Unified approach to nonlinear Cerenkov radiation in waveguides and bulk media

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We show the nonlinear Cerenkov radiation in bulk media and waveguides represents a particular type of nonlinear Bragg diffraction. It is therefore possible to describe them uniformly by considering the modulation of nonlinear polarization.

Key words: Nonlinear Cerenkov radiation; harmonic geneartion; nonlinear photonic crystal; nonlinear waveguide

I. INTRODUCTION

Nonlinear Cerenkov Second Harmonic Generation (CSHG) [1] is a special type of frequency doubling process that attracts lots of attention due to its versatile applications in all-optical processing and non-destructive visualization of ferroelectric domains. For a fundamental wave propagating in a normally dispersive nonlinear medium, the emitted Cerenkov Second Harmonic (SH) propagates at an angle $\cos\theta=2\boldsymbol{k}_1/\boldsymbol{k}_2$, with $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ representing the wave vectors of the fundamental and second harmonic waves, respectively. Figure 1(a) illustrates emission of Cerenkov SH signal as a cone in an as-grown strontium barium niobate crystal.

The common practical realizations of the Cerenkov frequency conversion involve either planar waveguides [2] or bulk crystals with a spatially modulated second-order nonlinear coefficient $\chi^{(2)}$ [3]. Accordingly, different theoretical approaches have been used to describe interaction in these two systems separately. In this contribution we show that the nonlinear Cerenkov processes in both planar waveguide and bulk nonlinear photonic crystal represent a particular type of the so-called nonlinear Bragg diffraction and hence can be described in uniform way by considering the spatial modulation of the nonlinear polarization. We also present experimental results that provide additional support of these conclusions.

II. CERENKOV SHG AS A NONLINEAR BRAGG DIFFRACTION

The amplitude of the Cerenkov signal can be written into the following formula if one considers the frequency conversion assuming undepleted fundamental beam:

$$E_{SH} \propto L\int_{-\infty}^{\infty}\chi^{(2)}(x)E^{2}(x)e^{ik_c x}dx \qquad (1)$$

Here κ_c denotes the transverse component of the wave-vector of the Cerenkov second harmonic. It is clear that the amplitude of the SH is given by just a Fourier integral of the nonlinear polarization. Obviously this integral acquires large value only when its kernel exhibits fast spatial modulation which can be achieved either by varying the strength of nonlinearity or by using strongly spatially localized fundamental beam, or both.

In Fig. 1(b) we depict far-field SH distributions versus the propagation distance, calculated using Eq. (1) with the fundamental beam propagating along $\chi^{(2)}$/-$\chi^{(2)}$ boundary in a $LiNbO_3$ crystal. The strong emission of CSHG is observed around ±28.6°, agreeing well with the experimental observations [3]. In figure Fig.1(c) we depict the normalized intensity of Cerenkov signal emitted in a waveguide geometry as a function of waveguide width (2***d***) for the case when the nonlinearity is located in the guiding layer (red/solid line) or substrate (black/dashed line). The lines are obtained with the simple Eq.(1), while points represent results of the exact numerical simulation of the nonlinear wave functions. The excellent agreement between the exact and simplified approach confirms the simple physical picture of the emission process based on spatial modulation of nonlinear polarization.

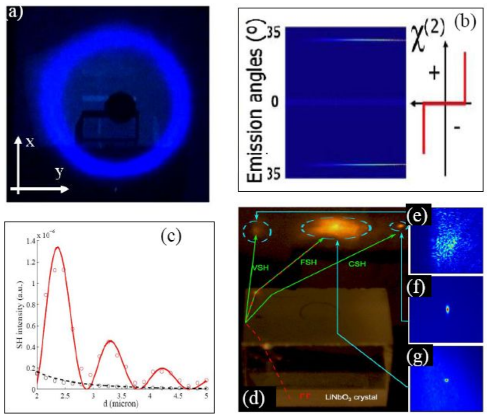

Fig. 1 (a) Experimentally recorded Cerenkov conical SH emission from as-grown strontium barium niobate crystal. (b) Far-field SH distribution when the fundamental beam propagates along the $\chi^{(2)}$/-$\chi^{(2)}$ boundary in a LiNbO3 crystal. (c) Normalized strength of Cerenkov signal excited by the fundamental mode of the symmetric waveguide as a function of the waveguide width (2d). (d-g) Experiment of Cerenkov emission at the boundary of a nonlinear crystal.

To complement our theoretical discussions we also provide a clear experimental evidence of our analysis. As shown in Figs. 1(d), we shine the fundamental beam across the boundary of a nonlinear crystal, where the second-order nonlinear coefficient changes from its value to zero. We observed three SH beams exiting the surface of the crystal, among which we confirm that the right one [Fig. 1(f)] is generated by the Cerenkov-type phase matching.

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