Mathematical consideration of Phase-Matching bandwidth, effective nonlinear coefficient and the walk-off effect for $LiGa(Se_xS_{1-x})_2$ nonlinear crystals by using Genetic algorithm

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***Abstract* — In this paper the Phase-Matching bandwidth, effective nonlinear coefficient and the walk-off angle within the effective bandwidth of the $LiGa(Se_xS_{1-x})_2$ biaxial nonlinear crystals are calculated using the Genetic algorithm (GA). This calculation is held for all tree principle XY, YZ and XZ planes individually. The results are shown the accuracy of the applied algorithm is quite qualified.**

KEYWORDS: Nonlinear Optics**,** Phase matching, effective nonlinear coefficient, Walk-off, Genetic Algorithm.

I. INTRODUCTION

In the mid-infrared spectral region, important tunable laser sources such as optical parametric oscillators and difference frequency generators are capable for many spectroscopic applications providing wide tuning range and flexibility. The heart of such laser devices is the nonlinear optical crystal which must be transparent in the whole region of interacting input waves.

The most important phase matching condition for given pump, signal and idler wavelengths must be verified for securing maximum conversion efficiency. In a typical biaxial nonlinear crystal phase matching condition in three individual principal planes, e.g. XY, YZ and XZ planes should also be respected for wide variety of input wavelengths [1].

However, the interaction gain is determined by the effective nonlinear coefficient d_{eff} of the crystal. On the other hand the effective length of the crystal is also depend on the walk-off angle of the extra-ordinary interacting waves. Recently nonlinear crystals $LiGa(Se_xS_{1-x})_2$,($0<x<1$) are being used for infrared radiation via nonlinear conversion. They belong to mm2 group of biaxial nonlinear crystals, with relatively large d_{eff} and wide transparency range (0.32-13.2 μm) [2]. In this paper the Genetic algorithm is used for phase-matching, walk-off and d_{eff} calculations of the crystal with respect to the x parameter within the phase-matching bandwidth of the crystals.

Genetic algorithm as a powerful and new technique is introduced for the optimization of a typical equation including many variables. This algorithm already opens new branches in optics and laser sciences. It can solve rate equation of lasers also multi variable laser cavity design equation and more important using is specifying of the optimized parameter for obtaining the best output [3].

In this paper in section II we describe phase-matching calculation for a typical biaxial nonlinear crystal and introduce Genetic Algorithm as a new technique to calculate the phase-matching angles of the $LiGa(Se_xS_{1-x})_2$ crystals with respect to the x parameter. In section III and IV we consider the walk-off effect and d_{eff} of the crystals, respectively. Finally paper is concluded in section V.

II. PHASE-MATCHING CONDITION

The most important phase mismatch parameter Δk is defined by [4]:

$$\Delta k = 2\pi\left(\frac{n(\theta,\varphi,\lambda)_p}{\lambda_p} - \frac{n(\theta,\varphi,\lambda)_s}{\lambda_s} - \frac{n(\theta,\varphi,\lambda)_i}{\lambda_i}\right) \quad (1)$$

where n and λ are refractive indices and wavelength of the interacting pump, signal and idler waves, respectively. For a given direction the above refractive indices can be calculated by using Fresnel equation as[5]:

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$$\frac{s_x}{\frac{1}{n^2(\vec{s})}-\frac{1}{n_x^2}}+\frac{s_y}{\frac{1}{n^2(\vec{s})}-\frac{1}{n_y^2}}+\frac{s_z}{\frac{1}{n^2(\vec{s})}-\frac{1}{n_z^2}}=0 \quad (2)$$

where $s_{x,y,z}$ are the unit vectors in an arbitrary polar coordinate associated with the crystal and $n_{x,y,z}$ are principal refractive indices which can be obtained using Sellemeier equation [2]. Basically, because of the coefficient d_{eff} vanishing in the type I interaction in the mm^2 group nonlinear crystals, type II Phase-Matching is just considered here. However, phase matching calculation for type II interaction where the polarization of signal and idler wave are perpendicular is not an easy task because equation (1) must be solved for two unknown parameters θ and φ, simultaneously.

Genetic algorithm is introduced as a powerful and new technique for the optimization of a typical equation including many variables. It is a search computerized technique which is generally implemented as a computer simulation. According to the algorithm the population of abstract representations (chromosomes) of candidate solutions (individuals) is directed toward better solutions. This evolution starts from a chosen population where in each generation the quality of each individual of the population is evaluated. Multiple individuals are selected from the current population (based on their quality) and then they modified by recombination of mutation to form a new population, with quite similar characteristics. Finally, this new current is used in the next iteration of the algorithm [3].

By utilizing this method, we start to solve equation (1) for a typical Nd:YAG laser operating at 1064nm as pump wavelength. Figure (1) shows the calculated phase-matching bandwidth for a given OPO interaction in which the GA is used.

From these figures, in one hand, the tuning range of the crystal is improved when the x parameter is increased. Furthermore, the tunability in the XZ plane is larger than that of XY plane, and therefore XZ plane can be chosen whenever the crystal is being to use for an optical parametric oscillation (OPO) purposes. Figure (3) shows also the results of same calculation in YZ plane of the crystal.

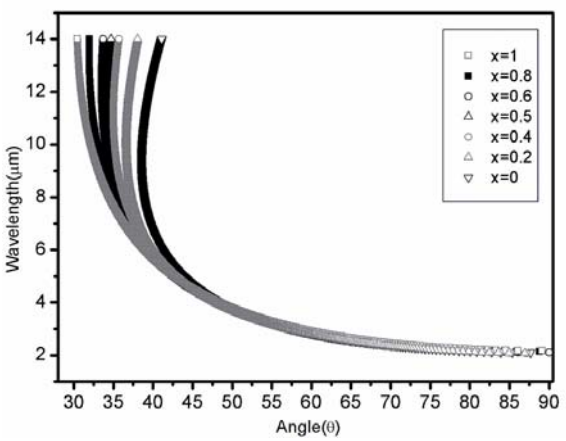

Fig. 1 Calculated phase-matching angles in XY principle plane for $LiGa(Se_xS_{1-x})_2$ ($0<x<1$) nonlinear crystals at λ_p=1064nm.

The same calculation can be applied in the XZ plane of the crystals as shown in Figure (2).

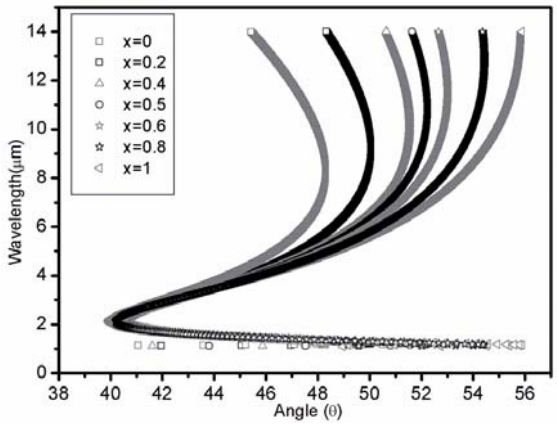

Fig. 2 Calculated phase-matching angles in XZ principle plane for $LiGa(Se_xS_{1-x})_2$ ($0<x<1$) nonlinear crystals at λ_p=1064nm.

As shown in Figure (3), YZ plane is not convenient because of the small Phase-Matching bandwidth even though the x parameter reaches to its maximum value.

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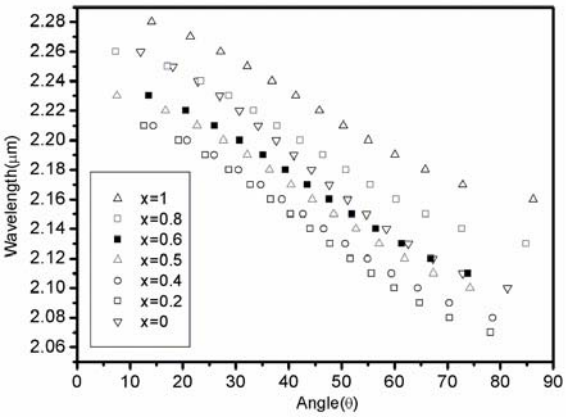

Fig. 3 Calculated phase-matching angles in YZ principle plane for $LiGa(Se_xS_{1-x})_2$ ($0<x<1$) nonlinear crystals at λ_p=1064nm.

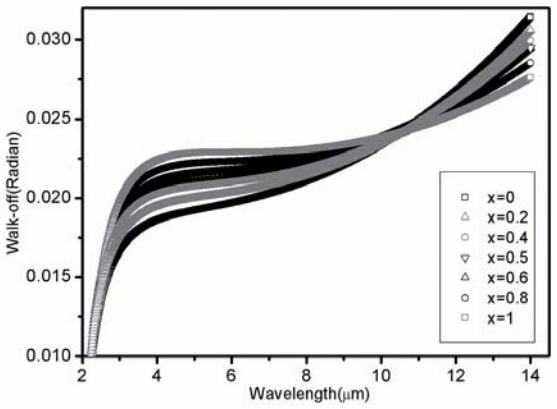

Fig. 4 Calculated walk-off angles for e-wave within the phase-matching bandwidth in XY plane for λ_p=1064nm and for different x values.

III. WALK-OFF EFFECT CALCULATION:

Walk-off effect occurs due to the angle between Poyinting and propagation vectors of the interacting extra-ordinary waves within the crystal. Walk-off is an undesirable effect that can cause a decrease in the effective length of the crystal. The walk-off angle "ρ" is obtained from [5]:

$$\tan(\rho) = n^2\left(\left(\frac{s_x}{n^{-2}-n_x^{-2}}\right)^2+\left(\frac{s_y}{n^{-2}-n_y^{-2}}\right)^2+\left(\frac{s_y}{n^{-2}-n_y^{-2}}\right)^2\right)^{-\frac{1}{2}} \quad (3)$$

Neglecting YZ plane due to its low tunability, the walk-off angles within the calculated Phase-Matching bandwidth in both XY and XZ principal planes are calculated in a similar way by using GA technique. The results are given in Figure (4) and Figure (5), respectively.

As a result, in the longer wavelengths, i.e. in the MIR region, the walk-off is increased in both planes while it is diminished by decreasing the x parameter of the crystal. Unlike the uniaxial crystals, walk-off effect cannot be neglected even if the XY plane is considered.

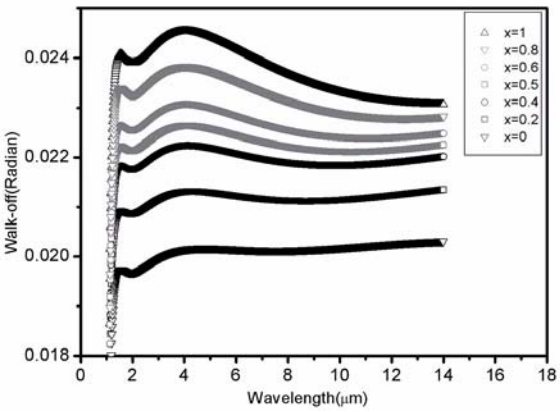

Fig. 5 Calculated walk-off angles for e-wave within the phase-matching bandwidth in XZ plane for λ_p=1064nm and for different x values.

IV. EFFECTIVE NONLINEAR COEFFICIENT (D_{EFF}):

Effective nonlinear coefficient plays an important role for either gain or threshold oscillation condition in all nonlinear processes. Therefore for a typical nonlinear interaction, maximum d_{eff} with moderate Phase-Matching condition must be respected. The amount of the d_{eff} can be calculated from the following equation [7]:

$$d_{eff} = (d_{24}-d_{15})\sin(2\varphi)\sin(2\theta) - \left(d_{15}\sin^2(\varphi)+d_{24}\cos^2(\varphi)\right)\sin(\theta) \quad (4)$$

It depends either on the propagation directions φ and θ, or on the susceptibility tensor elements, d_{ij} (ij=1...6) of the crystal. Using the available polarization matrix given by P. Geiko [2] for x= 0 and 1 one can calculate the d_{eff} for all Phase-Matching angles

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in each principle plane. The calculated d_{eff} of $LiGa(Se_xS_{1-x})_2$ ($0<x<1$) crystals in XY and YZ planes are given in Figures (6) and (7), respectively.

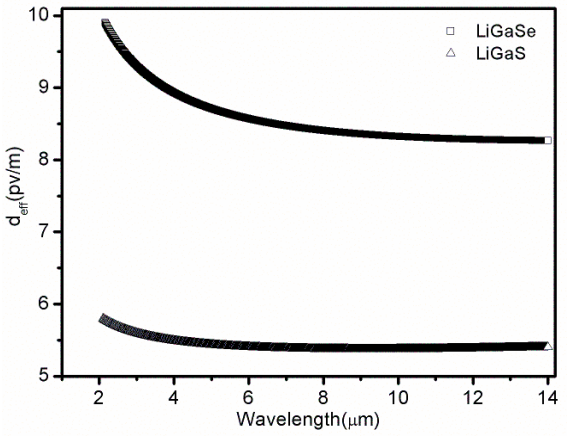

Fig. 6 Calculated d_{eff} in XY plane within the phase-matching bandwidth.

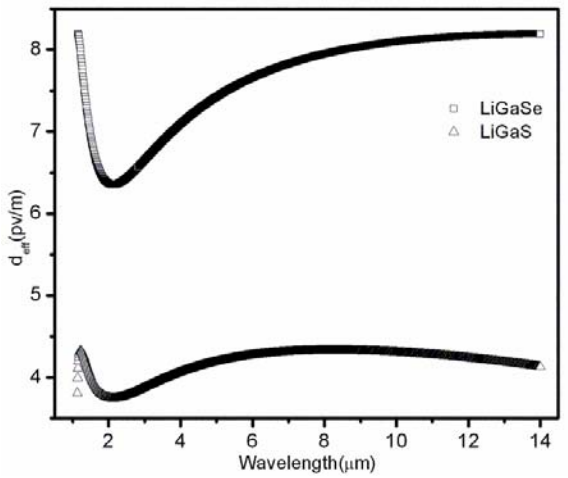

Fig. 7 Calculated d_{eff} in XZ plane within the phase-matching bandwidth.

As can be seen, in those XY and XZ planes d_{eff} is less related to the Phase-Matching angle and it is almost constant in XY plane, but $LiGaSe_2$ (x=1) crystal has more nonlinearity than $LiGaS_2$ (x=0) crystal. Concerning the results, XY plane of the crystal is more convenient for nonlinear laser generation providing high nonlinearity, wide tuning range and less walk-off effect.

V. CONCLUSION

It is shown that the Genetic algorithm provides quite new method through calculation of nonlinear properties of $LiGa(Se_xS_{1-x})_2$ crystals such as phase-matching bandwidth with minimum walk-off angle in a desirable principle plane. The wavelength tunability of the crystal in XY and XZ principle planes with respect to the x parameter is wide but it is less in the YZ plane.

Clearly, the walk-off effect is not a serious variable within phase-matching bandwidth in each individual plane and thus according to the Figures (4) and (5) in XZ plane it indicates more smooth behavior rather than in YZ plane. On the other hand the effective nonlinear coefficient (d_{eff}) of the $LiGa(Se_xS_{1-x})_2$ crystals is strongly depend on the x parameter so that the optical properties of the crystal is changed by increasing x to one.

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