REALIZATION OF QUASI-PHASE-MATCHED PARAMETRIC INTERACTIONS OF WAVES OF MULTIPLE FREQUENCIES WITH SIMULTANEOUS FREQUENCY DOUBLING

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Abstract

It is shown that nondegenerate optical parametric amplification of three waves with multiple frequencies $\omega$, $2\omega$, $3\omega$ and frequency doubling can be quasi-phase-matched simultaneously in media with spatially modulated nonlinear susceptibility. This provides the conditions for 100%-efficient frequency conversion of a pump wave ($3\omega$) to signal one ($2\omega$). Examples of simultaneous realization of parametric amplification for waves with multiple frequencies and second optical harmonic generation in lithium niobate crystals with a regular domain structure are given.

1. Introduction

Recently [1] it has been shown that the interaction of three waves with multiple frequencies $\omega$, $2\omega$, $3\omega$ in a nonlinear medium with quadratic nonlinearity can lead to a remarkable feature, namely, to total energy transfer from the pump wave ($3\omega$) to the signal one ($2\omega$). This evident violation of the Manley–Row relation, according to which the conversion efficiency in the above process cannot be greater than $2/3$, is associated with simultaneous energy conversion from the idler wave ($\omega$) to the signal one ($2\omega$). The features of the process dynamics were analyzed in [1], as well. On the other hand, in homogeneous nonlinear media (both optically positive and negative), it seems impossible to accomplish collinear phase matching for frequency doubling and nondegenerate parametric amplification simultaneously.

The main goal of the work was to demonstrate that both of the above-mentioned processes can be quasi-phase-matched in media with spatially modulated nonlinear susceptibility, which provides the conditions for 100%-efficient frequency conversion of the pump wave ($3\omega$) to the signal one ($2\omega$). We consider a lithium niobate crystal with a regular domain structure [2] as a medium with spatially modulated nonlinear susceptibility (see Fig. 1.)

These ferroelectric crystals possess a unique feature: having alternating signs in domains with opposite direction of the spontaneous polarization vector, and the physical properties described by the odd-rank polarization tensors are spatially modulated. Corresponding examples are pyro-, piezo-, linear electrooptic, photovoltaic effects and quadratic optical nonlinearity. Currently, lithium niobate crystals with a regular domain structure sufficient for different applications are produced successfully [3]. The potential of these crystals as an efficient material for, as an example, optical parametric oscillators [4] is completely recognized now.
Fig. 1. Lithium niobate crystal with regular (periodic) domain structure. Function $g(y)$ describes the modulation of the nonlinear susceptibility. Layers of the structure are in the $XZ$ plane. Arrows in the structure layers indicate the direction of the spontaneous polarization vector in adjacent domains.

2. Theoretical Approach: the Slowly Varying Amplitude Equations and the Second Simplification Method

The equations describing the parametric interaction of waves with multiple frequencies and slowly varying complex amplitude are as follows

$$\frac{dA_1}{dy} = -i\beta_3 g(y) A_3 A_2^* \exp(-i\Delta k_3 y) - i\beta_2 g(y) A_2 A_1^* \exp(-i\Delta k_2 y),$$

$$\frac{dA_2}{dy} = 2i\beta_3 g(y) A_3 A_1^* \exp(-i\Delta k_3 y) - i\beta_2 g(y) A_1 A_2^* \exp(i\Delta k_2 y),$$

$$\frac{dA_3}{dy} = 3i\beta_3 g(y) A_1 A_2 \exp(i\Delta k_3 y),$$

where $A_j$ are the amplitudes of interacting waves ($j = 1, 2, 3$), $\Delta k_3 = k_3 - k_2 - k_1$ and $\Delta k_2 = k_2 - 2k_1$ are the phase mismatches, $k_j$ are the wave numbers, $\beta_2$ and $\beta_3$ are the absolute values of nonlinear coupling coefficients, and $g(y)$ is a sign-alternating periodic function that describes the modulation of nonlinear susceptibility (see Fig. 1),

$$g(y) = \Phi(y) + 2 \sum_{n=1}^{N-1} (-1)^n \Phi(y - nl) + (-1)^N \Phi(y - nl),$$

where $\Phi(y)$ is the Heaviside step function, $n$ is the number of a layer in the regular domain structure, $l$ is the thickness of a layer, and $N$ is the the total number of layers in the structure. Note that Eqs. (1) differ from those given in [1] by the spatial nonuniformity of nonlinear coefficient $[g(y) \neq 1]$. 