

1.7. NONLINEAR OPTICAL PROPERTIES

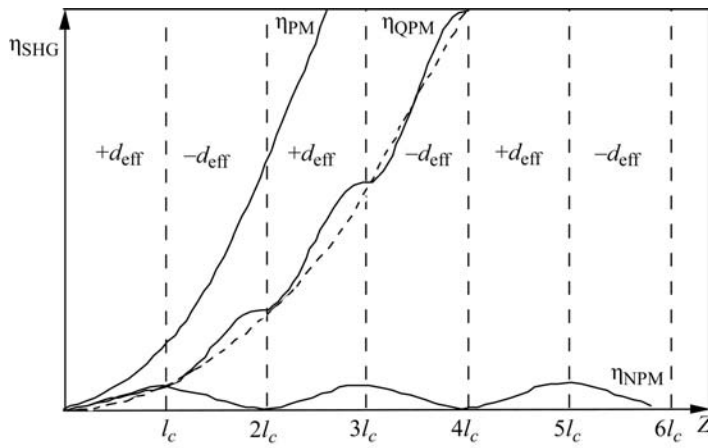


Fig. 1.7.3.7. Spatial growth evolution of second harmonic conversion efficiency, η_{SHG} , for non phase matching (NPM), $\Delta k \neq 0$, and phase matching (PM), $\Delta k = 0$, in a 'continuous' crystal, and for quasi phase matching (QPM) in a periodic structure. The dashed curve corresponds to $(4/\pi^2)\eta_{\text{PM}}(Z)$ where η_{PM} is the conversion efficiency of the phase-matched SHG. $l_c = \pi/\Delta k$ is the coherence length.

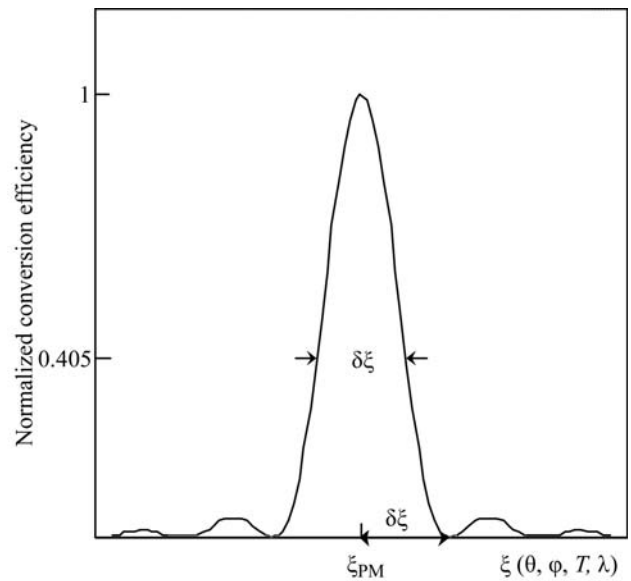


Fig. 1.7.3.8. Conversion efficiency evolution as a function of ξ for a given crystal length. ξ denotes the angle (θ or φ), the temperature (T) or the wavelength (λ). ξ_{PM} represents the parameter allowing phase matching.

conventions given in Section 1.7.2.2, the contracted field-tensor components for the phase-matched SHG are

$$\begin{aligned} F_{i1} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_x^+(\omega)]^2 \\ F_{i2} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_y^+(\omega)]^2 \\ F_{i3} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_z^+(\omega)]^2 \\ F_{i4} &= 2\mathbf{e}_i^-(2\omega)\mathbf{e}_y^+(\omega)\mathbf{e}_z^+(\omega) \\ F_{i5} &= 2\mathbf{e}_i^-(2\omega)\mathbf{e}_x^+(\omega)\mathbf{e}_z^+(\omega) \\ F_{i6} &= 2\mathbf{e}_i^-(2\omega)\mathbf{e}_x^+(\omega)\mathbf{e}_y^+(\omega) \end{aligned}$$

for type I and

$$\begin{aligned} F_{i1} &= \mathbf{e}_i^-(2\omega)\mathbf{e}_x^+(\omega)\mathbf{e}_x^-(\omega) \\ F_{i2} &= \mathbf{e}_i^-(2\omega)\mathbf{e}_y^+(\omega)\mathbf{e}_y^-(\omega) \\ F_{i3} &= \mathbf{e}_i^-(2\omega)\mathbf{e}_z^+(\omega)\mathbf{e}_z^-(\omega) \\ F_{i4} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_y^+(\omega)\mathbf{e}_z^-(\omega) + \mathbf{e}_y^-(\omega)\mathbf{e}_z^+(\omega)] \\ F_{i5} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_x^+(\omega)\mathbf{e}_z^-(\omega) + \mathbf{e}_x^-(\omega)\mathbf{e}_z^+(\omega)] \\ F_{i6} &= \mathbf{e}_i^-(2\omega)[\mathbf{e}_x^+(\omega)\mathbf{e}_y^-(\omega) + \mathbf{e}_x^-(\omega)\mathbf{e}_y^+(\omega)] \end{aligned}$$

for type II, with $i = (1, 2, 3)$ for F_{ij} , corresponding to $i = (x, y, z)$ for $\mathbf{e}_i^-(2\omega)$.

The ratio $d_{\text{eff}}^2/n_3^2\omega n_1^\omega n_2^\omega$ in formula (1.7.3.42) is called the figure of merit of the direction considered. The effective coefficient is given in Section 1.7.5 for the main nonlinear crystals and for chosen SHG wavelengths.

(ii) *Effect of the phase mismatch.*

The interference function $\sin^2(\Delta kL/2)$ is a maximum and equal to unity only for $\Delta k = 0$, which defines the phase-matching condition. Fig. 1.7.3.7 shows the effect of the phase mismatch on the growth of second harmonic conversion efficiency, η_{SHG} , with interaction distance Z .

The conversion efficiency has a Z^2 dependence in the case of phase matching. The harmonic power oscillates around Z^2 for quasi phase matching, but is reduced by a factor of $4/\pi^2$ compared with that of phase-matched interaction (Fejer *et al.*, 1992).

An SHG phase-matching direction ($\theta_{\text{PM}}, \varphi_{\text{PM}}$) for given fundamental wavelength (λ_{PM}) and type of interaction, I or II, is defined at a given temperature (T_{PM}). It is important to consider the effect of deviation of Δk from 0 due to variations of angles ($\theta_{\text{PM}} \pm d\theta, \varphi_{\text{PM}} \pm d\varphi$), of temperature ($T_{\text{PM}} \pm dT$) and of wave-

length ($\lambda_{\text{PM}} \pm d\lambda$) on the conversion efficiency. The quantities that characterize these effects are the acceptance bandwidths $\delta\xi$ ($\xi = \theta, \varphi, T, \lambda$), usually defined as the deviation from the phase-matching value ξ_{PM} leading to a phase-mismatch variation Δk from 0 to $2\pi/L$, where L is the crystal length. Then $\delta\xi$ is also the full width of the peak efficiency curve plotted as a function of ξ at 0.405 of the maximum, as shown in Fig. 1.7.3.8.

Thus $L\delta\xi$ is a characteristic of the phase-matching direction. Small angular, thermal and spectral dispersion of the refractive indices lead to high acceptance bandwidths. The higher $L\delta\xi$, the lower is the decrease of the conversion efficiency corresponding to a given angular shift, to the heating of the crystal due to absorption or external heating, or to the spectral bandwidth of the fundamental beam.

The knowledge of the angular, thermal and spectral dispersion of the refractive indices allows an estimation of $\delta\xi$ by expanding Δk in a Taylor series about ξ_{PM} :

$$\frac{2\pi}{L} = \Delta k = \left. \frac{\partial(\Delta k)}{\partial\xi} \right|_{\xi_{\text{PM}}} \delta\xi + \frac{1}{2} \left. \frac{\partial^2(\Delta k)}{\partial\xi^2} \right|_{\xi_{\text{PM}}} (\delta\xi)^2 + \dots \quad (1.7.3.43)$$

When the second- and higher-order differential terms in (1.7.3.43) are negligible, the phase matching is called critical (CPM), because $L\delta\xi \simeq |2\pi/[\partial(\Delta k)/\partial\xi]_{\xi_{\text{PM}}}|$ is small. For the particular cases where $\partial(\Delta k)/\partial\xi|_{\xi_{\text{PM}}} = 0$, $L\delta\xi = \{|4\pi L/[\partial^2(\Delta k)/\partial\xi^2]_{\xi_{\text{PM}}}| \}^{1/2}$ is larger than the CPM acceptance and the phase matching is called non-critical (NCPM) for the parameter ξ considered.

We first consider the case of angular acceptances. In uniaxial crystals, the refractive indices do not vary in φ , leading to an infinite φ angular acceptance bandwidth. $\delta\theta$ is then the only one to consider. For directions of propagation out of the principal plane ($\theta_{\text{PM}} \neq \pi/2$), the phase matching is critical. According to the expressions of n_o and $n_e(\theta)$ given in Section 1.7.3.1, we have

$$(1) \text{ for type I in positive crystals, } n_e(\theta, \omega) = n_o(2\omega) \text{ and}$$

$$L\delta\theta \simeq 2\pi/\{- (\omega/c)n_o^3(2\omega)[n_e^{-2}(\omega) - n_o^{-2}(\omega)] \sin 2\theta_{\text{PM}}\}; \quad (1.7.3.44)$$

(2) for type II in positive crystals, $2n_o(2\omega) = n_e(\theta, \omega) + n_o(\omega)$ and