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İntracavity laser frequency mixing under quasi-phase-matching condition

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Abstract

The current study describes frequency conversion processes in a poly domain consisting of two phases of "grating" modulation of nonlinear susceptibility (i.e., from four consecutively organized domains). As a result, the complex amplitudes of interaction waves at the outlet of each main serve as the entry values for the equivalent complex amplitudes in the subsequent domain. The factors that limit the effectiveness of frequency conversion have been investigated. In addition, the scenario of n domains has been considered. Furthermore, in this approximation, coherent length is found to be dependent on task characteristics such as basic radiation intensity and medium losses, as well as interaction wave mismatch. Constant-intensity approximation allows for a more rigorous analysis of nonlinear interaction of waves in regular domain structure (RDS) compared to constant-field approximation, which does not consider the given change. It has been found that selecting suitable pump intensity and phase ratio settings can greatly improve conversion efficiency when compared to the noncavity arrangement. The examination of η3(lj) indicates that as the main number increases, the steepness of dependence reduces. In other words, the process of frequency conversion has reached saturation. Using two domains increases conversion efficiency by 3.69, three domains by 1.97, four domains by 1.46, five domains by 1.22, and six domains by 1.02. As a result, the transit through the layer domains from the right to the left efficiently transfers laser radiation energy to energy of the sum-frequency wave [η3(l6), practically, achieves 100%]. Under realistic experimental conditions, numerical estimates closely match predicted efficiencies.The suggested theoretical method can be used to investigate parametric intracavity frequency conversion.

Keywords: Regular domain structure, frequency conversion, coherent length, intracavity, efficience, constant intensity approximation
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1. Introduction

Compact laser systems capable of generating high-intensity coherent radiation across a wide spectral range constitute an important category of nonlinear optical devices [1-4]. To enhance nonlinear interaction, intracavity configurations are commonly employed, as they effectively extend the interaction length within the nonlinear medium and simultaneously increase the intensity of the fundamental field. Compared with single-pass schemes, intracavity approaches provide notable benefits, including reduced system size, lower fabrication costs, and improved conversion efficiency with higher output power.

Among available nonlinear materials, MgO-doped periodically poled lithium niobate (MgO:PPLN) is particularly attractive for the development of low-cost, compact lasers operating at watt-level powers, such as those designed by our research group for laser display technologies and biomedical applications [1-3]. The fabrication process of MgO:PPLN enables the production of relatively long crystals with large transverse apertures (approximately 0.5–1 mm), which significantly exceed the typical beam diameters inside laser cavities (generally below 100 μm) [4-6]. The substantial volume of existing studies on MgO:PPLN highlights the importance of establishing reliable empirical relationships to support the design, optimization, and performance prediction of laser systems based on this material.

Intracavity frequency conversion represents a unified process in which the generation of the fundamental radiation and the nonlinear frequency transformation occur simultaneously within the same resonator. Under such conditions, the relative phase relationships among the interacting waves play a decisive role in determining the overall conversion efficiency. Phase mismatches or fluctuations directly influence the efficiency of sum-frequency generation, making phase effects a central factor in intracavity nonlinear interactions. Consequently, a detailed theoretical analysis is required to examine the influence of phase evolution on conversion performance and to identify optimal operating conditions. In this context, the constant-intensity approximation, which accounts for the phase behavior of all interacting waves, provides a suitable framework for modeling and analyzing intracavity frequency conversion processes.

2. Method of calculation

The theoretical study was built upon the optical approach described in [2,3]. We now consider the RDS, which consists of a sequence of layers with inverted quadratic nonlinearity arranged within the laser cavity.

Taking losses into account, the described process of quasi-phase-matched intracavity sum-frequency wave generation can be analyzed using the following set of simplified equations [5].

$$\frac{dA_1^{\pm}}{dz} \pm \delta_1 A_1^{\pm} = \mp i\gamma_1 A_3^{\pm}\left(A_2^{\pm}\right)^* exp(\pm i\Delta z),$$
$$\frac{dA_2^{\pm}}{dz} \pm \delta_2 A_2^{\pm} = \mp i\gamma_2 A_3^{\pm}\left(A_1^{\pm}\right)^* exp(\pm i\Delta z), \qquad (1)$$
$$\frac{dA_3^{\pm}}{dz} \pm \delta_3 A_3^{\pm} = \mp i\gamma_3 A_1^{\pm} A_2^{\pm}\, exp(\mp i\Delta z).$$

The boundary conditions for the nonlinear interaction of waves are defined as follows:

$$A_{1,n}(z=0) = A_{1,n-1}^{out} exp(i\varphi_{1,n}),$$
$$A_{2,n}(z=0) = A_{2,n-1}^{out} exp(i\varphi_{2,n}), \qquad (2)$$
$$A_{3,n}(z=0) = A_{3,n-1}^{out} exp(i\varphi_{3,n}),$$

in this context, z ~ 0 corresponds to the entrance of the nth domain. The complex amplitudes of the laser wave, pump wave, and sum-frequency wave at the entrance of the nth domain are denoted by A1,n, A2,n, and A3,n, respectively. The phase shifts at the boundary between the (n−1)th and nth domains for the frequencies ω1 , ω2, and ω3 are represented by ϕ1,n, ϕ2,n, and ϕ3,n respectively.
Assuming optimal phase matching between the interacting waves $\psi + \operatorname{atan}\left(\frac{2\lambda_5/\Delta}{tam(\lambda_5 l_5)}\right) = \pi m, m = 1,2,\ldots$, (3) the conversion efficiency to the sum-frequency wave in the fifth domain can be expressed by the following equation.

$$\eta_3(l_5) = \eta_3(l_4) exp(-2\delta_3 l_5) \times$$
$$\times \left\{ \boldsymbol{cos^2 \lambda_5 l_5} + \left[-\left(\frac{\Delta}{2} - \frac{\lambda_4^2}{\Delta - \frac{\lambda_3^2}{\frac{\lambda_2^2}{\Delta}}} \right) - \frac{\Delta}{2} \right]^2 \frac{\boldsymbol{sin^2 \lambda_5 l_5}}{\lambda_5^2} \right\} \qquad (4)$$

3. Results and discussion

Theoretical investiqation shows that, as the number of domains increases, the corresponding dependences become progressively less steep, indicating that the frequency-conversion process approaches saturation. Specifically, the use of two domains enhances the conversion efficiency by a factor of 3.69, while three, four, five, and six domains lead to efficiency increases of 1.97, 1.46, 1.22, and 1.02 times, respectively.

Figure 1. shows the evolution of the frequency-conversion process in a nondissipative medium. The dependence of the conversion efficiency η3(lj) on the selected domain lengths Γ1lj is presented for a fixed phase-mismatch parameter Δ/2Γ2=3.5.

Figure 2. illustrates how the intracavity conversion efficiency varies with the number of domains for two different phase mismatch values: $\Delta/2\Gamma_2 \approx 3.5$ (dashed line 1) and 3.7 (solid line 2 and dotted line 3).

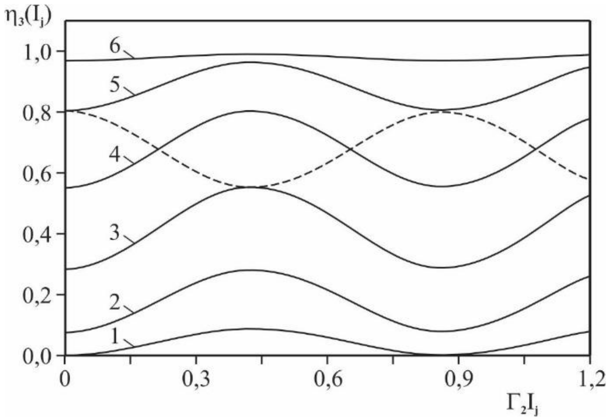

Fig. 1. Dependence of the $\boldsymbol{\eta_3(l_j)}$ on specified domain length $\boldsymbol{\Gamma_1 l_j}$ at $\boldsymbol{\Delta/2\Gamma_2 = 3,5}$.

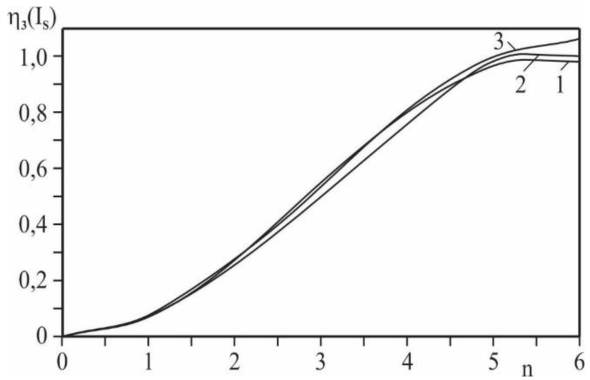

Fig. 2. Dependences of intracavity frequency conversion $\boldsymbol{\eta_3(l_5)}$ on number of domains calculated in CIA (curve 1 and 2) and in the constant field approximation (curve 3) where $\boldsymbol{\psi = \psi_{opt}\lambda_j I_{j,opt} = \pi/2\ (j = 1/4), \delta_3 = 0, \Delta/2\Gamma_2 = 3,5\ (1) and\ \Delta/2\Gamma_2 =,7\ (2,3)}$

4. Conclusion

The analysis of the conversion efficiency η3(lj) demonstrates that increasing the number of domains leads to a progressive reduction in the slope of the efficiency dependence, indicating the onset of saturation in the frequency conversion process. While the introduction of additional domains initially results in a significant enhancement of conversion efficiency—most notably with two and three domains—the incremental gain decreases substantially as the number of domains increases. Specifically, the efficiency improvement factors decline from 3.69 for two domains to nearly unity for six domains, showing that further domain multiplication yields diminishing returns.

This behavior confirms that efficient energy transfer from the fundamental laser radiation to the sum-frequency wave occurs during propagation through the layered domain structure, particularly when moving from right to left. Under optimal conditions, the conversion efficiency $\eta_3(l_6)$ approaches unity, corresponding to nearly complete energy transfer. Moreover, numerical simulations performed under realistic experimental parameters exhibit good agreement with the theoretical predictions, supporting the validity of the proposed model.

Overall, the presented theoretical framework provides a reliable and effective approach for analyzing and optimizing parametric intracavity frequency conversion processes. It can serve as a useful tool for the design and performance evaluation of nonlinear optical devices employing multilayer domain structures.

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