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Influence of stochastic deviations of domain boundary and varying effective index on difference frequency mixing in quasi-phase-matching waveguides

Li Yunchu [a,*], Qingpu Wang [a], Xingyu Zhang [a,*], Dongfeng Yuan [a], Zejin Liu [a], Zongfu Jiang [a], Zhaojun Liu [a], Shutao Li [a], Shuzhen Fan [a], Shaojun Zhang [b]

[a] *School of Information Science and Engineering, Shandong University, Jinan 250100, PR China*
[b] *State Key Laboratory of Crystal Materials, Shandong University, Jinan 250100, PR China*

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Abstract

Influence of stochastic deviations of domain boundary and varying effective index on the conversion efficiency of difference frequency mixing (DFM) in quasi-phase-matching waveguides are analyzed. By simplifying the coupled equations of DFM in waveguide according to the actual situation, we provide analytical expressions of the conversion efficiency for the first time. Four models for random errors of domains and variations of effective index are investigated. The results demonstrate that, when the effective index varies regularly along the waveguide, the normalized conversion efficiency $\hat{\eta}$ of DFM is dramatically reduced and the curves of $\hat{\eta}$ on phase mismatch are no longer sinc^2 function but ripple profiles, which is different from the situation in bulk crystals. With the same magnitude, random period error cast much larger effect on $\hat{\eta}$ than random duty cycle error, which is similar with the case in bulk crystals.

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1. Introduction

As the demand for optical fiber communications bandwidth grows, the implementation of signal processing functions using all-optical techniques becomes increasingly attractive. In recent years, a number of methods have been used

* Corresponding authors.
E-mail addresses: xyz@sdu.edu.cn (X. Zhang), wayofflying@yahoo.com.cn (L. Yunchu).

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to perform functions such as wavelength conversion for WDM systems and all-optical switching, etc. [1–5]. People are showing increasingly interests on optical frequency mixers implemented using annealed proton exchanged (APE) waveguides in periodically poled lithium niobate. In a difference frequency mixer, inputs at frequencies ω_p (pump) and ω_s (signal) generate an output at frequency $\omega_{out} = \omega_p - \omega_s$ (wavelength-converted-signal). For communication applications, operation is typically near degeneracy, where the signal and output wavelengths are both in the 1.55 μm band, and the pump is around 0.78 μm [6]. These devices consist of APE waveguides in periodically poled lithium niobate (PPLN). The electric poled process is described in [7].

Limited by the fabrication technique, the actual parameters of periodically poled crystals always have some deviations from those of ideal structures. In bulk periodically poled crystals, the effect of the random errors of domains and deviations of temperature, wavelength and period length on second harmonic generation has been analyzed by Fejer et al. [8]and that on singly resonant oscillation by Yunchu et al. [9]. However, the case in waveguides is somewhat more complicated in that the electric field consists of multiple waveguide transverse modes instead of uniform planewaves. In addition, the effective indices are determined by more parameters, such as the thickness and width of the waveguides, and show more complex variation. Investigations on effect of the random errors of domains and varying effective index on QPM-DFM would be significant to optimize the design of difference frequency mixers in waveguides. In our former work, we have fabricated periodically poled $LiNbO_3$ crystal [10]. In this paper, we investigated influence of stochastic deviations of domain boundary and varying effective index on QPM-DFM in waveguides under the assumption of low conversion efficiency and continuous-wave (cw) or long-pulse interaction. The results demonstrate that, when effective index varies regularly along the waveguide, the normalized conversion efficiency $\hat{\eta}$ of DFM is dramatically reduced and the curves of $\hat{\eta}$ on phase mismatch are no longer sinc^2 function but ripple profiles, which is different from the situation in bulk crystals. With the same magnitude, random period errors cast much larger effect on $\hat{\eta}$ than random duty cycle error, which is similar with the case in bulk crystals.

2. Theoretical approach

Both the theoretical description of second-order nonlinear interaction and the coupling of energy in waveguides have been treated by several authors [11–13]. The electric field is expanded in frequency and in terms of the waveguides transverse modes. The z-axis is taken to be the axis of the fiber, then the electric field is [14]

$$\vec{E}(x,y,z,t) = \sum_{l,m} \vec{e}_{lm} A_{\mathrm{lm}}(z) \varepsilon_m(x,y) \times \exp[\mathrm{i}(\beta_{lm} z - \omega_l t + \Phi_{\mathrm{lm}})] + c.c., \quad (1)$$

where l refers to the frequency, m the mode number, β_{lm} the wavevector, Φ_{lm} the phase, A_{lm} the amplitude, $\vec{e}_{lm}$ the polarization vector, ε_m the transverse distribution and ω_l the frequency. Considering that the transverse distribution $\epsilon_m(x, y)$ is normalized, we have [15]

$$\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \varepsilon_m(x,y) \varepsilon_m^*(x,y)\, \mathrm{d}x\, \mathrm{d}y = 1. \quad (2)$$

For the sake of simplicity, we limit the pump, signal and wavelength-converted-signal waves to single modes labeled p, s and c [14]. The coupled wave equations for DFM are described as:

$$\frac{\mathrm{d}A(\omega_\mathrm{s},z)}{\mathrm{d}z} = \mathrm{i}\frac{\omega_\mathrm{s}}{n_\mathrm{s} c} \mathrm{d}(z) I_{\mathrm{vol}} A(\omega_\mathrm{p},z) A^*(\omega_\mathrm{c},z) \mathrm{e}^{\mathrm{i}\Delta\beta z}, \quad (3a)$$

$$\frac{\mathrm{d}A(\omega_\mathrm{c},z)}{\mathrm{d}z} = \mathrm{i}\frac{\omega_\mathrm{c}}{n_\mathrm{c} c} \mathrm{d}(z) I_{\mathrm{vol}} A(\omega_\mathrm{p},z) A^*(\omega_\mathrm{s},z) \mathrm{e}^{\mathrm{i}\Delta\beta z}, \quad (3b)$$

$$\frac{\mathrm{d}A(\omega_\mathrm{p},z)}{\mathrm{d}z} = \mathrm{i}\frac{\omega_\mathrm{p}}{n_\mathrm{p} c} \mathrm{d}(z) I^*_{\mathrm{vol}} A(\omega_\mathrm{s},z) A(\omega_\mathrm{c},z) \mathrm{e}^{-\mathrm{i}\Delta\beta z}, \quad (3c)$$

where c is the light speed in vacuum space, d(z) consists of domains of nonlinear $\pm d_{\mathrm{eff}}$ with sign α_k changing at the position z_k, i.e., $\mathrm{d}(z) = \alpha_k d_{\mathrm{eff}} = (-1)^k d_{\mathrm{eff}}$. I_{vol} and $\Delta\beta$ are as follows [15]:

$$I_{\mathrm{vol}} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \varepsilon_\mathrm{p}(x,y) \varepsilon_\mathrm{s}^*(x,y) \varepsilon_\mathrm{c}^*(x,y)\, \mathrm{d}x\, \mathrm{d}y, \quad (4)$$