Phase Effects at third-Harmonic Generation in ZnO/PMMA Nanocomposite Films

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Abstract-- Theoretical investigation of frequency conversion in ZnO/PMMA structures with account for phase effects has been developed. For this the constant-intensity approximation of fundamental radiation is applied. The given approximation permits to take into account simultaneously an influence of phase mismatch and losses in medium on proceeding of nonlinear process. The numerical calculation of the efficacy, obtained in the constant-intensity approximation, confirms the next fact that at higher concentrations of ZnO, the films generate stronger third harmonic signal due to the larger interaction length of the nonlinear medium. It is shown that at the chosen pump intensity of laser radiation, it is possible to calculate the coherent length of a crystal converter as well. The analytical method also permits to estimate the expected conversion efficiency on different wavelengths of laser radiation. Method of analysis of third-harmonic generation in ZnO/PMMA structures, developed in the present work, may be used for investigation of other nanocomposite films.

Index Term-- Nanocomposite film; polymethylmethacrylate; third-harmonic generation; constant-intensity approximation; frequency conversion.

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INTRODUCTION

The main privilege of third-harmonic generations (THG) is that because we are dealing with high frequency this will result in electronic nonlinearity. ZnO crystals are extensively used in microelectronic and optoelectronic devices because of their wide range of application. They are being used specifically in the areas of solar cells, liquid crystal display and UV lasers. These materials are under extensive studies because of their applications in industrial regards that requires optoelectronics devices functioning at shorter wavelengths [3]. The possibility to get a nonlinear optical response in thin films is practically attractive, especially since they can be easily used for integrated nonlinear optical devices [1-5].

As it is mentioned in [6], it should be said that preparing bulk crystals is not very economic due to the use of expensive methods for crystal growth and also requirement of longer time for process. A series of works, for instance [2-6], are dedicated to the third order nonlinear optical properties of zinc oxide thin films. Authors of Ref. [2] studied the influence of silver and copper dopants on the nonlinear optical properties in ZnO films. It was established that the second and third harmonic generation intensity in these films are dependent on the doping material and its amount. In [3] the third order nonlinear optical properties of ZnO films have been investigated in experiment using z-scan method and the large nonlinear absorption effect was revealed by authors. In the Ref. [6] UV- induced second harmonic generation was applied to investigate the second harmonic signal in ZnO samples. It was shown that this harmonic generation behavior for the ZnO films depends on the grain sizes of films prepared by electron sputtering technique. In these works, the authors make an analysis of frequency conversion, particularly in the constant-field approximation (CFA) [1-8].

The simultaneous calculation of phase change and the losses of the interacting waves are possible to make in the constant-intensity approximation (CIA), [9], with regard to the reverse reaction of the excited wave on pump wave. Besides, in this approximation, it is found that the coherent length depends on such parameters like the basic radiation intensity and losses in the medium in addition to mismatch of interacting waves [10].

Thus, in the present article, we have carried out the theoretical analysis of influence of size and concentration of ZnO nanoparticles on cubic nonlinearity of ZnO/PMMA nanocomposite films. A comparison was made between the theoretical and experimental results for two samples of ZnO/PMMA 1 and ZnO/PMMA 2 with various concentrations of ZnO nanoparticles.

THEORY

As is known, THG may occur in any material, in contrast to SHG, obtaining only in materials which are noncentrosymmetric. For this reason, we will consider the dynamics of energy exchange between the waves of the fundamental radiation and third harmonic in the two layers (film+substrate) while each layer is signified with the cubic effective susceptibility \( \chi^{(3)}_f \) and \( \chi^{(3)}_{subst} \), respectively. We carried out the research in analogy to our own investigation in [11]. We will produce consecutive calculations of the nonlinear interaction from layer to layer in the structure. In the general case of dissipating nonlinear media, the process of direct third-harmonic generation in a separately considered layer is described by the corresponding reduced equations. The method of calculations assumes a solution of the problem with appropriate boundary conditions where the output parameters of the preceding layer are the input parameters of the subsequent layer.

We will investigate the process of frequency tripling in the first layer that is ZnO/PMMA film. The reduced equations describing THG in the first layer, taking into account the medium losses, read as follows [8]
\[
\frac{dA_1}{dz} + \delta^f A_1 = -i\gamma^f A_3^2(A_1^*)^2 \exp(i\Delta_f z),
\]
\[
\frac{dA_3}{dz} + \delta^f A_3 = -i\gamma^f A_1^3 \exp(-i\Delta_f z),
\]
where \(A_{1,3}\) are the complex amplitudes of the pump wave and third harmonic wave at frequencies \(\omega_{1,3}\) \((\omega_3 = 3\omega_1)\) and \(\delta^f\) and \(\gamma^f\) are the absorption coefficients and nonlinear coefficients of interacting waves for ZnO/PMMA film at corresponding frequencies \(\omega_j\) \((j = 1, 3)\).

\[
\gamma^f = \left(3\pi^2 / n^f \lambda^f_1\right)\chi^{(3)}_f, \quad \gamma^f = \left(3\pi^2 / n^f_3 \lambda^f_1\right)\chi^{(3)}_f,
\]
\(n^f_{1,3}\) are the refractive indices of film at frequencies \(\omega_{1,3}\), \(\lambda^f_1\) is the wavelength of the pump radiation, and

\[
A_3(\ell_1) = -i\gamma^f (t_{sf}^{3f}) A_3^{\ell_1} \cdot \text{sinc} \lambda^f_1 \ell_1 \cdot \exp \left[2i\varphi_{10} - \left(\delta^f_3 + 3\delta^f_1 + i\Delta_f\right)\ell_1 / 2\right],
\]
where \(\lambda^f_{1,3} = 3\Gamma^2_{1,3} - \left(\delta^f_3 - 3\delta^f_1 - i\Delta_f\right)^2 / 4\).

As it follows from Equation 3, the basic and harmonic fields energy interchange takes place periodically and as a result, spatial variations of the third harmonic field is observed. This time, the minimums of harmonic intensity beating, as an analysis shows in CIA, depend on nonlinear susceptibilities of substances by a simple way more precise than in the CFA [13].

Now, we consider the generation of the third harmonic in the second layer, i.e. in the substrate. The behavior of the complex amplitudes in this case are also described by the system of Equations 1, but the nonlinear coefficients in the second layer are denoted as \(\gamma^f_{\text{subs}}\), the phase mismatch of the waves is \(\Delta_{\text{sub}} = k^f_3 - 3k^f_1\), and the initial values of the complex amplitudes of the fundamental radiation and third harmonic are determined by the values at the output of the first layer, i.e., the boundary conditions are as follows:

\[
A_{1,3}(z = 0) = i\varphi \cdot A_{1,3}(\ell_1) \exp(i\varphi_{1,3}(\ell_1)).
\]
Here \(\varphi_{1,3}(\ell_1)\) is the wave-phase change at the transition from the first to the second layer at frequencies \(\omega_{1,3}\), respectively, \(t_{sf}^{3f}\) are the Fresnel transmission coefficients for film-substrate boundary for fundamental and harmonic beam and \(z = 0\) again corresponds to the input but of the second layer,

\[
A_1(\ell_1) = t_{sf}^{3f} A_{10} \left[\cos \lambda^f_1 \ell_1 + \left(\delta^f_3 - 3\delta^f_1 + i\Delta_f\right) \sin \lambda^f_1 \ell_1 / 2 \lambda^f_1 \right]^{1/2} \exp \left[i\varphi - \left(\delta^f_3 + 3\delta^f_1 + i\Delta_f\right) \ell_1 / 6\right].
\]
In CIA, by solving the system of Equations 1 and taking into account condition (4) for the complex amplitude of the third harmonic at the output of the second layer \(z = \ell_2\), we get \(\delta^f_3 = 3\delta^f_1\) [13]
\[ A_3 (\ell_2) = t_{fs}^{3\omega} \cdot t_{sa}^{3\omega} \cdot A_3 (\ell_1) \left\{ \cos \lambda_2 \ell_2 + \left[ \lambda_2 \text{ctg} \ell_1 + \frac{i \Delta_f - i \Delta_{\text{sub}}}{2} \left( \frac{\gamma_3^{\text{sub}}}{\gamma_3} e^{i \varphi} - \frac{i \Delta_{\text{sub}}}{2} \right) \sin \lambda_2 \ell_2 \right] \times \exp \left[ i \varphi (\ell_1) - \delta_{3 \text{sub}} \ell_2 + i \Delta_{\text{sub}} \ell_2 / 2 \right] \right\}, \]

where \( t_{sa}^{3\omega} \) is the Fresnel transmission coefficients for substrate-air boundary for harmonic beam.

\[ \psi = 3 \varphi_1 (\ell_1) - \varphi_2 (\ell_1) - \Delta_f \ell_1, \quad \lambda_2^2 = 3f^2 + \Delta_{\text{sub}}^2 / 4, \]
\[ \Gamma_2 = \gamma_1^{\text{sub}} / \gamma_3^{\text{sub}} \Gamma_1 (\ell_1). \]

\[ \eta_3 (\ell_2) = \left( t_{sa}^{3\omega} \right)^2 \left( t_{fs}^{3\omega} \right)^2 \eta_3 (\ell_1) \left[ \cos \lambda_2 \ell_2 + c_1 \sin \frac{\lambda_2 \ell_2}{\lambda_2} \right]^2 + b^2 \sin^2 \frac{\lambda_2 \ell_2}{\lambda_2} \exp (-2 \delta_3 \ell_2), \]

where
\[ c_1 = \frac{\gamma_3^{\text{sub}}}{\gamma_3} \lambda_2 \text{ctg} \ell_1, \quad b = \left( \frac{\gamma_3^{\text{sub}}}{\gamma_3} \Delta_f - \Delta_{\text{sub}} \right) / 2. \]

Here, \( \eta_3 (\ell_1) = I_3 (\ell_1) / I_{10} \) is the efficiency of conversion to the third harmonic when the wave passes through the first layer and it is determined from Equation 3.

The phase mismatch of the fundamental and third harmonic waves within the Zno/PMMA film and PMMA can be expressed as

\[ \frac{\Delta_f}{2} = \frac{6 \pi}{\lambda_1} \ell \left( n_f \cos \theta_3^{\text{sub}} - n_1 \cos \theta_1^{\text{sub}} \right), \]
\[ \frac{\Delta_{\text{sub}}}{2} = \frac{6 \pi}{\lambda_1} \ell \left( n_3^{\text{sub}} \cos \theta_3^{\text{sub}} - n_1^{\text{sub}} \cos \theta_1^{\text{sub}} \right). \]

where \( \theta_1^{\text{sub}}, \theta_3^{\text{sub}} \) are the refractive angles for fundamental and third harmonic waves of the film and substrate while \( n_3^{\text{sub}} \) and \( n_1^{\text{sub}} \) are the refractive indices for the substrate at frequencies \( 3 \omega \) and \( \omega \). The refractive indices have been evaluated according to the Sellmeier model [14-16].

Under consideration case, when the nonlinear material is a crystalline particle inside the polymeric film in [6], the notion of equivalent thickness of nonlinear medium inside PMMA \( d_{\text{ZnO}}^{\text{equivalent}} \) is being used and signifies the thickness which could have ZnO nanocrystals without host PMMA

\[ d_{\text{ZnO}}^{\text{equivalent}} = \frac{\% \text{ wt}_{\text{ZnO}} \rho_{\text{PMMA}} \ell_1}{100 - \% \text{ wt}_{\text{ZnO}} \rho_{\text{ZnO}}}, \]

where \( \rho_{\text{PMMA}} \) and \( \rho_{\text{ZnO}} \) are densities of PMMA and ZnO, respectively, and \( \% \text{ wt}_{\text{ZnO}} \) is the weight concentration of ZnO nanocrystals inside a polymeric matrix. In Equation 7, instead of ordinary thickness \( \ell_1 \) of Zno/PMMA film, we used the introduced equivalent thickness according to [6].

\[ \ell_{\text{eff}} = d_{\text{ZnO}}^{\text{equivalent}} / \cos \theta, \]

where \( \theta \) is the incidence angle of laser beam.

**RESULTS AND DISCUSSION**

In Figures 1-7, the dynamic process of frequency conversion is shown for the third harmonic in ZnO/PMMA structures. The dependencies are carried out taking into
account the phase effects at nonlinear wave interaction due to the analysis in CIA. Here, we have also considered the refraction phenomena in the structure, different values of losses at fundamental wavelength and harmonic wave frequencies, different concentration of ZnO in structures and Fresnel transmission coefficients. A numerical estimate of the expected transformation power to the third harmonic (under the published experimental conditions for the given ZnO nanocomposite [6]) was carried out based on an analysis in the CIA.

For a fundamental beam, there are considered the output beam of a Q-switched Nd doped yttrium aluminum garnet laser generating at $\lambda = 1064$ nm with 16 ps pulse duration and 10 Hz repetition rate. The fundamental beam has the s-polarization. The absolute value of the effective cubic susceptibility for this nanocomposite films is experimentally measured in the work [6]. In bulk nonlinear materials, where $\chi^{(3)} = 1.7 \times 10^{-21}$ m$^2$/V$^2$ [14], increasing of ZnO concentration leads to the growth of a cubic susceptibility. In case of the nanocomposite films, the opposite effect takes place. The surface effects in the films play defining role in comparison to volume effects that accounts for the transition to compound size which is about nanoscale [6].

In work [6], the value for the cubic susceptibility of ZnO/PMMA film has been obtained and is equal up to $5.7 \times 10^{-20}$ m$^2$/V$^2$. In [17], the value of the cubic order susceptibility of pure PMMA was estimated to be $3 \times 10^{-14}$ esu. According to Refs. 14-16 and 18, the Sellmeier's coefficients are experimentally established for ZnO. Using these values of coefficients, we'll calculate the ordinary and extraordinary refractive indices in case of third harmonic generation. Because of lack of experimentally measured value of the Sellmeier's coefficients for ZnO/PMMA at different weight concentrations (of ZnO nanocrystals inside a polymeric matrix), the same order of coefficients was supposed for the considered concentrations.

The numerical calculations of the analytical expression obtained in CIA on length of nonlinear interaction $\ell$ at different value of parameters are displayed in Figure 1 for ZnO/PMMA 1. From behavior of curves which differs from monotonous increase in case of CFA (curve 7), it follows that there exists optimum value of crystal length at which conversion efficiency is maximum. With decrease of pump intensity (compare curves 1, 3 and 5 or 2, 4 and 6) and increase of losses (compare curves 1 and 2; 3 and 4 or 5 and 6), the conversion efficiency falls down. In addition, an analysis of the behavior of the curves indicates that the period of spatial beatings and optimum length of crystal change. The latter is explained by the fact that at lower values of pump intensity or at higher losses for achievement of maximum conversion, longer geometrical lengths of crystal are required.

For the ZnO concentration of 16% wt at $I_{10} = 20$ GW/cm$^2$, according to expression obtained in CIA for optimal length, conversion efficiency is maximum at coherent length equal to 0.64 mcm (curve 6) for $\delta_3^{(f)} = 1.45 \times 10^4$ and equal to 0.54 mcm for $\delta_3^{(f)} = 1.81 \times 10^5$ cm$^2$ (curve 5). Analogical behavior depends on the ZnO nanocomposite [2].

Let us consider the behavior of conversion efficacy $\eta_3(\ell_1)$ at different value of ZnO concentration for example for the ZnO/PMMA 2 films (Figure 2). An increase of this concentration from 10% up to 15% permit to obtain for film the maximum efficiency which exceeds the initial values approximately $\sim 1.31$ times (curves 2 and 3). However, decreasing ZnO concentration from 5% to 10%, the conversion efficiency falls down approximately $\sim 4$ times (curves 1 and 4). This result from the fact particularly that at 5% ZnO concentration, the ZnO/PMMA 2 film possess cubic susceptibility, $\chi^{(3)}$, which is equal to $8.3 \times 10^{-20}$ m$^2$/V$^2$ occurring 1.5 times more great value than $\chi^{(3)}$ at other concentrations (10% and 15%). As expected, with growing losses approximately $\sim 2.42$ times, the conversion efficacy decreases 1.9 times (curves 1 and 2). The coherent length for these cases defines by expression obtained in CIA for optimal length [11].

In Fig. 3, there are the results of the dependencies of conversion efficacy to third harmonic on the reduced phase mismatch of interacting waves $\Delta \ell_1$. As one can expect, the curve for $\eta_3(\Delta \ell)$ depends on several parameters. As is seen in figure decreasing of conversion efficiency is observed by rising of weight concentrations of ZnO at fixed length of nonlinear interaction (curves 2 and 4) and decreasing pump intensity (curves 2 and 3) and losses (curves 1 and 2). The width of angular phase matching is reduced with decrease in pump intensity (compare curves 2 and 3) and with increase in weight concentrations of ZnO (compare curves 1 and 4).

Let us consider practical example of the nonlinear interaction of optical waves at third-harmonic generation in ZnO/PMMA compounds, in other words, let us estimate the efficiency of conversion to this wavelength for experimentally realized value of intensity of laser generation.

Figure 4 shows the effectiveness of frequency conversion in ZnO/PMMA 1 structure (for input laser wave intensities of $I_{10} \sim 20$ GW/cm$^2$) for the third harmonic as a function of the length of the structure. The effectiveness is signified by $\eta_3(\ell_1)$ (at the end of the first layer (solid curves 5-8) and later with $\eta_3(\ell_2)$ at the end of the second layer (dashed curves 1-4).

We get the same behavior for $\eta_3(\ell_{1,2})$ for the structure ZnO/PMMA 2 (Figure 5). The variation of length of nonlinear interaction in experiment were carried out by means of the rotation of the ZnO/PMMA 1$^{st}$ and 2$^{nd}$ structures, allowing to change of the incidence angle $\theta$. The difference of these films depends on the variation in the dimensions of
ZnO nanocrystals. As is seen in Figure 4, by decreasing the ZnO concentration (at losses obtained in experiment for corresponding concentration) the conversion efficiency falls down (compare curves 6-8 and 2-4). As the concentration of ZnO increase from 3% to 16%, the efficiency of frequency conversion increases almost 1.6 times. This result is due to the fact that on one side, with growth of ZnO concentration the absolute value of the effective cubic susceptibility decreases and on the other side, nanocrystal generates stronger cubic harmonic wave due to the larger interaction length of the nonlinear medium (see Figure 7). This fact was noted earlier in [6]. Also shown here, there are the differences of behavior of dependencies for concentration of 12 % for ZnO in ZnO/PMMA 1 nanocomposite film (curves 1 and 5). Such behavior of curves 1 and 5 can be explained by the experimental value of the losses, due to dispersion of losses, which are experimentally obtained in [6].

The change in angle, in the given diapason, would permit us to vary \( \ell_{\text{eff}} \) on nanometer scale. For 3% wt concentration of ZnO in ZnO/PMMA 1, the effective length, \( \ell_{\text{eff}} \), is changed in the range of 4.4-5.21 nm (curve 6), while for 7%, this range will be about 10.7-12.7 nm (curve 7), and for 12%, we will have the range of about 19-22.9 nm (curve 5), and also for concentration of 16%, it is changed in the range of 27-32.1 nm (curve 8). Thus, the numerical calculation of the efficacy obtained in CIA confirms the next fact that at higher concentrations of ZnO, the films generate stronger third harmonic signal due to the larger interaction length of the nonlinear medium (see Figure 6).

Let’s estimate the dependencies of the ratio of the third harmonic intensity (after transmitting from two layers) per cube of input laser intensity \( I_{3} / I_{10}^{3} \) in ZnO/PMMA 1 (curves 1 and 2) and ZnO/PMMA 2 nanocomposite films (curves 3 and 4) as a function of its ZnO weight concentrations. This is calculated by authors in CIA (dashed curves 1 and 3, correspondingly) (see Figure 7). As is known, the criterion of every analytical method is through experiment. Here, the results of the analogical experiment are given (solid curves 2 and 4) from [4]. It can be seen that the theoretical curve is consistent with the experimental curve which is given in the figure (dashed and solids curves 1 and 2 and 3, 4). The difference in the absolute value might be explained by the accuracy of the measured linear and nonlinear optical coefficients, for example, absorption coefficients, ZnO concentration, quadratic susceptibilities and etc.

**Conclusion**

Thus, theoretical investigation of frequency conversion in ZnO/PMMA structures with account for phase effects allows one to reveal the ways of increasing conversion efficiency. Namely at the given values of the length of crystal converter, it is possible to calculate the optimum value of pump intensity. Also at the chosen pump intensity of laser radiation, it is possible to calculate the coherent length of a crystal converter as well. The analytical method also permits to estimate the expected conversion efficiency on different wavelengths of laser radiation. Thus, the numerical calculation of the efficacy, obtained in CIA, confirms the next fact that at higher concentrations of ZnO, the films generate stronger third harmonic signal due to the larger interaction length of the nonlinear medium.

The results of carried out researches will be useful at elaborations of the modern devices of the quantum electronics and in the nanoscale optoelectronic circuitry. Method of analysis of third harmonic generation in ZnO/PMMA structures, developed in the present work, may be used for investigation of other nanocomposite films.

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**References**


Fig. 1. Dependencies of conversion efficiency of pump wave (\(\lambda=1.064\) mcm) to the wave of the third harmonic \(\eta_3(\ell_1)\) on effective length \(\ell_{\text{eff}}\) for ZnO/PMMA 1 nanocomposite films calculated in CIA (curves 1-6) and CFA (curve 7) for \(\Delta=1.28\times10^{4}\) cm\(^{-1}\), 16 % ZnO concentration, pump intensity of \(I_{10}=20\) GW/cm\(^2\) (curves 5-7), 13 GW/cm\(^2\) (curves 3 and 4), 7 GW/cm\(^2\) (curves 1 and 2) and \(\delta_3 = 3\delta_1 = 20\) (curve 7), 1.81\times10^7 cm\(^{-1}\) (curves 1, 3 and 5), 1.45\times10^7 cm\(^{-1}\) (curves 2, 4 and 6).
Fig. 2. Dependencies of conversion efficiency of pump wave to wave of third harmonic $\eta_3(l_{1})$ calculated in CIA versus the effective length $l_{\text{eff}}$ for ZnO/PMMA 2 nanocomposite films for $\Delta=1.28*10^4$ cm$^{-1}$, pump intensity of $I_{10}=20$ GW/cm$^2$, 15% ZnO concentration (curve 3), 10% (curves 1 and 2) and 5% (curve 4), and $\delta_1=\delta_2=0.12*10^4$ cm$^{-1}$ (curves 2 and 3), $0.29*10^4$ cm$^{-1}$ (curves 1 and 4).
Fig. 3. Dependencies of conversion efficiency of pump wave to wave of third harmonic $\eta_3(I_1)$ as a function of the phase mismatch $\Delta' = \Delta l_1$ calculated in CIA for ZnO/PMMA 1 nanocomposite films with different ZnO concentration: 7% (curve 4) and 16% (curves 1-3) for $\delta_3 = 3\delta_1 = 1.086 \times 10^4 \text{cm}^{-1}$ (curves 1-4) at pump intensity of $I_{10} = 23 \text{ GW/cm}^2$ (curves 3), 15 GW/cm$^2$ (curves 1, 2 and 4).
Fig. 4 Dependencies of conversion efficiency of pump wave to wave of third harmonic $\eta_3(l_1)$ (curves 5-8), $\eta_3(l_2)$ (curves 1-4) calculated in CIA versus the incidence angle $\theta$ for ZnO/PMMA 1 nanocomposite films with different ZnO concentration: 3\% (curve 2 and 6), 7\% (curves 3 and 7), 12\% (curves 1 and 5) and 16\% (curves 4 and 8) at pump intensity of $I_{10} = 20 $ GW/cm$^2$ and $\delta_1^3 = 3\delta_1^3 = 1.81*10^4$ cm$^{-1}$ (curves 4 and 8), $1.46*10^4$ cm$^{-1}$ (curves 1 and 5), $1.6*10^4$ cm$^{-1}$ (curves 3 and 7) and $1.27*10^4$ cm$^{-1}$ (curves 2 and 6). The thickness of all films is equal to 1 mcm [4].
Fig. 5. Dependencies of conversion efficiency of pump wave to wave of third harmonic $\eta_3(l_1)$, $\eta_3(l_2)$ calculated in CIA versus the incidence angle $\theta$ for ZnO/PMMA 2 nanocomposite films with different ZnO concentration: 5% (curves 1 and 3), 10% (curves 2 and 4) and 15% (curves 5 and 6) at pump intensity of $I_{10} = 20$ GW/cm$^2$. $\delta_3 = 3\delta_1 = 0.06 \times 10^4$ cm$^{-1}$ (curves 1 and 3), $0.076 \times 10^4$ cm$^{-1}$ (curves 2 and 4) and $0.13 \times 10^4$ cm$^{-1}$ (curves 5 and 6). The thickness of all films is equal to 1 mcm [4].
Fig. 6. Dependencies of conversion efficiency of pump wave to wave of third harmonic $\eta_3(l_1)$ at pump intensity of $I_{10} = 20 \text{ GW/cm}^2$, $\delta_3 = 3\delta_1 = 0.06 \times 10^4 \text{ cm}^{-1}$ (curves 1 and 3), $0.076 \times 10^4 \text{ cm}^{-1}$ (curves 2 and 4) and $0.13 \times 10^4 \text{ cm}^{-1}$ (curves 5 and 6). The thickness of all films is equal to 1 mcm [4].
Fig. 7. Dependencies of the ratio $I_3 / I_{10}^3$ for ZnO/PMMA 1 (curves 1 and 2) and ZnO/PMMA 2 (curves 3 and 4) nanocomposite films on its ZnO weight concentrations calculated in the CIA (dashed curves 1 and 3, correspondingly). Experimental results are given (solid curves 2 and 4) from [4]. The thickness of all films is equal to 1 mcm [4].