# Čerenkov second harmonic generation in nonlinear crystals

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**Abstract:** We investigate the role of the fundamental beam width on Cerenkov second harmonic generation in periodically poled crystal. We show that broader beam yields stronger signal and enhanced wavelength sensitivity of the emission process.

The efficient parametric process requires phase compensation of optical dispersion of the nonlinear medium. The technique of choice nowadays is the so called quasi-phase matching which involves spatially periodic modulation of the sign of the $\chi^{(2)}$ nonlinearity [1]. This is commonly achieved in ferroelectric crystals by periodic poling [2].

The quasi-phase matched optical parametric processes have been intensively studied in schemes of collinear interaction, where the direction of propagation of the fundamental wave coincides with a normal to the walls of the domains [the boundaries between the positive and negative domains, see Fig. 1(a)]. In this case the reciprocal vectors representing spatial modulation of the nonlinearity are parallel to the wave vectors of the interacting waves. In the simplest case of second harmonic generation (SHG) the so called quasi-phase matching condition which maximizes the interaction, reads $k_2$-$2k_1$=$mG_0$, where $k_1$, $k_2$ represent wave vectors of the fundamental and second harmonic waves, $G_0$=$2\pi/\Lambda$ is reciprocal vector with $\Lambda$ being the period of $\chi^{(2)}$ modulation, and $m$ is an integer representing the order of QPM interaction.

Recently there has been a strong interest in the noncollinear second harmonic generation via the so-called Čerenkov-type quasi-phase matching [3,4]. With the fundamental beam propagating along the domain walls, the Čerenkov second-harmonic (SH) is observed as a conical wave defined by the longitudinal phase matching condition $k_2\cos\theta=2k_1$, where $\theta$ is the Čerenkov angle [see Fig. 1(b,c)]. While several works reported the observation of Čerenkov SHG in homogenous bulk nonlinear crystal it has been shown that this type of SHG is much more easily observed in periodic media as the $\chi^{(2)}$ modulation can greatly enhance the harmonic emission intensity [4]. The exact physical origin of this enhancement is still unclear and it is a subject of intense investigations considering either the role of

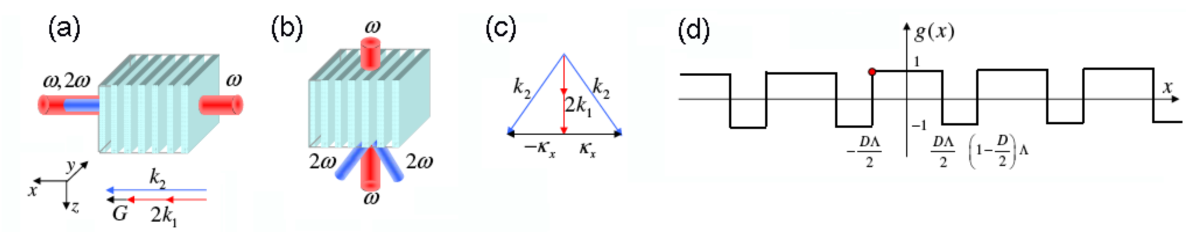


Fig.1 (a) Traditional quasi-phase matched SHG with fundamental beam propagating along normal to the domain walls ($x$-axis). (b) Čerenkov-type SHG with fundamental wave directed along the domain walls (z-axis). (c) The triangle constructed by the vectors $k_2$, $2k_1$, and $\kappa_x$ when the Čerenkov phase-matching condition is fulfilled. (d) Schematic representation of the spatially periodic nonlinearity (g(x)). Here D represents the duty factor.

the reciprocal vectors of the nonlinear photonic structure [5] or enhancement of the quadratic nonlinearity on the domain walls. For traditional QPM interactions with the $\chi^{(2)}$ modulation coinciding with the propagation direction of the pump wave, [see Fig. 1(a)], the intensity of the emitted SH is mainly defined by the crystal physical size. Therefore, the beam width of the fundamental wave does not affect greatly the SH emission in this scheme. Here we show that the situation is quite different in the Čerenkov-type SHG. With the fundamental beam propagating along the domain walls, as shown in Fig. 1(b), only those domains that are illuminated by the beam contribute to the nonlinear optical interaction.

For our analytical studies we choose the $LiNbO_3$ crystal as the nonlinear medium. Its nonlinear coefficient $d_{22}$=1.1 pm/V and its ordinary refractive index is given by the corresponding Sellmeier formula. The crystal length is assumed to be 500 μm and the poling period is set to Λ=9μm. The duty cycle is set as D=0.5319. Unless otherwise specified, the pump Gaussian beam is located centrally at the position of $x_0$=-DΛ/2, i.e. it coincides exactly with one of the domain walls [see Fig. 1(d)].

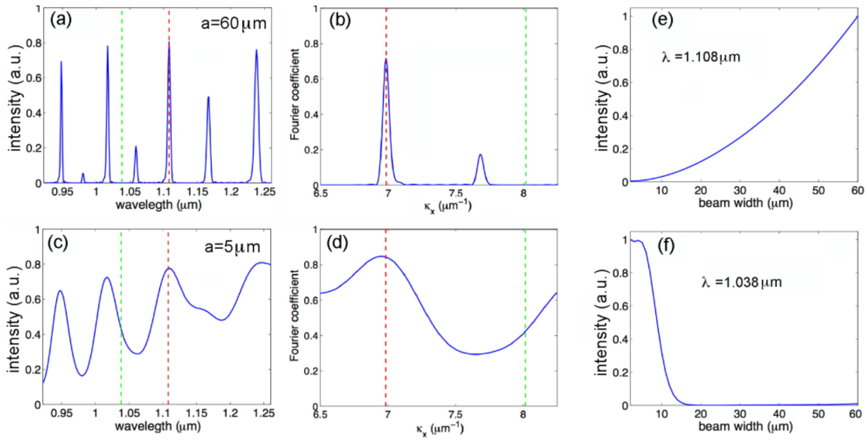


Fig.2 (a,c) The spectral response of the Čerenkov SHG for a beam size of (a) 60 μm and (b) 5 μm. (b-d) Corresponding spatial Fourier spectra of the Čerenkov emission. (e-f) Intensity of the Čerenkov SHG as a function of the beam width for different wavelengths of the fundamental beam.

We first consider the role of the beam width on the dependence of the second-harmonic intensity on the wavelength of the fundamental wave. In Fig. 2(a,b) we show the wavelength response, i.e. the value of the intensity of the Čerenkov second harmonic generated by the fundamental Gaussian wave with different beam widths. In these simulations we assumed that the peak intensity of the fundamental beam was kept constant which represent closely experimental situation when the beam width could be adjusted by optical system. It is very interesting to see that, depending on the value of a, the wavelength tuning curves show quite different behaviors. When we use a relatively wide beam, of a=60μm [Fig. 2(a)], the Čerenkov signal shows a series of sharp peaks as the wavelength varies. At these peak wavelengths the intensity of the emitted signal is quite high [e.g. at $\lambda_1$=1.108μm, marked by the red line in Fig. 2(a)], while at the other positions it falls dramatically (e.g. at $\lambda_1$=1.038m, marked by the green line). When the beam width is reduced to 5μm, as shown in Fig.2 (c), the wavelength tuning peeks of the Čerenkov second harmonic become much broader and even overlap. Moreover, while the previously (i.e. for a= 60μm) strongest peaks decrease the emission at the wavelengths which previously led to weak signal now significantly increases. This behavior is clearly illustrated in Fig.2 (e,f) which show dependence of the intensity of the emitted second harmonic as a function of the fundamental beam width for two wavelengths of the fundamental beam.

For very narrow fundamental beam (comparable with the domain width) one needs to consider the effect of the center position of this beam with respect to domain structure. To this end, in Fig. 3(a) we show the calculated Čerenkov second harmonic intensity as function of the position of the fundamental beam. The beam width is set to a=2, 4 and 15 μm, respectively and the fundamental wavelength is $\lambda_1$=1.108μm. For clarity, we also indicate in this figure the considered domain structure (the positive domains are marked by gray color). It can be seen that with a narrow fundamental beam (e.g. a=2 μm and 4 μm), the Čerenkov emission is much stronger when the center of the fundamental beam is positioned exactly on or close to the domain wall. The second harmonic becomes rather weak

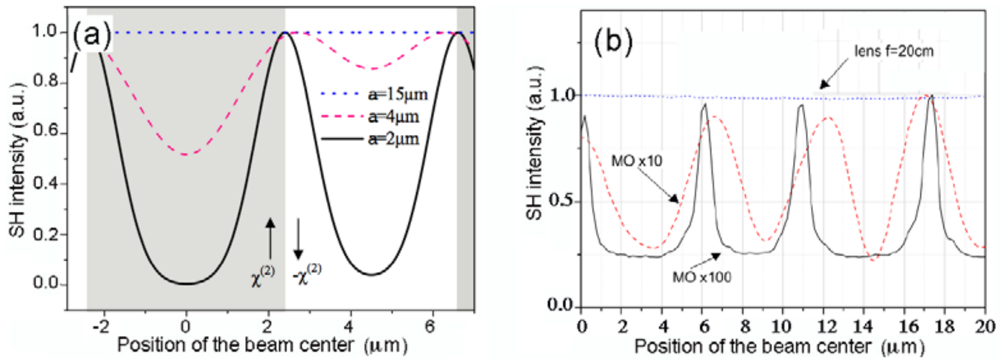


Figure 3. The Ĉerenkov second harmonic intensity as a function of the location of the fundamental beam. (a) theory (b) experiment. The gray and white blocks represent the positive and reversed domains, respectively. It is clear that in the case of narrow beam, the Ĉerenkov SH is stronger when the beam is located exactly at domain wall.

when
fundamental beam moves away from the domain wall. This enhancement of Čerenkov emission by the domain walls agrees quite well with our previous experimental results [5]. When a wider fundamental beam is used (e.g. a=15 μm) the center position of the beam does not affect the Čerenkov second harmonic intensity significantly. This is because in this case the fundamental beam covers almost the same number of domain walls no matter where it is located. Plots in Fig.3 (b) illustrate experimentally recorded Čerenkov signal in periodically poled lithium niobate for varying position of the fundamental beam. The fundamental beam was focused in the sample using either ×100, ×10 microscope objectives or 20cm lens. This led to the effective beam size raging from few to tens of microns. One can see that the emission peaks broaden with the beam size l they completely disappear for very broad fundamental beam.

In conclusion, we studied analytically the Čerenkov harmonic generation by a Gaussian wave in one-dimensional periodically poled $LiNbO_3$ crystal. In particular, we considered the dependence of the harmonic radiation on the beam width of the fundamental wave. We found that the second harmonic produced by the fundamental wave with a small beam width has a broader wavelength tuning response than that formed by a wider beam. We also demonstrated that for very narrow fundamental beam the efficiency of the Čerenkov emission critically depends on the beam position with respect to domain wall.

**References**


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