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Idler energy dependence of nonlinear diffraction in X → X + EUV parametric down-conversion

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The idler energy dependence was investigated for the rocking curve of nonlinear diffraction in parametric down-conversion of X-rays into extreme ultraviolet. The line shape of the rocking curve changed drastically from a nearly Lorentzian peak to a dip as the idler energy decreased. The rocking curve was analyzed using the Fano formula.

1. Introduction

Parametric down-conversion is one of the most fundamental nonlinear process, where a photon (the pump) is converted into two photons (the signal and the idler). A unique feature of the parametric down-conversion in the X-ray region is that it is observed as nonlinear diffraction (Eisenberger & McCall, 1971; Danino & Freund, 1981; Yoda *et al.*, 1998; Adams *et al.*, 2000; Adams, 2003), when both the conservation of energy, $|K_p| = |K_s| + |K_i|$, and the conservation of momentum,

$$n_p K_p + Q = n_s K_s + n_i K_i, \quad (1)$$

are fulfilled. Here, K is the wavevector in vacuum, Q is the reciprocal-lattice vector, n is the refractive index. The subscripts p, s and i denote the physical quantities for the pump, the signal and the idler waves, respectively. The momentum conservation (phase matching) is achieved by using Q, leading to the nonlinear diffraction.

Recently, the rocking curve in the parametric down-conversion of X-rays into extreme ultraviolet (X → X + EUV parametric down-conversion) was measured with sufficient accuracy, and was found to be asymmetric, while a Lorentzian line shape was predicted theoretically (Tamasaku & Ishikawa, 2007). At present, the underlying mechanism of the asymmetric rocking curve is unknown. In this short note, we will report the idler energy dependence of the rocking curve in X → X + EUV parametric down-conversion to provide the experimental evidence for theoretical investigation.

2. Experimental

The experiment was performed at RIKEN SR physics beamline (BL19LXU) at SPring-8 (Yabashi *et al.*, 2001). We used a high-quality synthetic type IIa diamond (Tamasaku *et al.*, 2005) as a nonlinear crystal. The photon flux of the pump wave was 9.3×10^{11} photons s^{-1} at an energy of $E_p = 11.0$ keV. The energy of the signal wave was selected to be $E_s = E_p - \Delta E$ by a bent crystal analyzer with the Ge 220 reflection and an NaI scintillation counter. The idler wave at $E_i = \Delta E$ could not be measured due to strong absorption in the EUV region. The other parameters were the same as the previous report (Tamasaku & Ishikawa, 2007).

We used a special geometry for phase matching (Fig. 1), where the signal wave counter-propagated with the idler wave (Danino & Freund, 1981). In this geometry, the phase-matching condition (1) may be written as

$$|K_p + Q| = |K_s| - n_i|K_i|. \quad (2)$$

Here, the refractive indices in the X-ray region were set to unity. When ΔE was decided, the orientation of Q for the exact phase matching was given uniquely by (2).

The rocking curve was measured with the 111 nonlinear diffraction in the reflection geometry. The measured angular range extended over two degrees, so that the scattering angle, Θ, to detect the signal wave was changed according to a geometrical relation, $\cos\Theta = K_p(K_p + Q)/|K_p||K_p + Q|$. This scan corresponded to the so-called θ–2θ scan in X-ray reflectometry.

3. Results and discussion

Fig. 1 shows the rocking curves measured at various phase-matching conditions from $\Delta E = 40$ to 130 eV. The glancing angle, $\Delta\theta$, was measured from the Bragg angle, θ_B, at E_p. The exact phase matching was realized at a slightly higher angle than θ_B by $\Delta\theta_0$. The calculated phase-matching angle varied from $\Delta\theta_0 = 0.098^\circ$ at $\Delta E = 40$ eV to 2.52° at 130 eV. The X → X + EUV parametric down-conversion was observed at the calculated angle, $\Delta\theta_0$, except for $\Delta E = 40$ eV.

As evidenced by Fig. 1, the line shape of the rocking curve depended strongly on ΔE, *i.e.* E_i and E_s. The rocking curve, which was nearly Lorentzian at $\Delta E = 130$ eV, became asymmetric gradually as ΔE decreased. The peak became weaker and the dip more pronounced. For smaller ΔE, the rocking curve became symmetric but was characterized by the dip. The magnitude of signal wave increased monotonically as ΔE decreased, then vanished suddenly at 40 eV.

Now we would like to analyze the rocking curve using the Fano formula (Fano, 1961). Here, we assumed an interference effect between the phase-matched parametric down-conversion, considered as the discrete level, and the Compton scattering, considered as the continuum excitation (Tamasaku & Ishikawa, 2007). One of the most controversial points of the interpretation is the fact that the final state of the parametric down-conversion might be different from that of the Compton scattering even when absorption of the idler wave is taken into account, so that the interference effect could not be expected.

The rocking curves were fitted by the Fano formula,

$$I(\Delta\theta) = I_0\left[\frac{(q+\varepsilon)^2}{1+\varepsilon^2} - 1\right] + b(\Delta\theta), \quad (3)$$

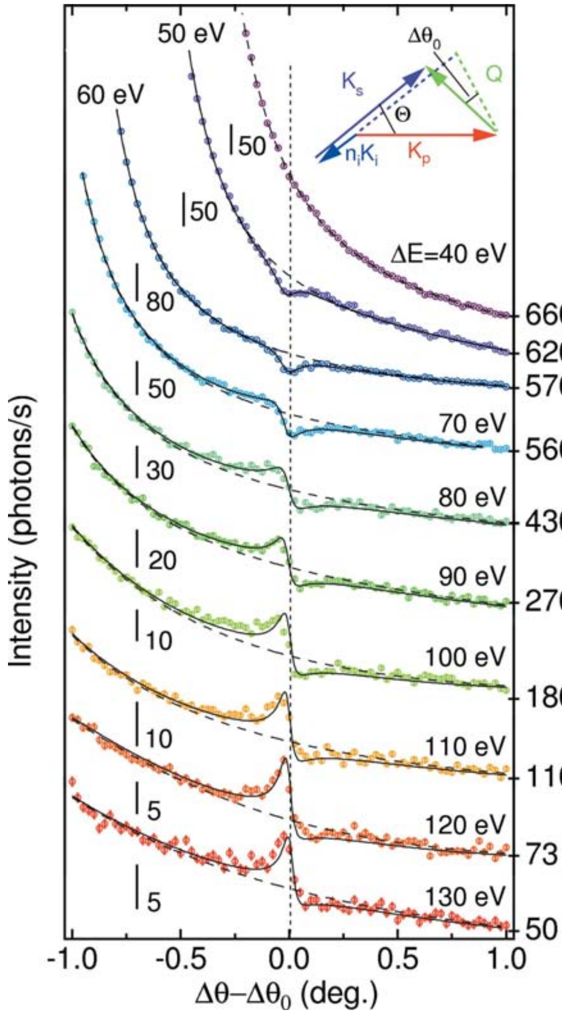

Figure 1
Rocking curves of nonlinear diffraction measured at various phase-matching conditions from $\Delta E = 40$ to 130 eV. The solid line is fitting with (3). The dashed line is the estimated background with (4). The vertical bar indicates the scale for each curve. The inset shows the schematic phase-matching geometry. The broken lines correspond to the Bragg diffraction ($E_i = 0$).

where q is the asymmetric parameter, $\varepsilon = 2[K_s(\Delta\theta) - K_s(\Delta\theta_0 + \beta)]/\Gamma$, $K_s(\Delta\theta)$ is calculated by (2), Γ is the linewidth, β is an offset angle to fit (3) to the measured rocking curve and $b(\Delta\theta)$ is background.

We used a phenomenological function to fit the background,

$$b(\Delta\Theta) = c_1/\Delta\theta^2 + c_2/\Delta\theta + c_3\Delta\theta + c_4, \quad (4)$$

which reproduced the background well (Fig. 1). Here, the first two terms represented contribution from elastic scattering, and the rest from the Compton scattering. Note that the Compton scattering decreased for larger $\Delta\theta$ due to self-absorption, and the elastic part increased at smaller $\Delta\theta$ and ΔE, where the phase-matching geometry approached the Bragg condition.

The rocking curves were fitted well by (3) with the fitting parameters, I_0, q and Γ, plotted in Fig. 2. The magnitude of the other fitting parameter, $|\beta|$, was less than 0.01°. The energy dependence of I_0 was much steeper than the theoretical prediction, $I_0 \propto \Delta E^{-3}$ (Freund, 1972). At smaller ΔE below 60 eV, I_0 dropped suddenly. The asymmetric parameter changed gradually from $q = 2.0$, which represented the Lorentzian-like peak, to $q = 0$ corresponding to the

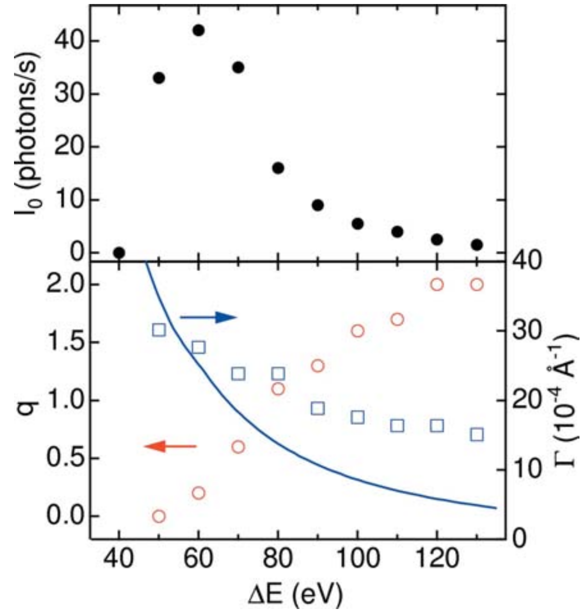

Figure 2
Energy dependence of I_0 (closed circle), q (open circle) and Γ (open square). The solid line in the lower panel is $\Gamma = 2\mu_i$.

dip. The line width at smaller ΔE was comparable to the width of the phase-matching condition, which is given by $2\mu_i$ (Tamasaku & Ishikawa, 2007). Here, μ_i is the amplitude attenuation coefficient of diamond for the idler wave (Henke *et al.*, 1993). However, Γ deviated from the theoretical curve at larger ΔE. The deviation may be accounted for by the finite aperture of the detector, and the energy bandwidth of incidence.

4. Concluding remarks

The rocking curve of nonlinear diffraction in X → X + EUV parametric down-conversion showed the strong idler energy dependence, which we consider as a key test of theoretical models of nonlinear diffraction and X → X + EUV parametric down-conversion.

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