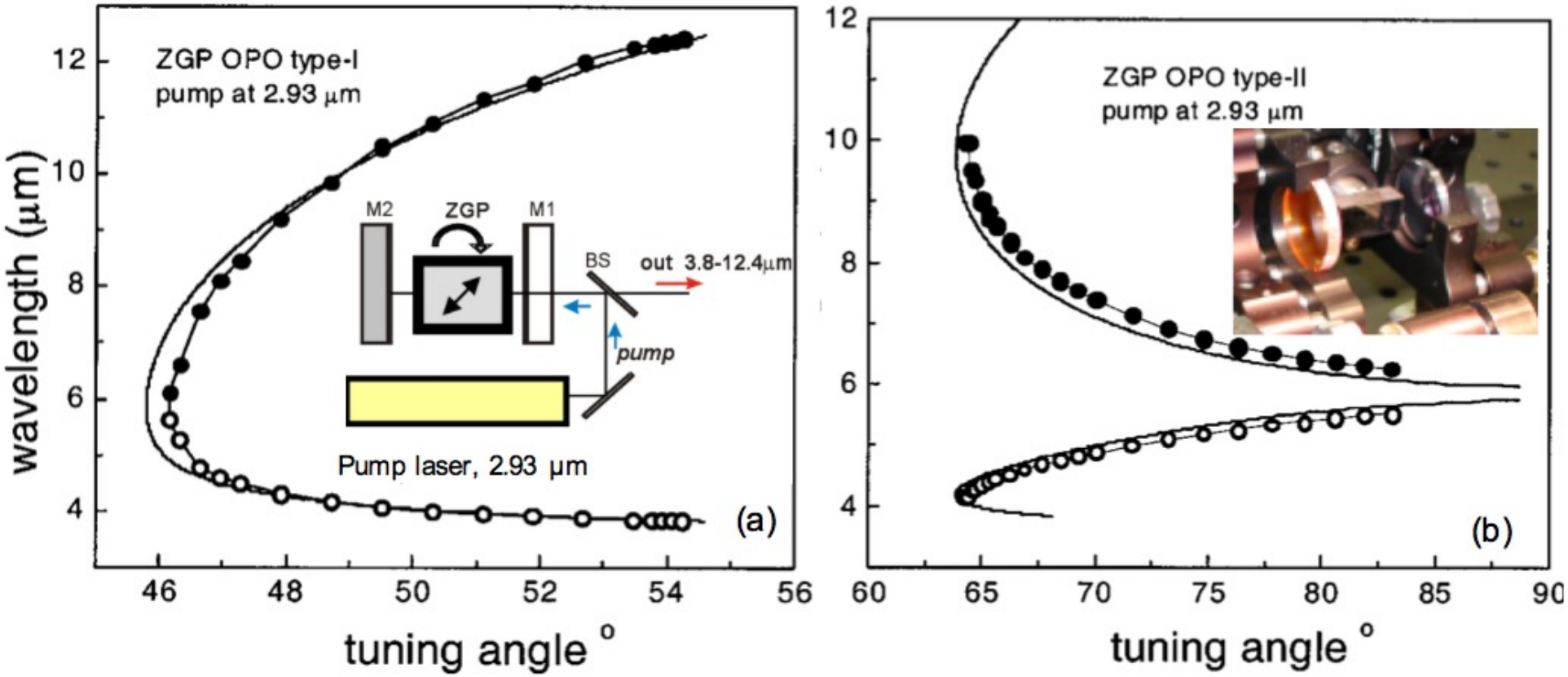
AGS type-II OPO angular tuning curve (idler wave only). Solid line - theoretical tuning curve. Inset: OPO threshold fluence as a function of the idler wavelength.

Angle phase matching



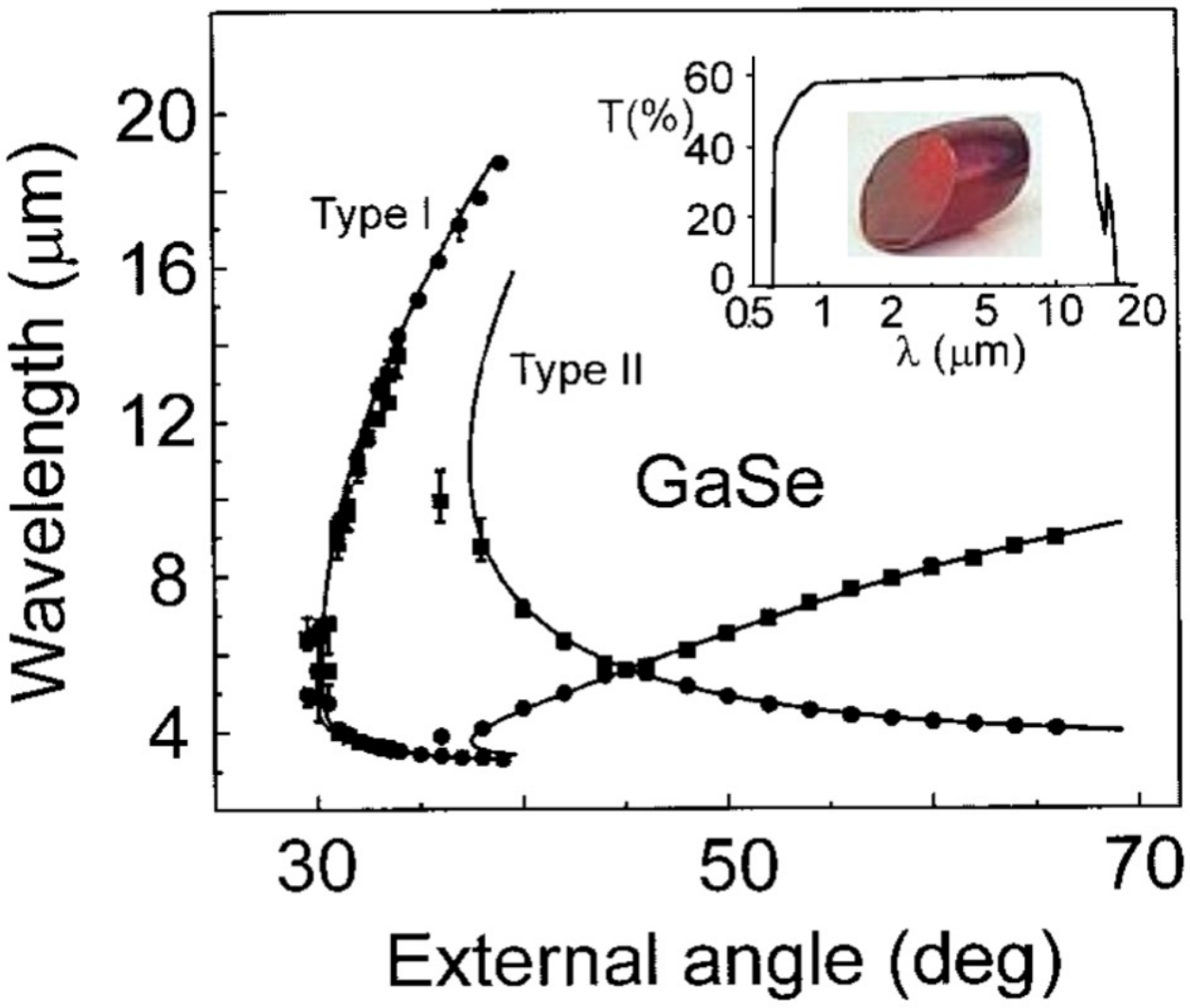
BGSe ($BaGa_4Se_7$) type I and type II OPO angular tuning curves with pump at 1.064 µm

Angle phase matching



ZGP type I and type II OPO angular tuning curves

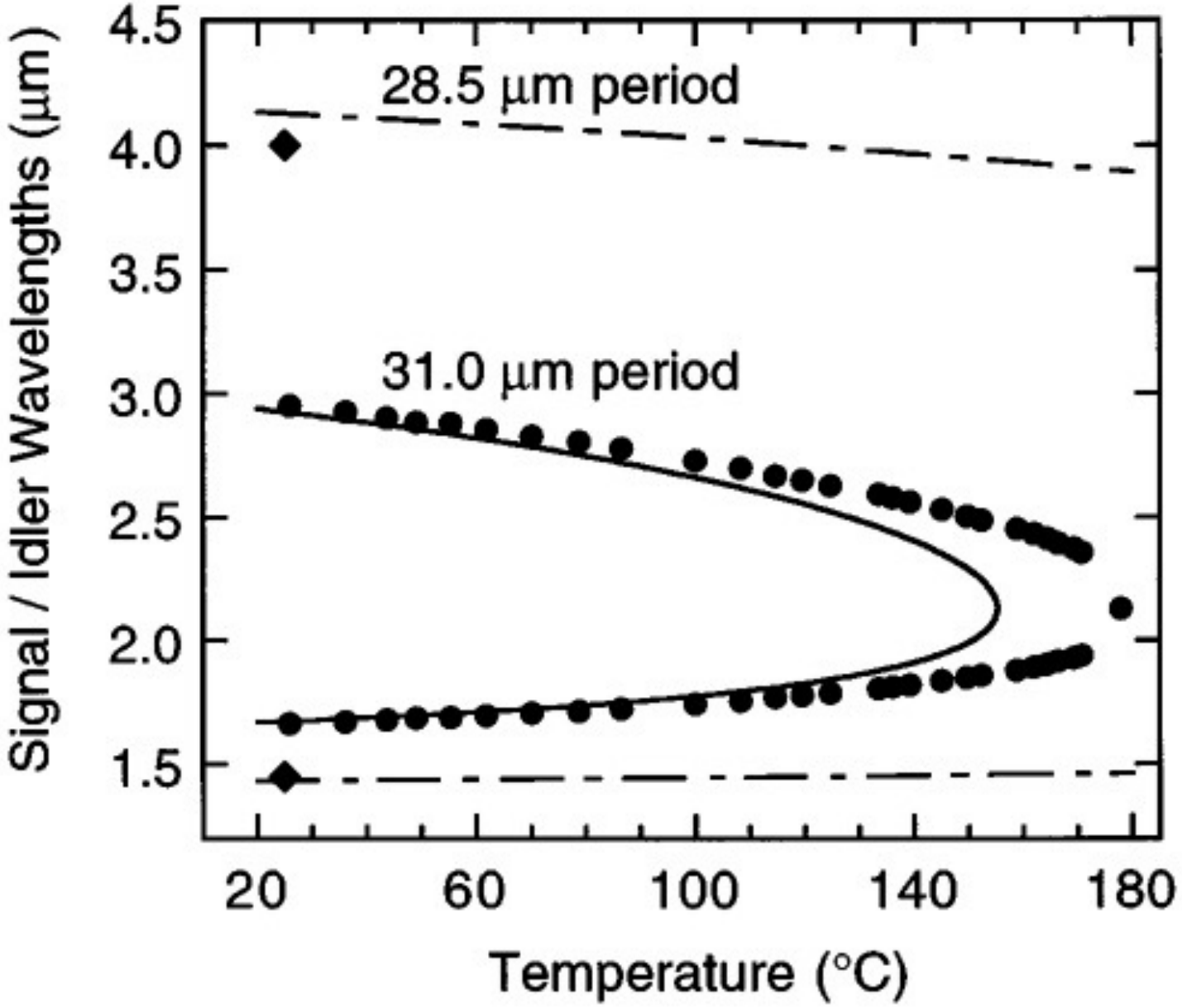
Angle phase matching



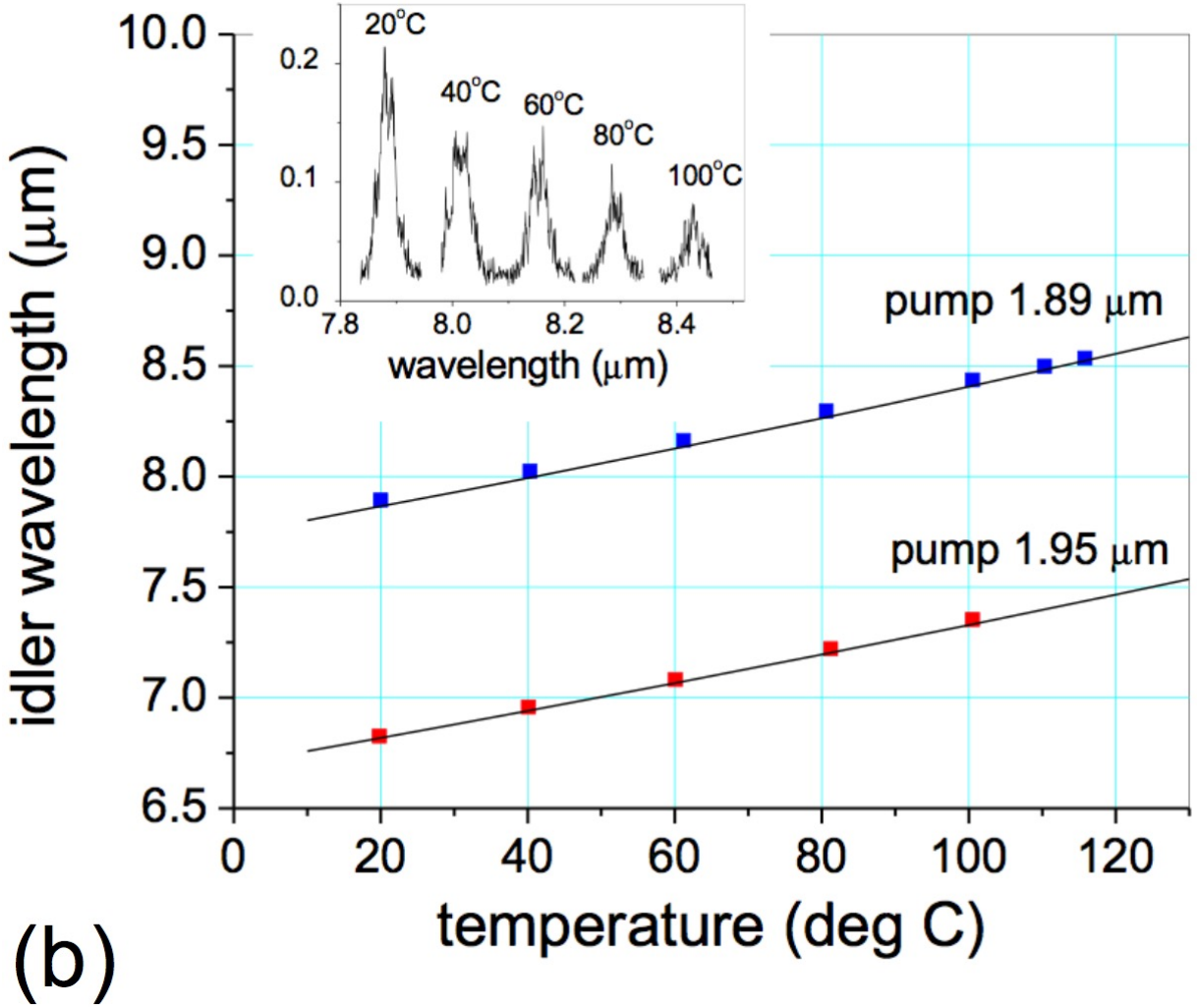
OPG type I and type II tuning curves obtained with a single z-cut GaSe crystal pumped at 2.8 μm

Varying the temperature of the crystal

OPO temperature tuning in PPLN (QPM crystal)



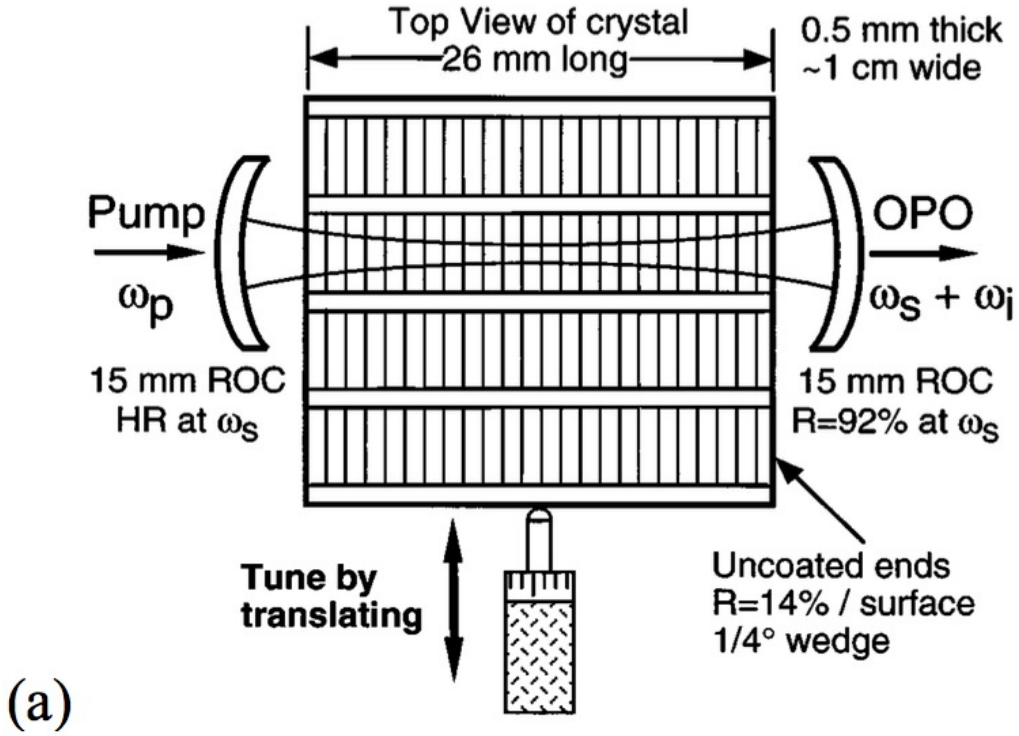
OPO temperature tuning in GaAs (QPM crystal)

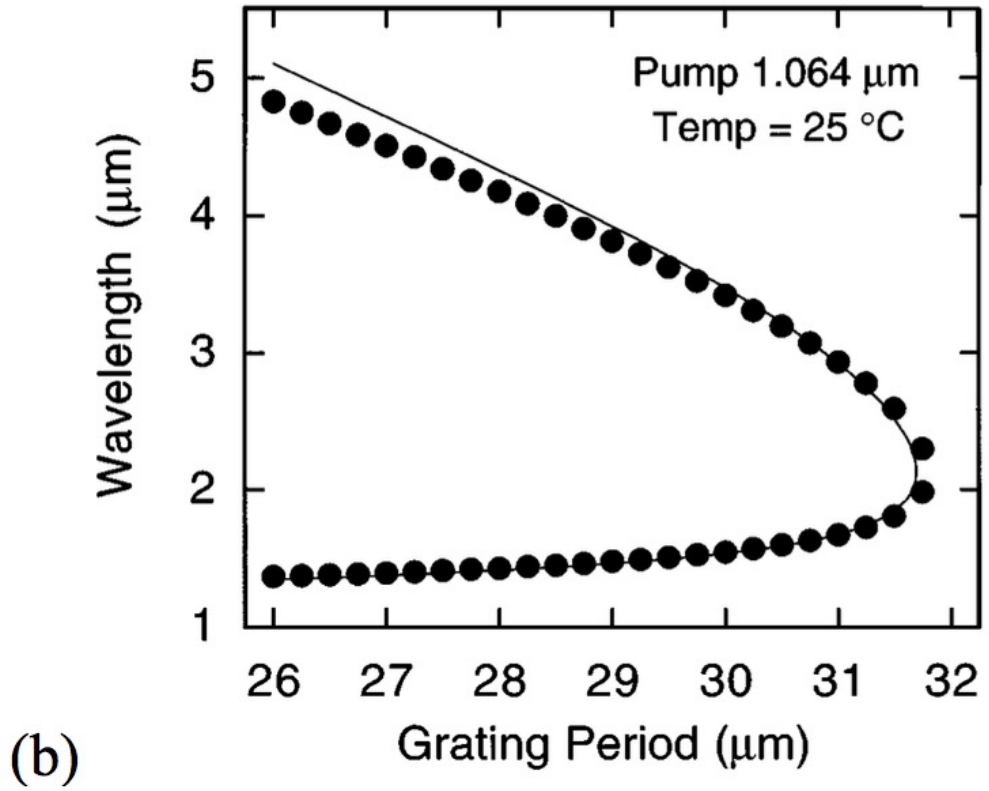


OP-GaAs OPO temperature-tuning curves for two selected pump wavelengths

Changing the inversion period for QPM crystals

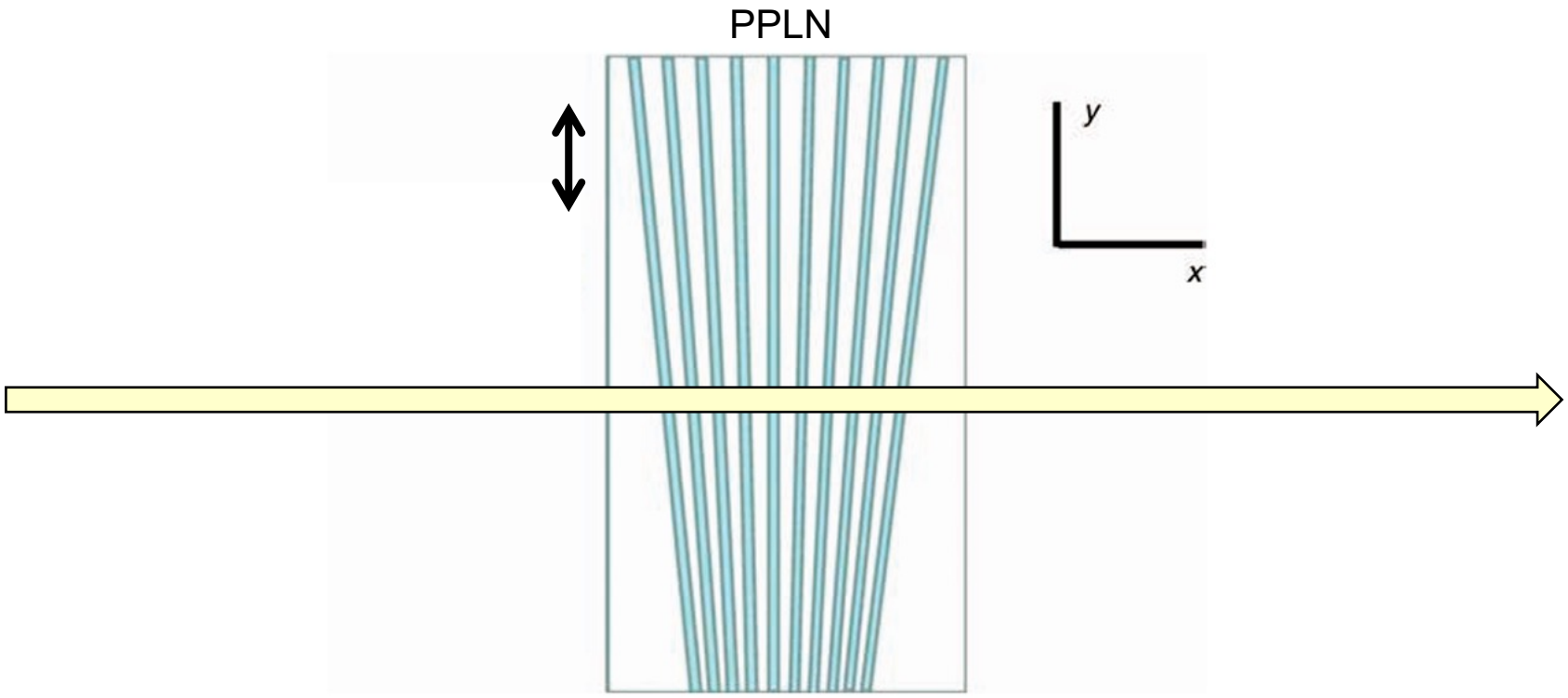
Changing the inversion period for QPM crystals





Bosenberg 1995

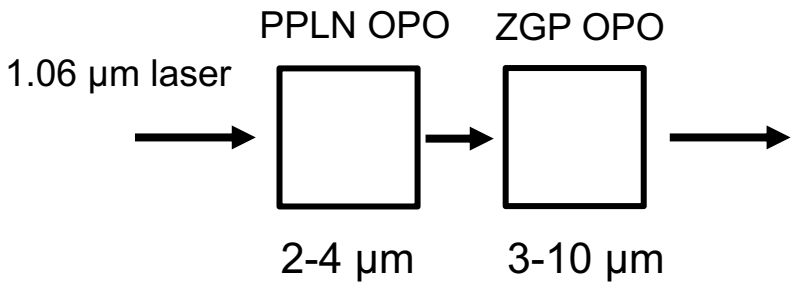
Changing the inversion period for QPM crystals

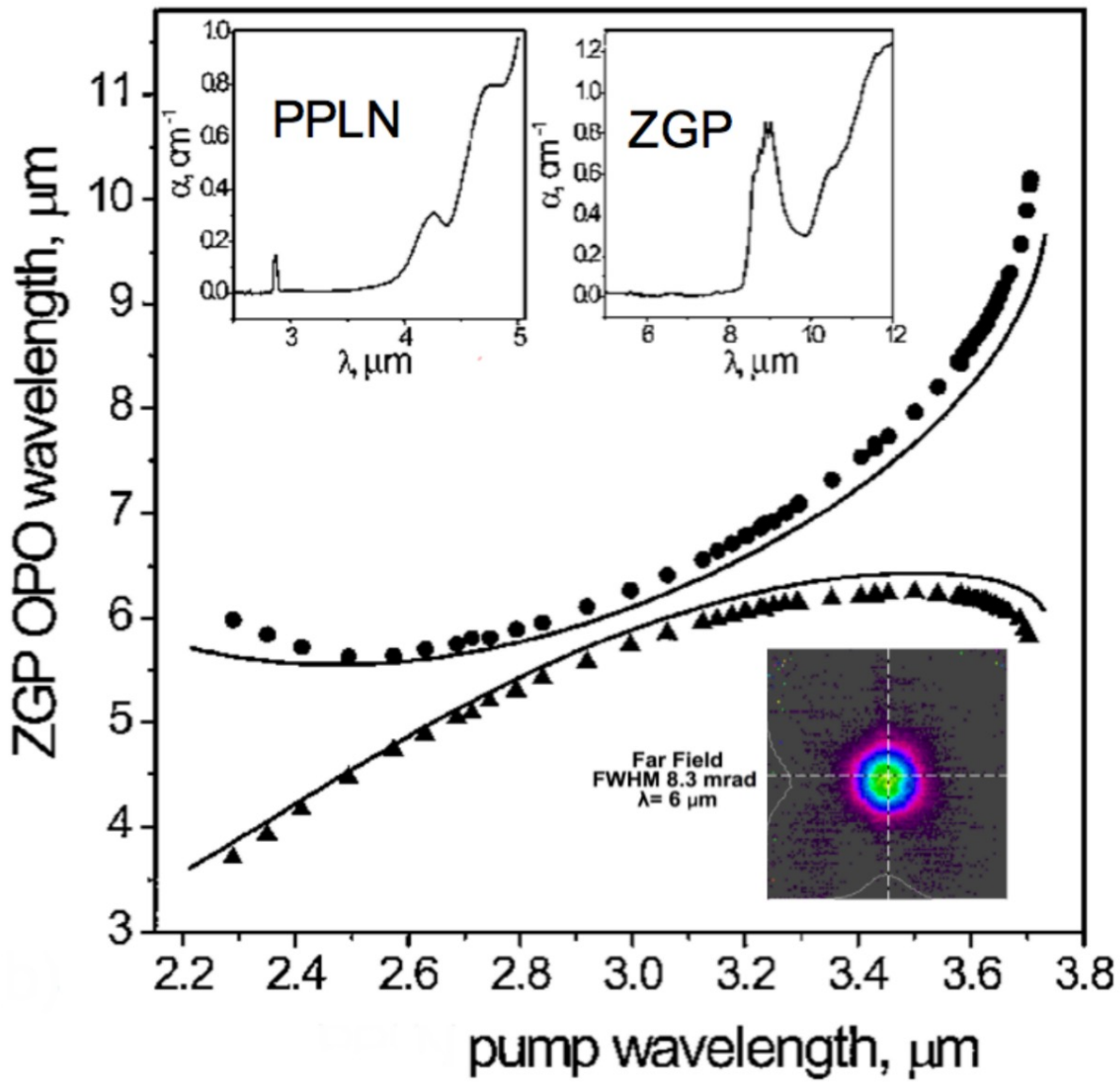


“Fan-”shaped poling period such that the *k*-vector matching condition changes along the y-axis.

Tuning the wavelength of the pump

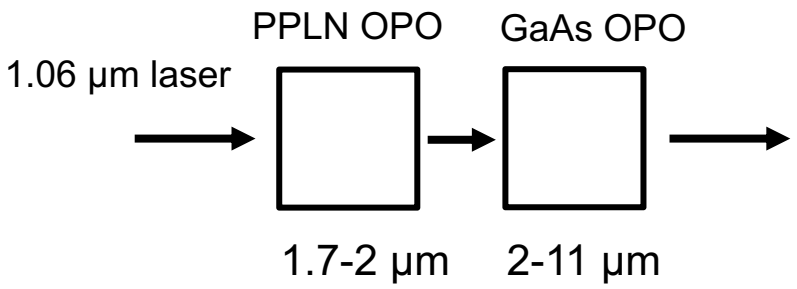
Tuning the wavelength of the pump (ZGP OPO)

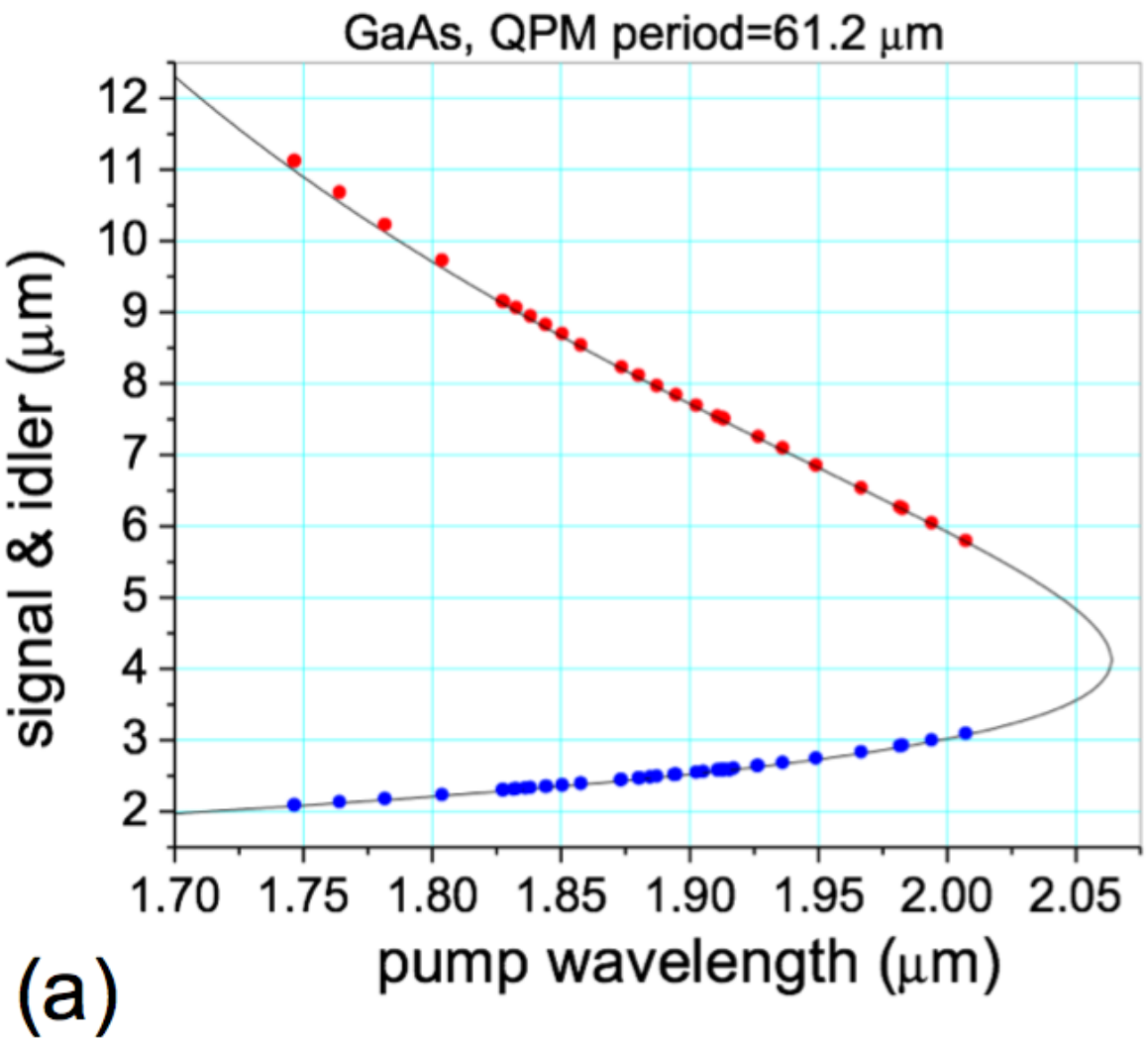




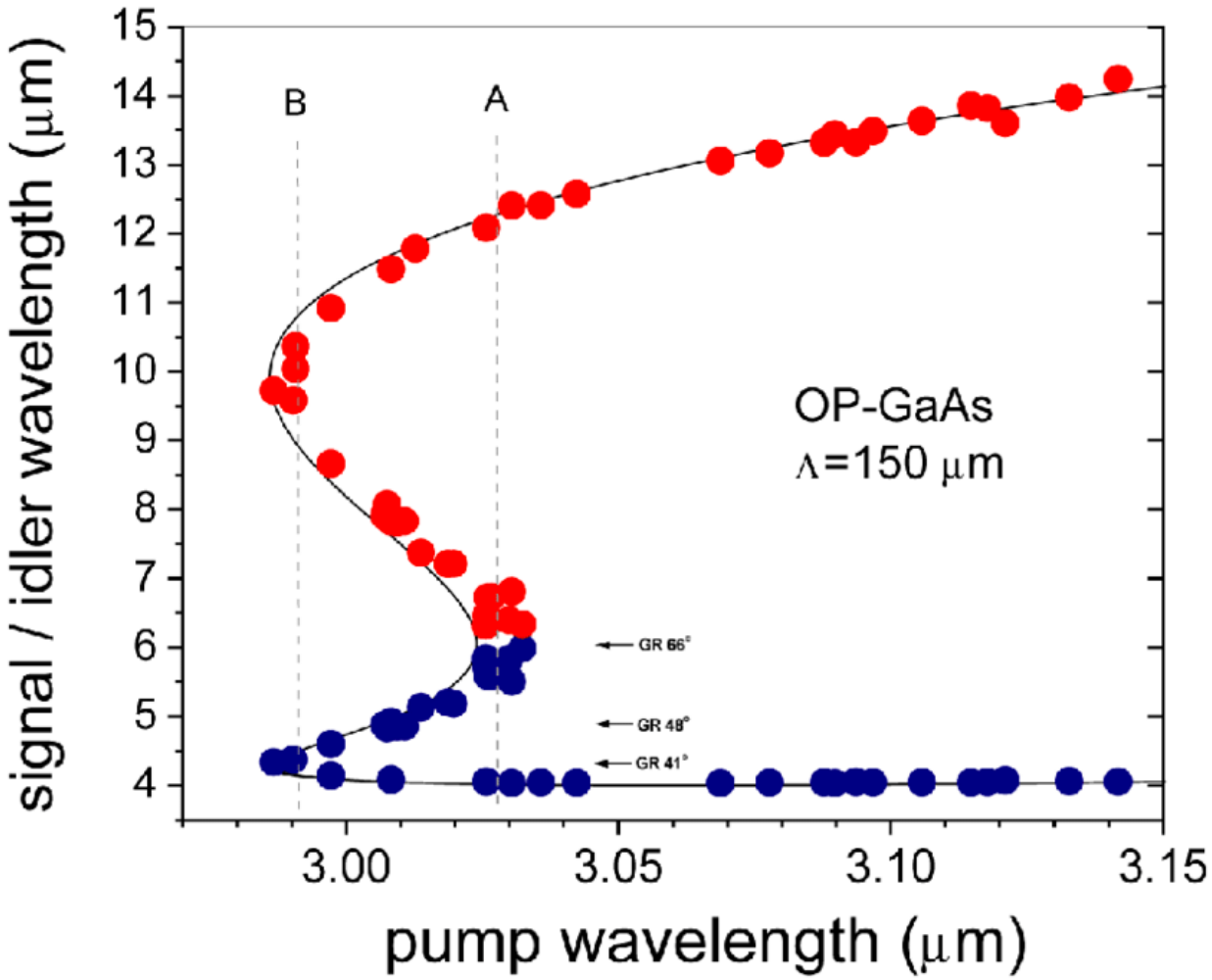
(PPLN OPO)

Pump wavelength tuning (GaAs OPO)





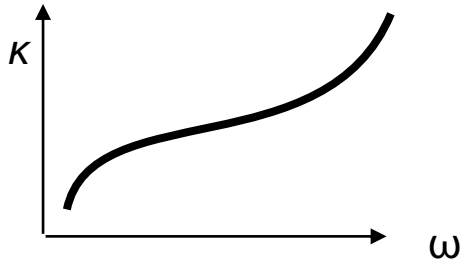
Tuning the wavelength of the pump (GaAs OPO)

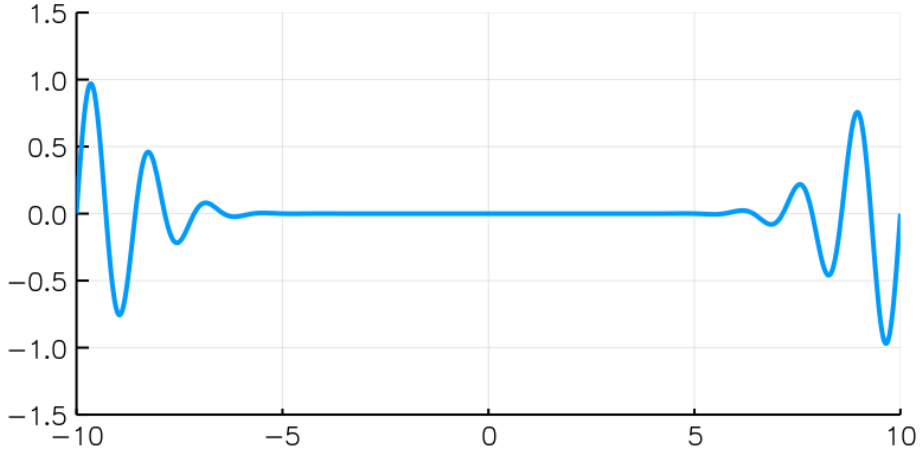


Changing the OPO cavity length (in case of ultrafast OPOs)

Group velocity vs phase velocity

$$v_{\mathrm{p}} = \omega/k, \quad v_{\mathrm{g}} = \frac{\partial \omega}{\partial k}$$





$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

Sync-pumped OPO

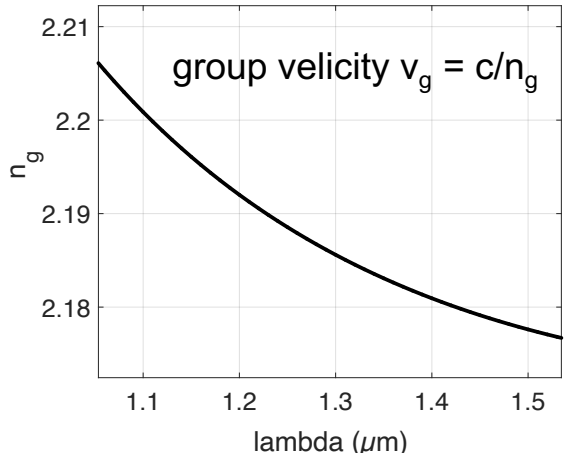
For resonating **signal** wave, different spectral component have different group velocities.

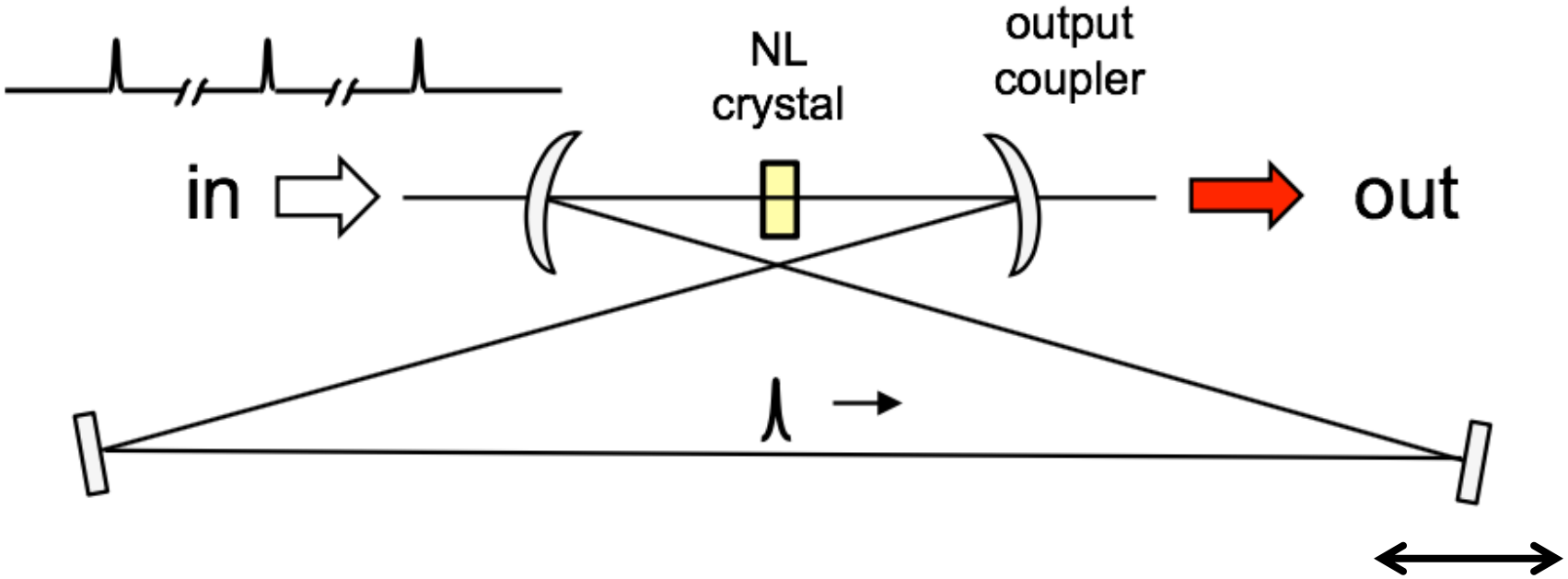
Hence for different cavity lengths synchronous pumping condition will be fulfilled only at certain frequencies → tuning.

Example: 1.06 μm -> 1.5 μm + 3.6 μm

L=5-mm crystal
n_g changes by 0.005 →
cavity length changes by 25 μm
resonating wave changes from 1.5 to 1.35 μm
idler wave changes from 3.6 to 4.9 μm

Lithium niobate
group index dispersion

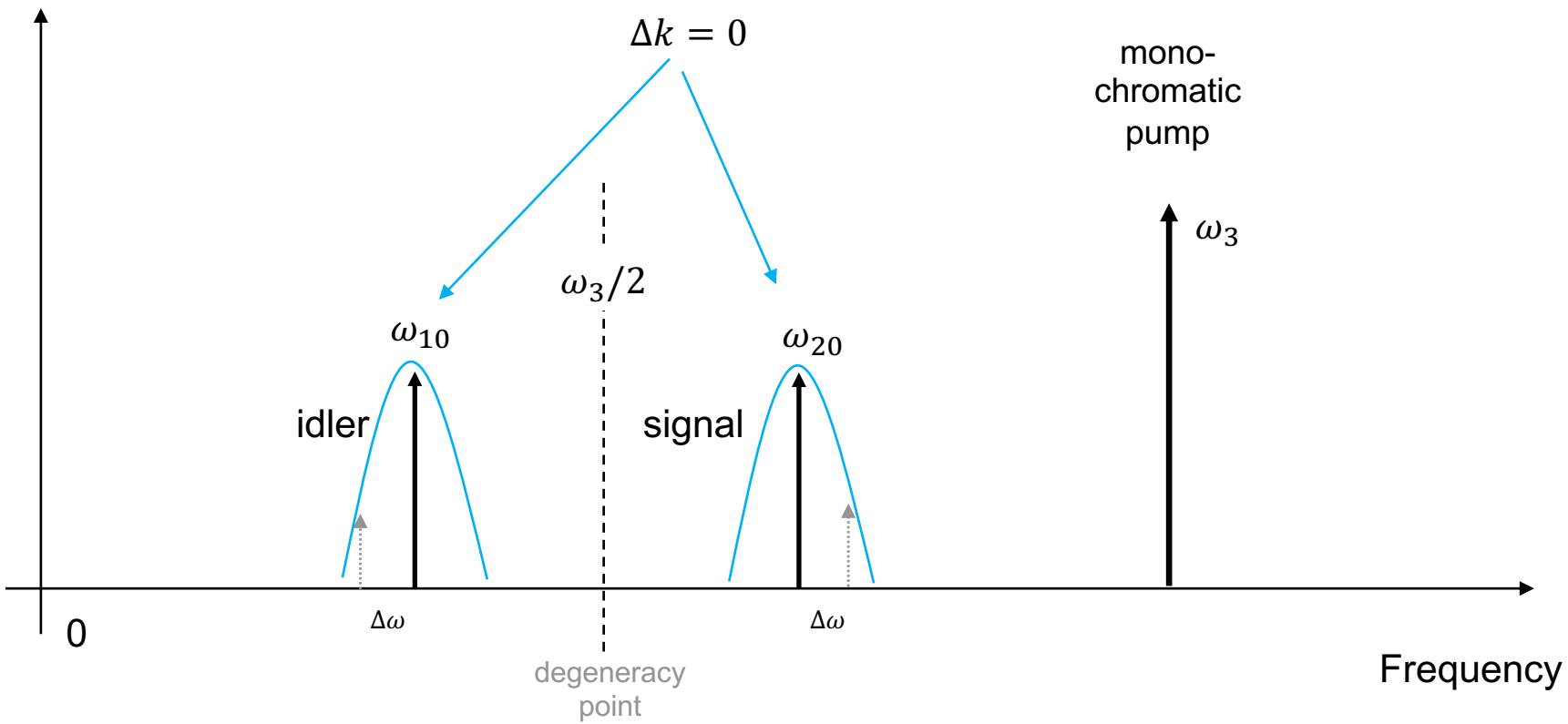




Sync-pumped OPO, ps and fs pulses

OPO bandwidth

Bandwidth for type I OPO



$\Delta k = k_3 - k_2 - k_1 = 0$ at ω_{10} ω_{20}

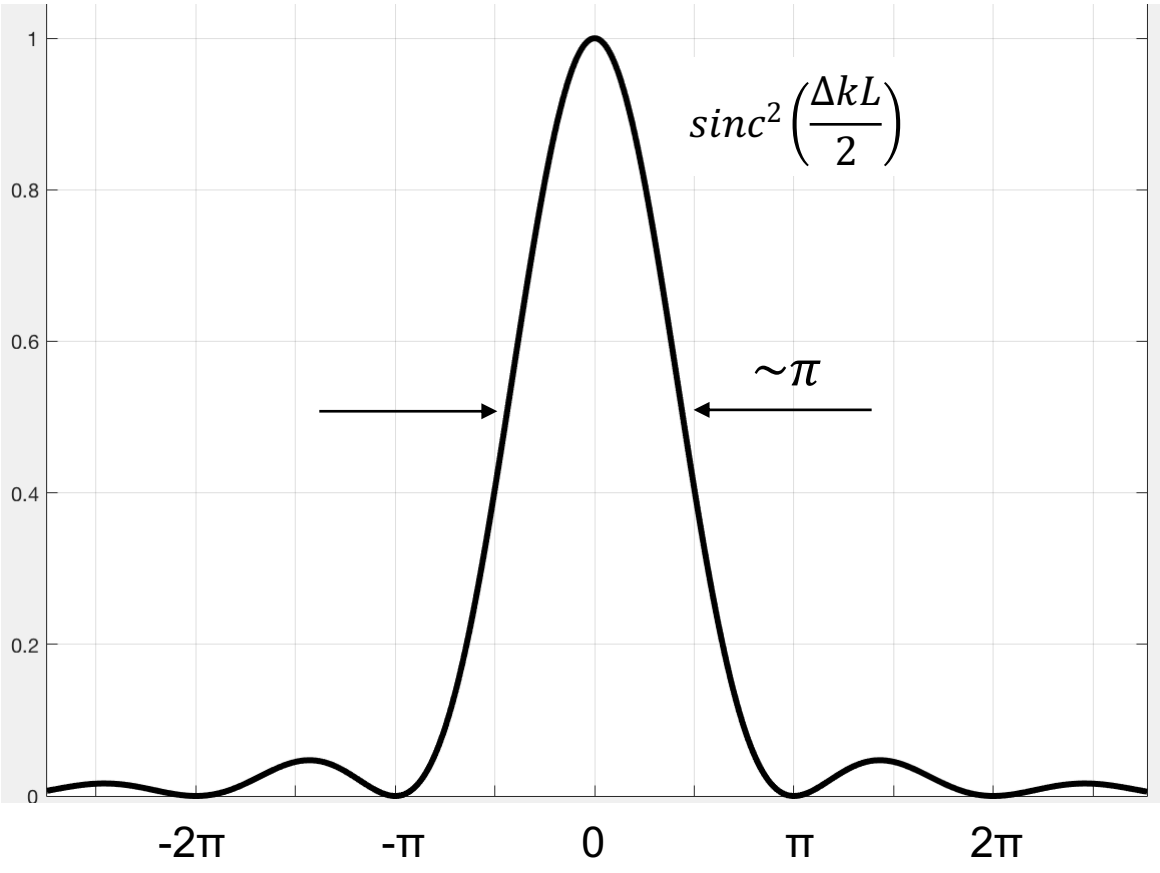
$$\delta(\Delta k) = -\delta(k_2) - \delta(k_1) =$$
$$= -\frac{dk_2}{d\omega}\Delta\omega - \frac{dk_1}{d\omega}(-\Delta\omega) =$$

$$= \Delta\omega\left(\frac{dk_1}{d\omega} - \frac{dk_2}{d\omega}\right) =$$

$$= \Delta\omega\left(\frac{1}{v_{g1}} - \frac{1}{v_{g2}}\right) = \Delta\omega\frac{(n_{g1} - n_{g2})}{c} = \Delta\omega\frac{\Delta n_{g12}}{c}$$

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

OPO Gain vs. mismatch Δk



$$\delta\left(\frac{\Delta kL}{2}\right) = \pm\frac{\pi}{2}$$

$$\delta(\Delta k) = \pm\frac{\pi}{L}$$

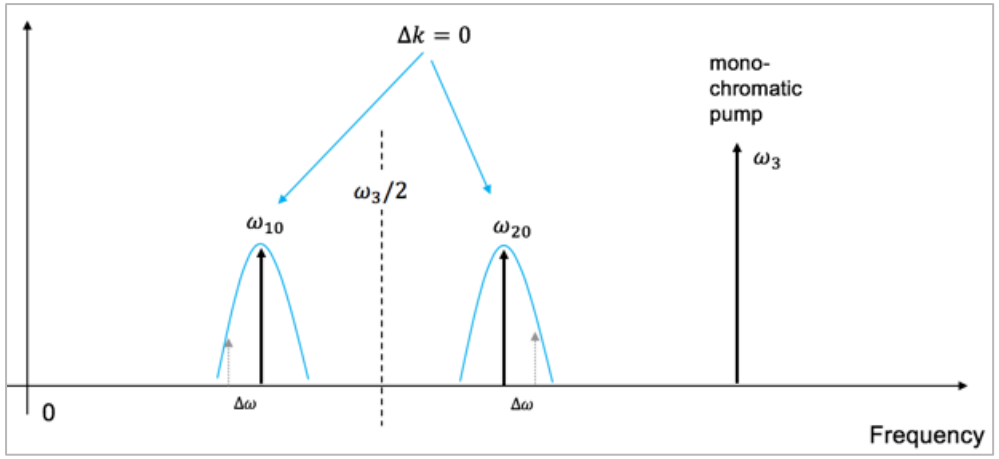
$$\rightarrow \quad \Delta\omega\frac{\Delta n_g}{c} = \pm\frac{\pi}{L}$$

$$\Delta\omega_{FWHM} = \frac{2\pi c}{L\Delta n_g}$$

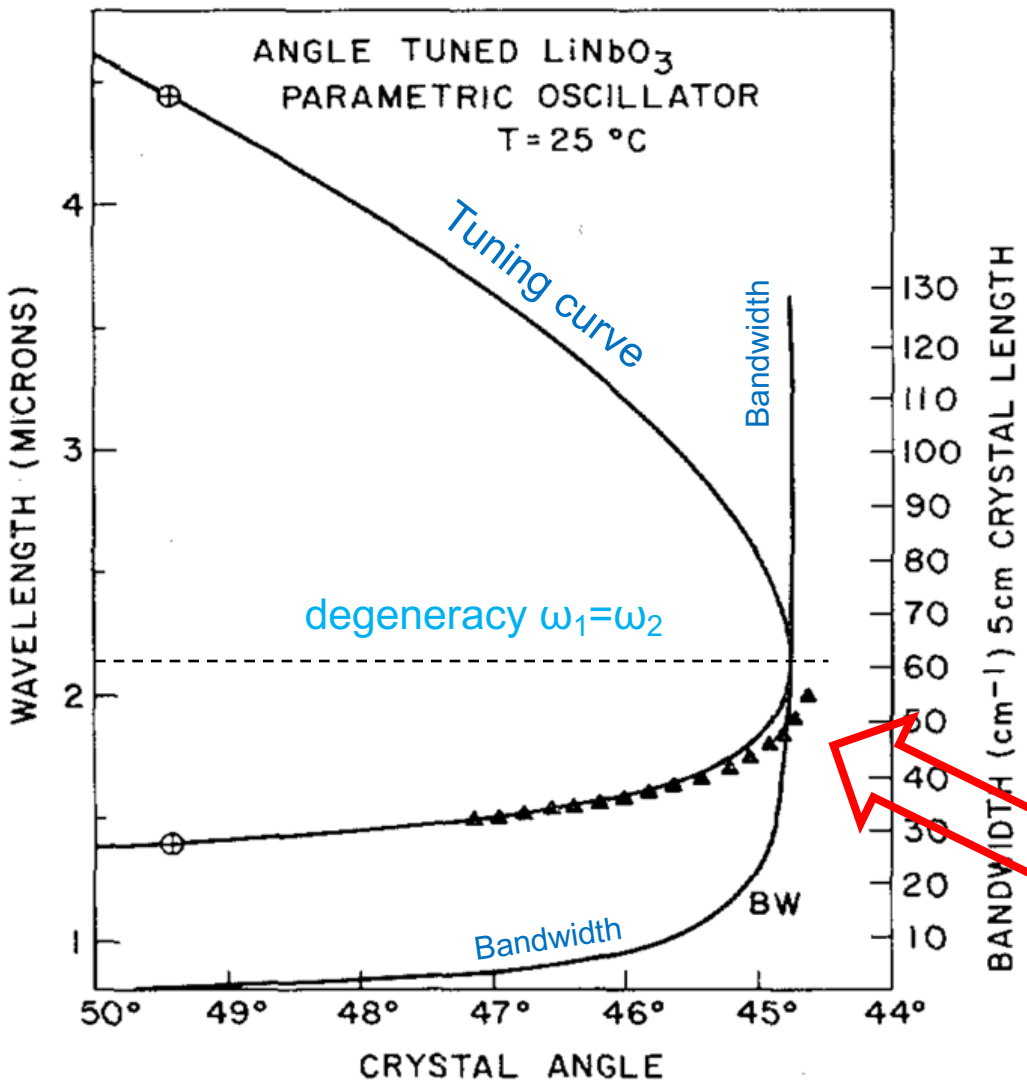
OPO bandwidth (monochromatic pump)

$$\Delta\nu_{FWHM} = \frac{c}{L\Delta n_g} \qquad (13.1)$$

Example: L=1cm, Δn_g=0.1
$\Delta\nu_{FWHM}$=**300 GHz**



OPO bandwidth



$$n_{g1} - n_{g2} \rightarrow 0$$

Bandwidth at degeneracy is very broad for type I OPOs

OPO bandwidth: time-domain picture

Let us look at (13.1) from a different point of view:

Ultrashort pulses with duration τ should have a minimum bandwidth of $\Delta\nu_{FWHM} \approx 1/\tau$

Pulses at ω_1 and ω_2 walk off in time, due to the group velocity difference by:

$$\Delta t = \frac{L}{v_{g1}} - \frac{L}{v_{g2}} = \frac{L\Delta n_g}{c}$$

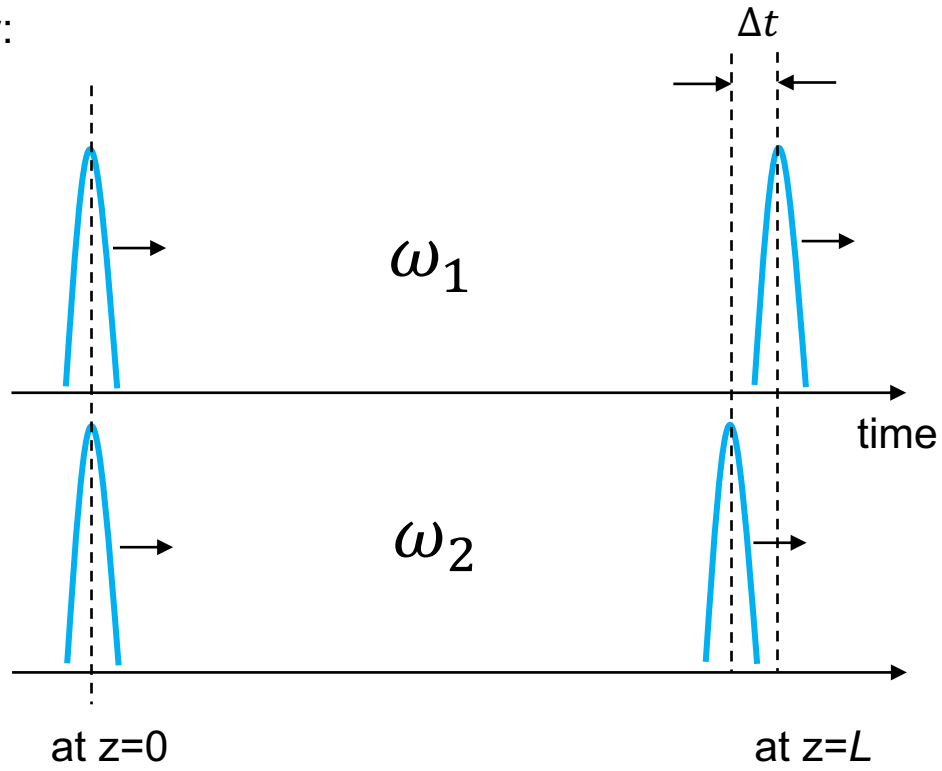
Pulses' walk-off in time should be less than their pulse duration, otherwise they will not interact

$$\Delta t < \tau$$

$$\rightarrow \quad \frac{L\Delta n_g}{c} < \tau \approx \frac{1}{\Delta\nu_{FWHM}}$$

$$\rightarrow \quad \Delta\nu_{FWHM} < \frac{c}{L\Delta n_g}$$

effective OPO bandwidth



Got the same OPO bandwidth as from previous slide !

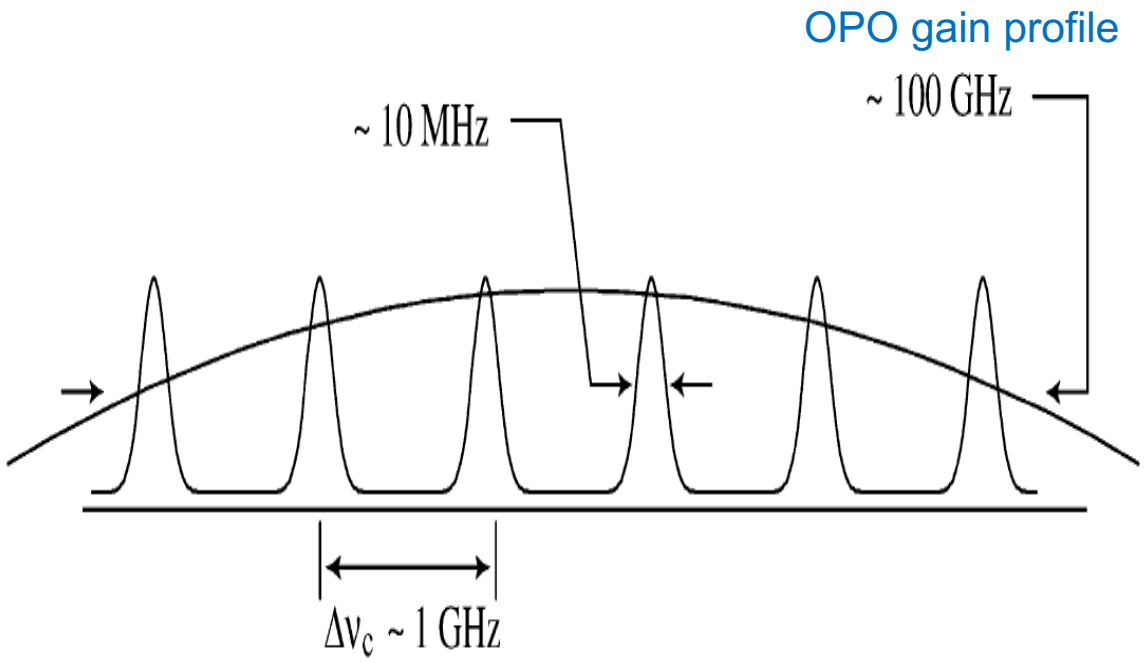
$$\max\{\Delta\nu_{FWHM}\} = \frac{c}{L\Delta n_g}$$

- same result form **time domain** perspective!

This sets the limit to the crystal length *L*

Modes of singly- and doubly- resonant OPOs

Modes of a singly resonant OPO



Gain spectrum and cavity modes of an OPO. Note that typically many cavity modes lie beneath the gain profile of the OPO.

Getting narrow-linewidth output

The output frequency bandwidth can often be narrowed by placing wavelength-selective items (such as etalons) inside the OPO cavity.

BROSNAN AND BYER: OPTICAL PARAMETRIC OSCILLATOR . . .

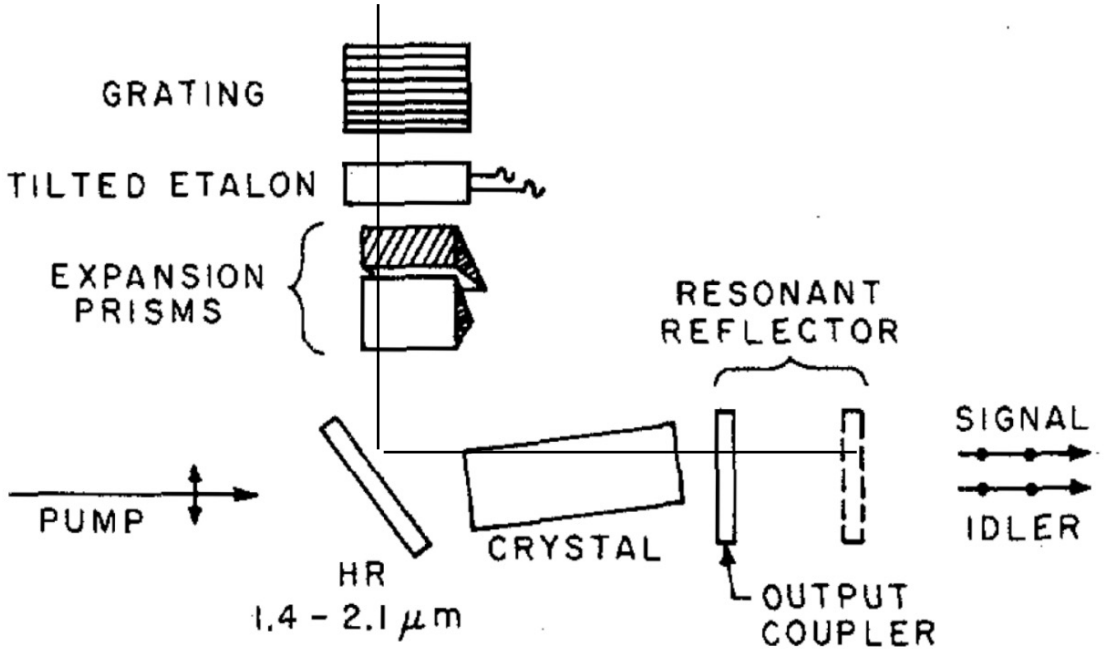
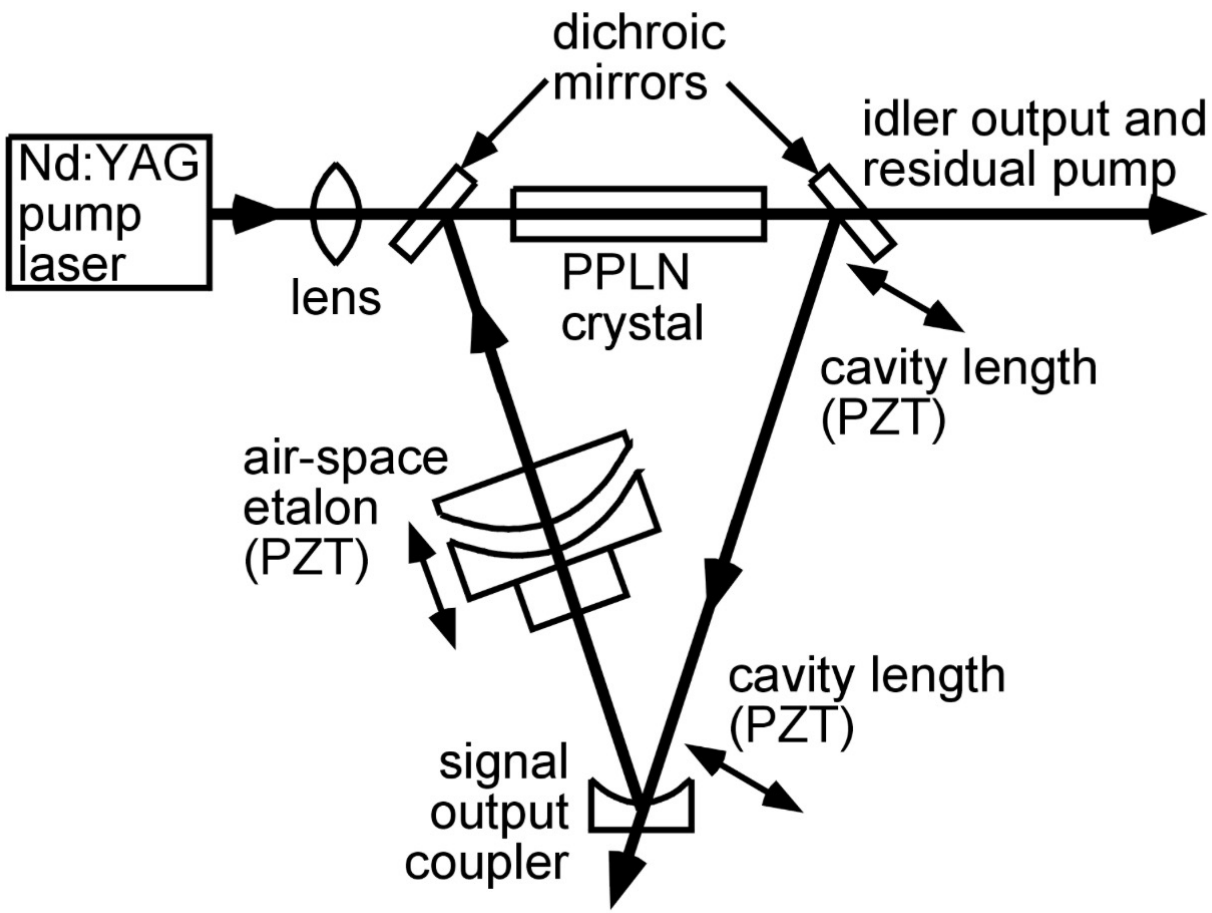


Fig. 10. Schematic of the SRO cavity for linewidth studies. Primary linewidth control is provided by prisms and grating combination. Line narrowing is accomplished with a tilted etalon. A resonant reflector used as an output coupler collapses the linewidth to a single axial mode.

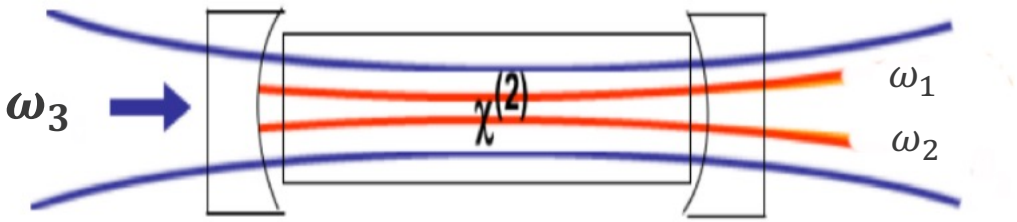
Getting narrow-linewidth output

The output frequency bandwidth can often be narrowed by placing wavelength-selective items (such as etalons) inside the OPO cavity.

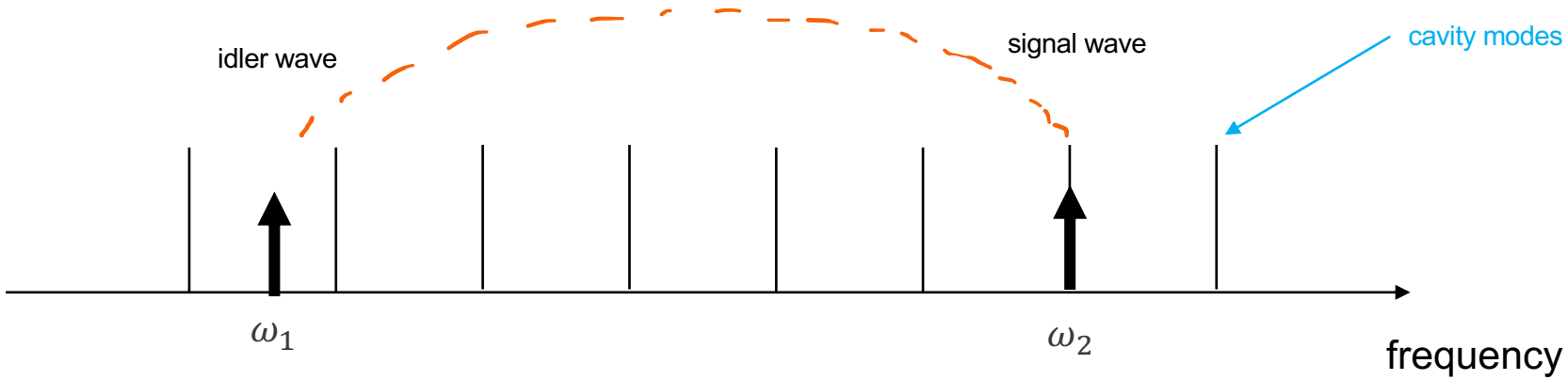


Schematic of a pulsed single-longitudinal-mode tunable PPLN OPO

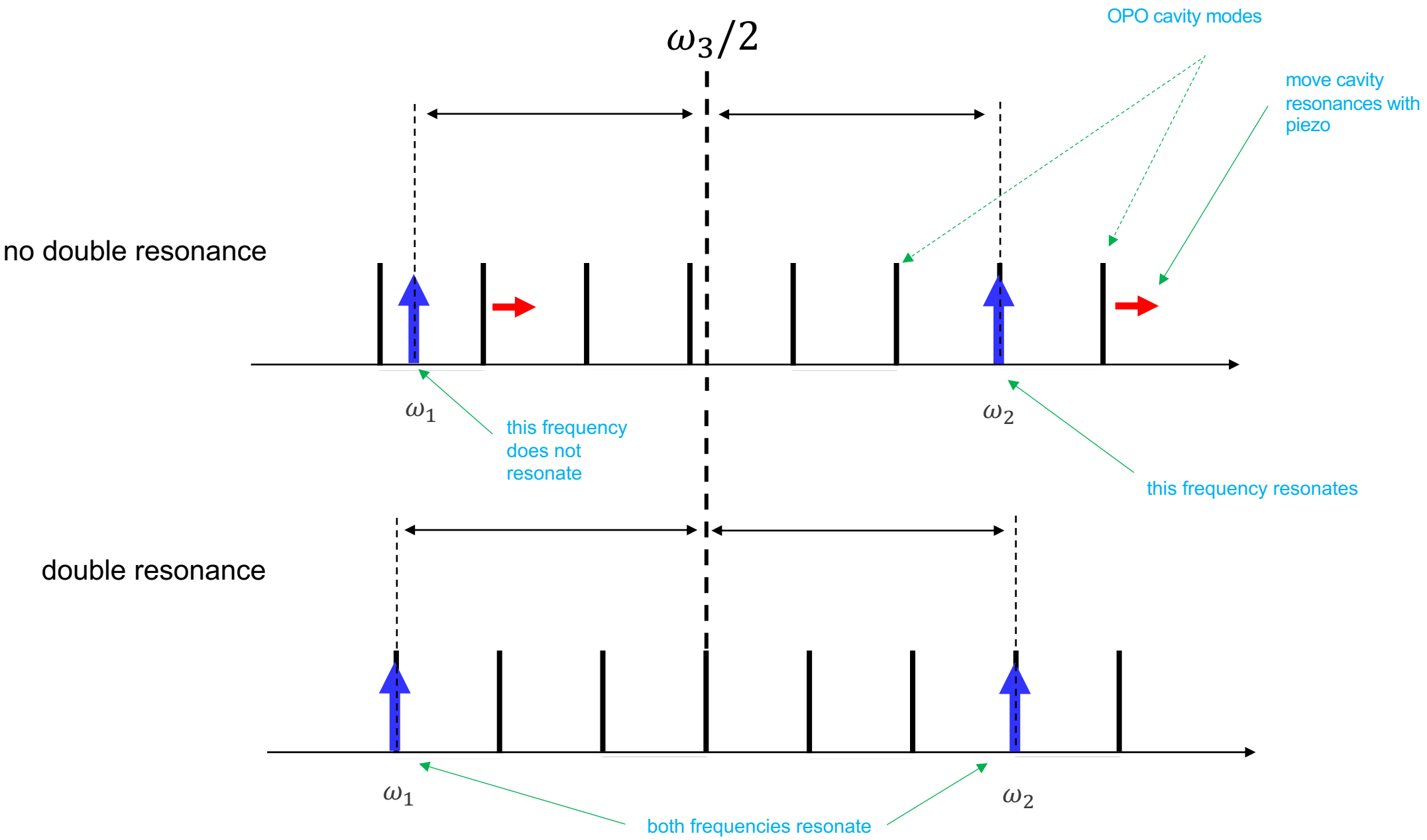
Modes of a doubly resonant OPO



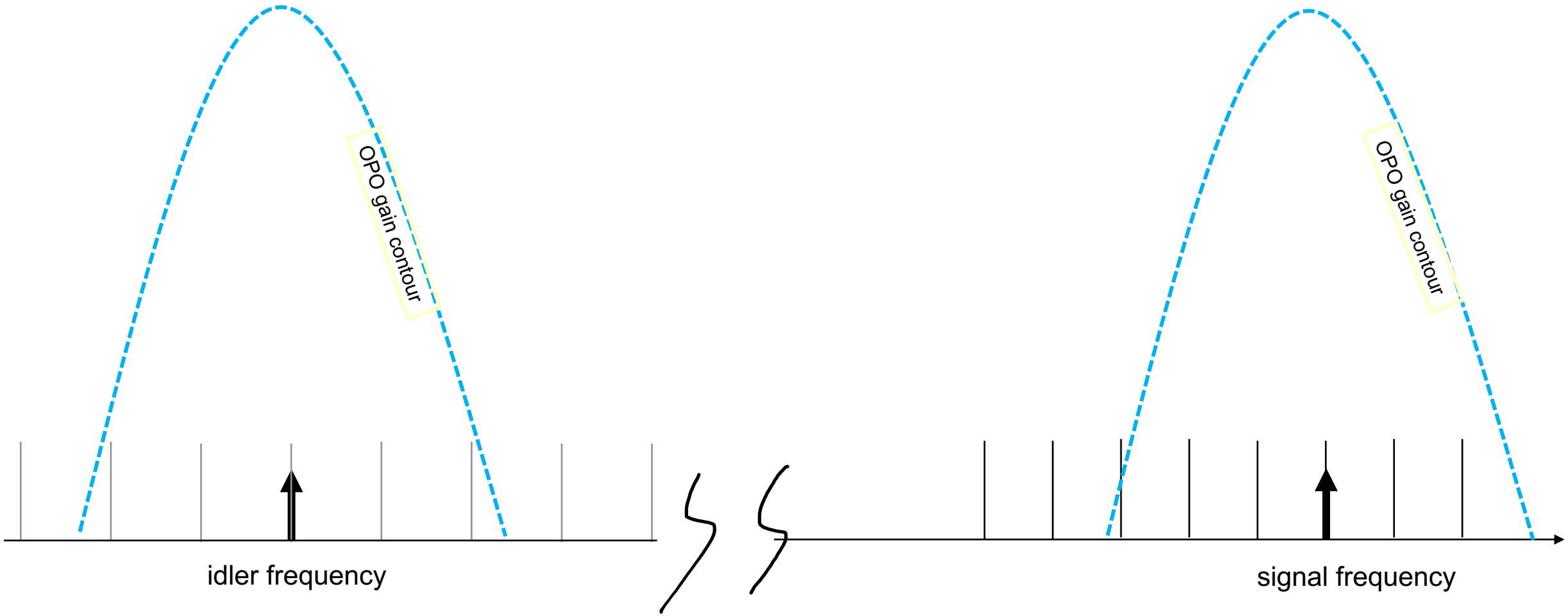
A doubly resonant OPO cavity should **simultaneously** support oscillation at a signal and its corresponding idler mode. Hence the system is **overconstrained** - will not oscillate in general



Doubly-resonant OPO



Single-mode operation of a doubly resonant OPO



(+) Can get a single-longitudinal-mode performance

(-) Need control of the cavity length (accuracy of ~ nm needed)