The units are the same as in equation (1.7.3.42).

Equations (1.7.3.90) and (1.7.3.91) show that both idler and signal powers grow exponentially. So, firstly, the generation of the idler is not detrimental to the signal power, in contrast to DFG ($\omega_s - \omega_p = \omega_i$) and SFG ($\omega_s + \omega_p = \omega_i$), and, secondly, the signal power is amplified. Thus DFG ($\omega_p - \omega_s = \omega_i$) combines two interesting functions: generation at $\omega_i$ and amplification at $\omega_s$. The last function is called optical parametric amplification (OPA).

The gain of OPA can be defined as (Harris, 1969)

$$G(L) = \left|\frac{P_s(L)}{P_s(0)} - 1\right|. \qquad (1.7.3.92)$$

For example, Baumgartner & Byer (1979) obtained a gain of about 10 for the amplification of a beam at 0.355 µm by a pump at 1.064 µm in a 5 cm long $KH_2PO_4$ crystal, with a pump intensity of 28 MW cm$^{-2}$.

According to (1.7.3.91), for $\Delta k^2 L^2/4 \gg \Gamma^2 L^2$, $\sinh^2(im) \to -\sin^2(m)$ and so the gain is given by

$$G_{\text{small gain}} \simeq \Gamma^2 L^2 \sin c^2\left(\frac{\Delta k \cdot L}{2}\right). \qquad (1.7.3.93)$$

Formula (1.7.3.93) shows that frequencies can be generated around $\omega_s$. The full gain linewidth of the signal, $\Delta\omega_s$, is defined as the linewidth leading to a maximum phase mismatch $\Delta k = 2\pi/L$. If we assume that the pump wave linewidth is negligible, *i.e.* $\Delta\omega_p = 0$, it follows, by expanding $\Delta k$ in a Taylor series around $\omega_i$ and $\omega_s$, and by only considering the first order, that

$$\left|\Delta\omega_s^{\text{small gain}}\right| = \left|\Delta\omega_i^{\text{small gain}}\right| \simeq (2\pi/Lb) \qquad (1.7.3.94)$$

with $b = [1/v_g(\omega_i)] - [1/v_g(\omega_s)]$, where $v_g(\omega) = \partial\omega/\partial k$ is the group velocity.

This linewidth can be termed intrinsic because it exists even if the pump beam is parallel and has a narrow spectral spread.

For type I, the spectral linewidth of the signal and idler waves is largest at the degeneracy: $b = 0$ because the idler and signal waves have the same polarization and so the same group velocity at degeneracy, *i.e.* $\omega_i = \omega_s = \omega_p/2$. In this case, it is necessary to consider the dispersion of the group velocity $\partial^2\omega/\partial^2 k$ for the calculation of $\Delta\omega_s$ and $\Delta\omega_i$. Note that an increase in the crystal length allows a reduction in the linewidth.

For type II, $b$ is never nil, even at degeneracy.

A parametric amplifier placed inside a resonant cavity constitutes an optical parametric oscillator (OPO) (Harris, 1969; Byer, 1973; Brosnan & Byer, 1979; Yang *et al.*, 1993). In this case, it is not necessary to have an incident signal wave because both signal and idler photons can be generated by spontaneous parametric emission, also called parametric noise or parametric scattering (Louisell *et al.*, 1961): when a laser beam at $\omega_p$ propagates in a $\chi^{(2)}$ medium, it is possible for pump photons to spontaneously break down into pairs of lower-energy photons of circular frequencies $\omega_s$ and $\omega_i$ with the total photon energy conserved for each pair, *i.e* $\omega_s + \omega_i = \omega_p$. The pairs of generated waves for which the phase-matching condition is satisfied are the only ones to be efficiently coupled by the nonlinear medium. The OPO can be singly resonant (SROPO) at $\omega_s$ or $\omega_i$ (Yang *et al.*, 1993; Chung & Siegman, 1993), doubly resonant (DROPO) at both $\omega_s$ and $\omega_i$ (Yang *et al.*, 1993; Breitenbach *et al.*, 1995) or triply resonant (TROPO) (Debuisschert *et al.*, 1993; Scheidt *et al.*, 1995). Two main techniques for the pump injection exist: the pump can propagate through the cavity mirrors, which allows the smallest cavity length; for continuous waves or pulsed waves with a pulsed duration greater than 1 ns, it is possible to increase the cavity length in order to put two 45° mirrors in the cavity for the pump, as shown in Fig. 1.7.3.18. This second technique allows us to use simpler mirror coatings because they are not illuminated by the strong pump beam.

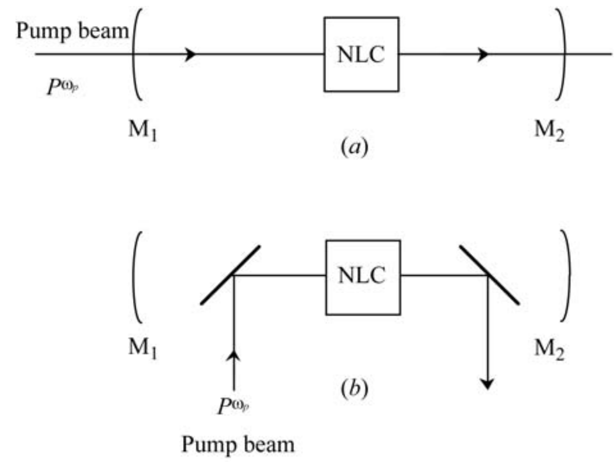


Fig. 1.7.3.18. Schematic OPO configurations. $P^{\omega_p}$ is the pump power. (*a*) can be a SROPO, DROPO or TROPO and (*b*) can be a SROPO or DROPO, according to the reflectivity of the cavity mirrors ($M_1$, $M_2$).

The only requirement for making an oscillator is that the parametric gain exceeds the losses of the resonator. The minimum intensity above which the OPO has to be pumped for an oscillation is termed the threshold oscillation intensity $I_{\text{th}}$. The oscillation threshold decreases when the number of resonant frequencies increases: $I_{\text{th}}^{\omega_p}$(SROPO) > $I_{\text{th}}^{\omega_p}$(DROPO) > $I_{\text{th}}^{\omega_p}$(TROPO); on the other hand the instability increases because the condition of simultaneous resonance is critical.

The oscillation threshold of a SROPO or DROPO can be decreased by reflecting the pump from the output coupling mirror $M_2$ in configuration (*a*) of Fig. 1.7.3.18 (Marshall & Kaz, 1993). It is necessary to pump an OPO by a beam with a smooth optical profile because hot spots could damage all the optical components in the OPO, including mirrors and nonlinear crystals. A very high beam quality is required with regard to other parameters such as the spectral bandwidth, the pointing stability, the divergence and the pulse duration.

The intensity threshold is calculated by assuming that the pump beam is undepleted. For a phase-matched SROPO, resonant at $\omega_s$ or $\omega_i$, and for nanosecond pulsed beams with intensities that are assumed to be constant over one single pass, $I_{\text{th}}^{\omega_p}$ is given by

$$I_{\text{th}}^{\omega_p} = \frac{1.8}{KL^2(1+\gamma)^2}\left\{\frac{25L}{c\tau} + 2\alpha L + Ln\left[\frac{1}{(1-T)^{1/2}}\right] + Ln(2)\right\}^2. \qquad (1.7.3.95)$$

$K = (\omega_s\omega_i\chi_{\text{eff}}^2)/[2n(\omega_s)n(\omega_i)n(\omega_p)\varepsilon_o c^3]$; $L$ is the crystal length; $\gamma$ is the ratio of the backward to the forward pump intensity; $\tau$ is the 1/e$^2$ half width duration of the pump beam pulse; and $2\alpha$ and $T$ are the linear absorption and transmission coefficients at the circular frequency of the resonant wave $\omega_s$ or $\omega_i$. In the nanosecond regime, typical values of $I_{\text{th}}^{\omega_p}$ are in the range 10–100 MW cm$^{-2}$.

(1.7.3.95) shows that a small threshold is achieved for long crystal lengths, high effective coefficient and for weak linear losses at the resonant frequency. The pump intensity threshold must be less than the optical damage threshold of the nonlinear crystal, including surface and bulk, and of the dielectric coating of any optical component of the OPO. For example, a SROPO using an 8 mm long $KNbO_3$ crystal ($d_{\text{eff}} \simeq 10$ pm V$^{-1}$) as a nonlinear crystal was performed with a pump threshold intensity of 65 MW cm$^{-2}$ (Unschel *et al.*, 1995): the 3 mm-diameter pump beam was a 10 Hz injection-seeded single-longitudinal-mode Nd:YAG laser at 1.064 µm with a 9 ns pulse of 100 mJ; the SROPO was pumped as in Fig. 1.7.3.18(*a*) with a cavity length of 12 mm, a mirror $M_1$ reflecting 100% at the signal, from 1.4 to