Investigation on Performance development of the Second harmonic generation(SHG) with LiNbO3 application

Luma Hafedh Abed Oneiza* R.Sh.Alnayli ** Adnan Falh Hassan*
* AL-Kufa University, college of Sciences, Physics Department
**AL-Qadissiyah University-Physics Department

Abstracts

Investigation to approach the ideal conditions to optimized the performance of the single pure crystal LiNbO3 which has dimension (7.5×7.5 ×10) mm ^{3} as proposal element model for the Second Harmonics Generation (SHG) with semiconductor laser in the spectral wave length around 1.064 µm have been the main goals for this paper . The dependences' of depth efficiency conversion, under the best condition of the matching for this sample crystal are theoretically analytically treatments and evaluated .The comparison are strongly agreed with the more earlier researchers calculations [1[,[2] but slightly different with some researcher measurements which were owing to experiment errors .The main results are very satisfied to applied this proposal model as optimum controlling element for SHG at 1.064 µm.

الخلاصة

البحث يتضمن تحقيق الظروف المثالية لتطوير اداء بلورة الليثيوم نوبات الأحادية النقية ذات الأبعاد (7.5×7.5 ×10) mm ^{3} كعنصر مقترح لتوليد التوافقية الثانية من خلال ضخ ليزر شبة موصل ضمن طول موجي 1.064 µm وذلك من خلال التحكم بكفاءة التحويل التي تكون الأساس لتوليد التوافقية الثاني وان كفاءة التحويل تعتمد على عدة مؤثرات وبتحقيق بعض الشروط نستطيع تحقيق كفاءة التحويل المطلوبة أن هذا البحث حقق نتائج مرضية وجاءت مطابقة لبعض البحوث لقد حقق البحث النتائج الجيدة بتقنية البلورة المستخدمة.

1 – Introduction

The polarization induced in a medium by an electric field which is usually described by a linear expression. Results in the amplitude of the field nonlinear increasing in. One of the second order nonlinear effects is the generation of polarization oscillating at twice the frequency υ_f of the excitation field. The polarization emits a new wave of frequency $\upsilon_{SH} = 2\upsilon_f$ which is spatially superimposed with the fundamental wave. This effect is called second harmonic generation (SHG) [3] [4]

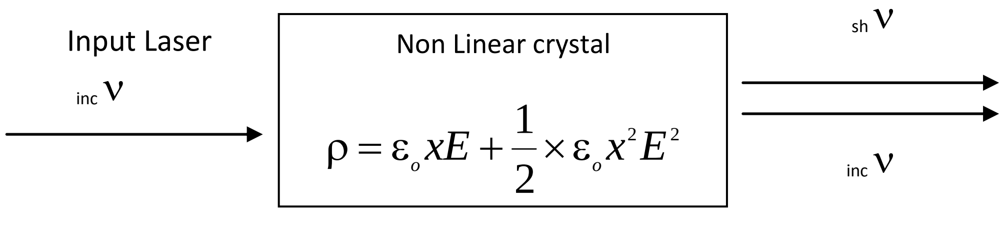


Figure [1] Basic principle of second Harmonic generation .

In the following parts of this chapter , the most important factors have investigated with respect to the conversion efficiency of our proposal model for the both operations, frequency doubling and pragmatics oscillation .

If one assumes a law conversion rate, the conversion efficiency after a distance, z in the nonlinear medium is given by[3]

$$\eta(z) = \frac{P_{SH}(Z)}{P_F} = \frac{8\pi^2}{n_{SH} n_F^2 \lambda_F^2 C \varepsilon_o} . \frac{P_F}{A} d_{eff}^2 [\frac{\sin(\frac{\Delta KZ}{2})}{\frac{\Delta k}{2}} \quad \text{------ (1)}$$

With $\Delta K = |K_{SHG} - K_f|^2$,
Where, K is the wave number ,

Where, K is the wave number, P_F and P_{SH} , are the power of the fundamental and SH beam respectively n_F and n_{SH} the refractive indexes at the fundamental and second harmonics wavelength respectively A the cross sectional area of the beam and d_{eff} a coefficient representing the nonlinearity of the crystal.

2 - The Studied Model

The Studied Model $LiNbO_3$ Crystal with dimensions (7.5×7.5 ×10) mm ^{3} is widely used as frequency doublers for wavelength > 1μm pumped at 1064 nm as well as quasi-phase-matched (QPM) devices.[5]

$LiNbO_3$ crystals with high quality and large sizes for laser frequency doublers, OPOs and quasi-phase-matched doublers.

High quality $LiNbO_3$ components with apertures of (2-15) × (2-15) mm² and length up to 50 mm for frequency doublers [6],

In this *researched* the complex interpolation and mathematical treatments have estimated in order to presented the final aspect and requirement properties of sample design which are proposal to study for the goals of this research as the following.

For the two special cases with respect around 1.06 µm wave - length of low – absorption , the refractive index became nearly constant , therefore the suitable model in this case is Cauchy form as (2) :-

$$n^2 = 1+S_0+S_1/\nu_1^2\, \nu^2 \qquad \text{…. … (2)}$$

The second case is the transparency to low-dispersion in this case the refractive index model can be calculated only by complete Sellemeier treatment [7] and the mean equation become as :

$$n^2 = 1+S_0+\frac{S_1}{\nu_1^2-\nu^2} + \frac{S_2\nu_2^2}{\nu_2^2-\nu^2} \quad \text{......} \quad (3)$$

From all the above the refractive index equation and with the respect at 1.064 µm at room temperature to the form of this Sellemeier treatment to cover the wide transparency of this type nonlinear material (LiNbO3), therefore this work need only to have calculated the index refraction with respect the infrared wave lengths in exactly 1.064 µm by using the following expressions also:

$$n^2 = 1 + (\frac{A\lambda^2}{\lambda^2 - D}) + (\frac{B\lambda^2}{\lambda^2 - D})(\frac{C\lambda^2}{\lambda^2 - D}) \text{.........(4)}$$

Where A,B,C,D are the Sellemeier constants for LiNbo3. For wide transparency 0.420 to 0.5200 of this LiNbO3 type there are many difference values of the ordinary (n_o), extraordinary (n_e) but the spectrum of such this work the range of the infrared wavelengths can regard in order to cover the field of the investigation which are listed in table below, but for applied our chosen wavelength 1.06 μm with this types crystal the below expressions are used .

$n_o = [4.9048+ 0.11768\{ (1.064)^2 - 0.04750\} – \{0.027169×(1.046)^2 \}]^{1/2}$
$n_e = [4.5820 + 0.09916 \{(1.064)^2 - 0.04443 \}- \{0.021950×(1.064)^2 \}]^{1/2}$

To get the calculation according to specification characteristics of our model the index refraction values of the ordinary (no), extraordinary (ne) will be 2.232 and 2.156 respectively , which are very important quantities to used for indicated on the phase matching condition for second harmonics generation,in order to interpolation our suggested spectrum with other wavelengths, these values have estimated 2.28 and 2.203 for the wave length 0.632 μm .as listed in table(1).

Table (1) indices coefficients of LiNbO3 crystals

λ(μm)	n_o	n_e
0.632	2.28	2.203
1.064	2.232	2.156

there are some properties for LiNbo3 crystal in table (2,3,4)

Table (2) physical properties

Dimension (μm)	Density (g/cm^3)	formula	Damage threshold MW/cm2	Lattice parameter		
				A	c	z
(7.5×7.5×10)	4.64	LiNbO3	250	0.515	13.652	6

Table(3) Non liner optical coefficients

d33	d31	d15	d22	deff
34.4	5.95	5.95	3.07	17.6 pm/v for 1064μm

Table (4) electro-optical properties

Damage threshold mw/cm^2	Half-wave voltage k volt	Extinction ratio	Transmission for λ=1064nm
300	3.03 and 4.02	250	0.4-5.0

3- results of work

3-1 normalized intensity dependence

In order to determination of the depended of the normalization intensity beam on the title angle with phase matching, firstly must done the checking of the ability of this proposal our model to produce the harmonics and oscillation operations for difference order which is the most step of same of any this work .

The emphases on the production signal characteristics must be regard in this type operations as derive the formula of the second harmonics generation (SHG)- Signal varies according to the normalized intensity as the following[8]

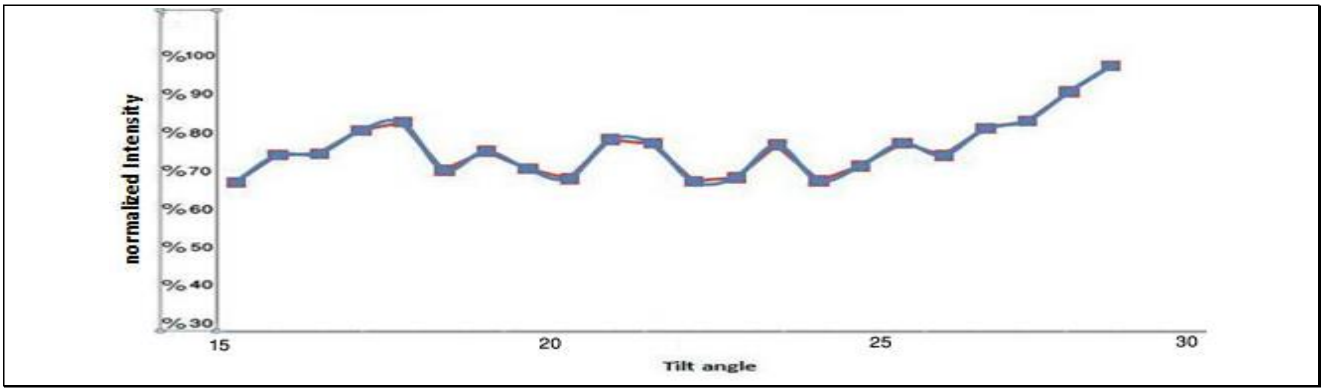
$$\frac{I}{I_0} = \sqrt{I/\mathrm{d}\!\int\!\mathrm{d}\ell\left(\mathrm{I}-\frac{\ell}{\mathrm{f}}\right)^4} \quad \ldots\ldots(5)$$

Therefore , this led us to calculate the effective intensities of the linear polarized beam diameter which are varied, with angles tuning around the phase matching.

For this our $o + o \rightarrow e$ transverse LiNbO3 type crystal sample for the direct order harmonic (Second) and for optical oscillation , Which are listed in table (5) and shown figure (3).it has been drawing by Excel program

Table (5) effective intensity vary with angle tuning with polarized beam

I effective VPm	7.427	8.852	8.925	10.15	10.57	8.057	9.051	8.134	7.616	9.667	9.464
	7.455	7.665	9.387	7.497	8.279	9.485	8.827	10.26	10.64	12.18	13.52
Angle	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23
	23.5	24	24.5	25	25.5	26	26.5	27	27.5	28	28.5



Figure(3)Dependence of the Normalized intensity on the tilt angle with 1064μm polarized beam

3.2 Conversion Efficiency dependences

The characteristic of LiNbO3 sample model which are evaluated and mentioned in the last section 2 of this research, a computer numerical solution by using Fortran language has been used for the précised evaluation of the almost effective parameters for the nonlinear optical conversion with the dimensions (7.5 *7.5 * 10 mm^3) of this our samples LiNbO3 crystal for harmonic generation with infrared range, as well as the derived conversion efficiency equation for second harmonic generation and for some higher harmonics generation were solved numerically using Mat-lab technical computer program [9]

The effect of the conversion performance for both SHG of this model were also illustrated as shown in figures (4).

We note from the Figure (4) conversion efficiency increases when the power increase depending on the equation(6)

$$\eta \approx pL^2 \left(d_{eff} \sin(\Delta KL)/\Delta KL\right)^2 \qquad ....(6)$$

but here the increase bearing nonlinear properties by relationship

$$P^2 = \varepsilon_0 \left(\chi_1 E + \chi_2 EE + \chi_3 EEE + ...\right) \qquad ....(7)$$

But according to this our proposal condition, when electric field is not weak , which estimated more than 10^{10} V/cm, the equation (7) became for second harmonics generation as a frequency doubled term ,

$P^2 = \chi_2 EE$ ……………..…..(8)

in this case the term of second harmonics generation , i.e doubling frequency2ω
The term, cos 2ωt must be introduce and the expression above can be re right as,

$\mathbf{P^2 = \chi_2 Eo^2 \cos^2 \omega t}$ ……….. (9)

When the laser beam incident on such this nonlinear LiNbO3 crystal at proper angle with the condition of phase matching direction of this material , the transfer efficiency of second harmonic frequency generator can be derived comparing to that of the fundamental frequency the relation between the length of the crystal (**L**), and($\mathbf{I_\omega}$ & $\mathbf{I_{2\omega}}$) the intensities of the input and output laser beam respectively , as in below expressions,

$\eta = I_{2\omega} / I_\omega \approx \chi_2 L^2 I_\omega [\sin^2(0.5\ \Delta k) / (0.5\ \Delta k)]$…………..(10)

According to equation (6), When approaching difference phase matching from null , must be note that conversion efficiency increasing with the nonlinearity increasing of the input power , this work has proved actual by Mat Lap program sketchy as done plotted of figure below (4), that the efficiency of conversion increases when phase matching value alignment phase of zero , the increasing in any point can be agree with the nonlinearity recipe however in the point of phase matching condition not be very close to zero, this owing to the error rate treatments and for the Observed through planned.

As in this figure (4), it is very clear to obtained that the efficiency of conversion of the most highest value when phase matching around value of 0.1. the increasing of the input power must regarding the withstand damage of the nonlinear material, the red strip in the net of this figure are represent the point of the limited withstand power of the studied sample(7.5 mm 7.5mm 10 mm)of pure LiNbO3, in this work was estimated no more than 1.2 kw.

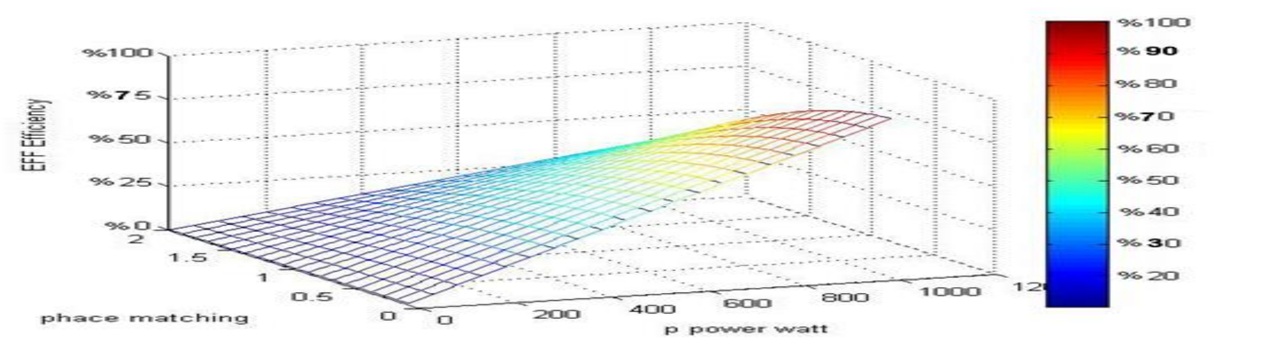


Figure (4) Dependent conversion efficiency on the power with phase matching condition

According to equation (10) , if the term power of no any increasing (p is constant, i.e, with no any thermal fluctuation inside the crystal sample) , in this case the dependence conversion efficiency is still dependence only on the effective length of the nonlinear crystal as and can be obtained the expression of equation (11) .

$\boldsymbol{\eta = (c \times c)(L \times L)/A}$ **P……..(11)**

Where, A the cross section of the crystal

The planned to gradually increase the conversion efficiency without any increased or decreasing values of power (p is constant) but variation only in the factor of the lengths of the crystal sample are also done by 3D-Matlab programming and can be shown in figure (5) below, it clear in the configuration of this figure(5), that the great percentages values of the conversion were around (1.5 0.8) cm(L=8-15 mm) LiNbO3 crystal length. The limitation of the length factor owing to the increasing the walk-off ray and the temperature tuning influences (thermal effect influences).

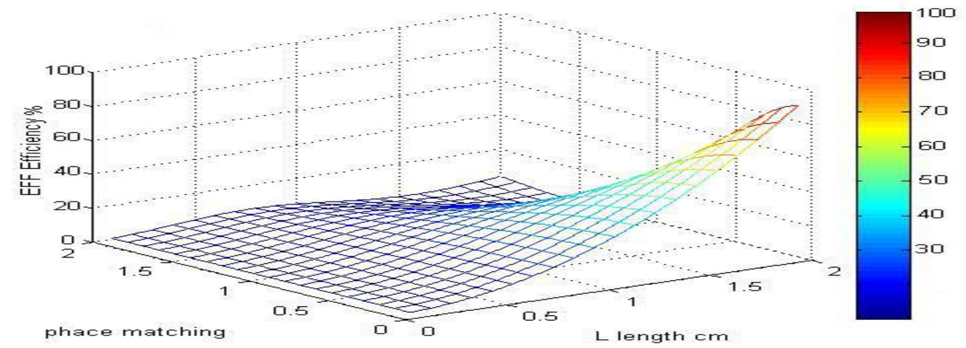


Figure (5) Dependent of conversion efficiency of the second harmonics generation on the lengths LiNbO3 crystal

The increase conversion efficiency with certain optimum value of the crystal length which shown in the above around (8-15) mm(limited range of the crystal length factor) ,in put power increasing but we cannot be more than the 500 watt, that the crystal gets damage for more than this value figure(6) [10]

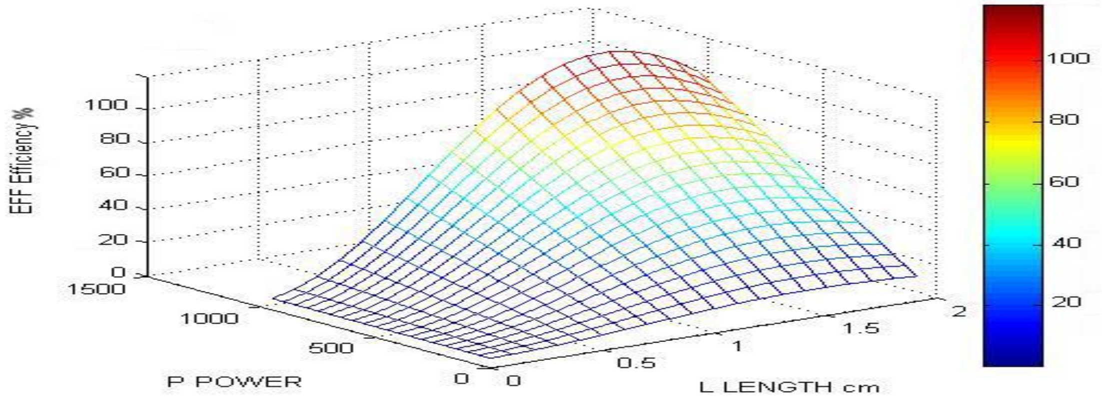


figure (6) output power Dependence on percentage conversion efficiency with limited length for second harmonic

According to the Equation

$$P_{2\omega} = \left[kl^2 P_\omega^2 / A \right] \sin c^2 \left(\Delta kl / 2 \right) \quad \text{.....(12)}$$

The dependence of the second harmonics power ($p_{2\omega}$) on the fundamental pumping power (p_ω) was also plotted in figure below(7)

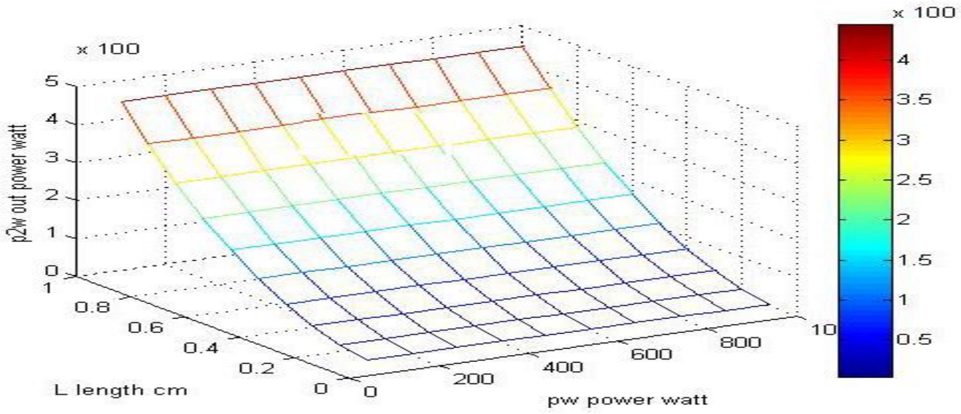


Figure (7) Dependent output power on input power with length for optical parametric oscillation

Showing clearly also in the construction of figure (7), the output optical parametric oscillation power is also deeply dependent on the both factors, the efficiency conversion with values length of the nonlinear crystal in range 6 mm to 12 mm) will be increasing as increasing the parametric oscillation powers , but no more than 500 watt owing to the thermal effect. The range of the crystal length in this operation is coincidence on the range of the lengths crystal for second harmonics (8-15 mm) which are mentioned earlier presented of figure (7)

3-3 The Phase Matching Condition .

By applied the 2D- Mathlab programming on the following expression on equation (6), which is represented the relationship between the conversion efficiency, length of the crystal and the power for the both types nonlinear operation, i.e the second harmonics generation (SHG) with substation to the effective nonlinear coefficients (d_{eff}) for these two nonlinear operation

$$\eta \approx pL^2 \,(d_{eff} \sin(\Delta KL) / \Delta KL)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

We get the reprove confirming sketchy for the phase matching condition of the second harmonics generation with these our proposal conditions as shown by figures(8), [11]

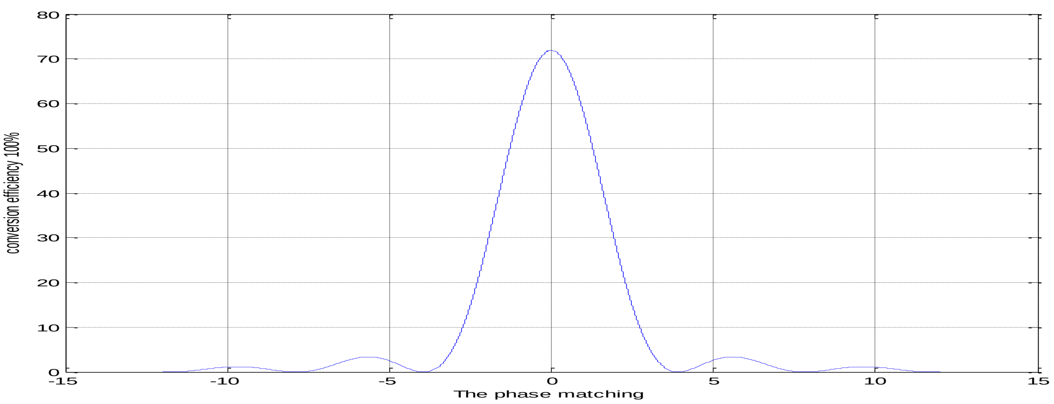


Figure (8) Dependent conversion efficiency on The phase matching

The figure (9) was constructed according to our results obtained from earlier in this work about the optimums ranges values of the length crystal with the phase matching conditions, shown very well that all these range (8-15mm) for the second harmonics and the range (6-12 mm) are satisfied for the phase matching condition therefore, this work can strong suggesting this our(7.5 mm7.5mm 10mm) LiNbO3 to combination the second harmonics generation

From *Figure* (9) we get the result that explains when the length crystallize is equal to the value of 0.8 cm that the phase matching = zero, When applied to the equation (6) by a Mathlab program The result was perfect when using crystallization LiNbO3 the condition will be essential to achieve a conversion efficiency on SHG

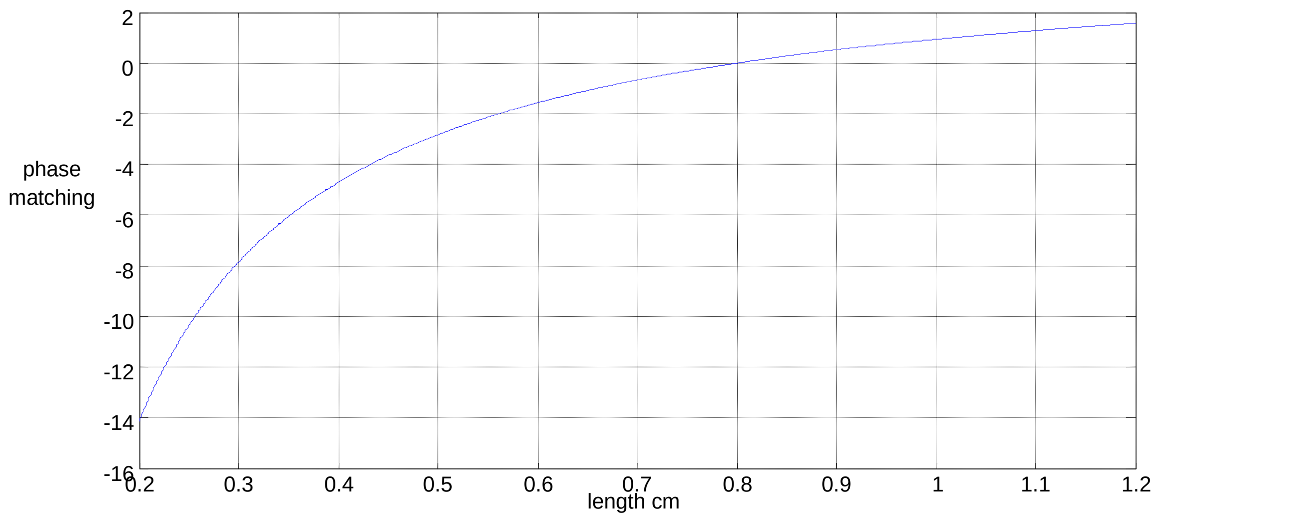


Figure (9) The values of the length of LiNbO3 which Conformity with the requirement of the phase matching condition for SHG

From Figure (10) , we get the result that explains when the length crystallize is equal to the value of 0.8 cm that the phase matching = zero, When applied to the equation (6) by a Mat lab program .The result was perfect when using crystallization LiNbO3 the condition will be essential to achieve a conversion efficiency SHG

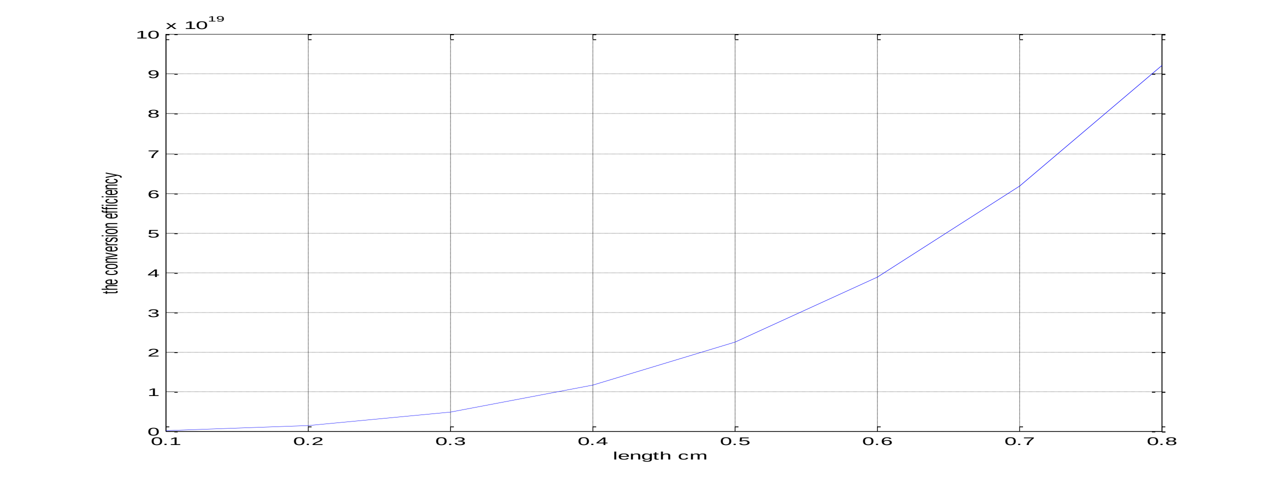


Figure (10) Conversion efficiency increases when the length of the crystal up to 0.8

4- Discussion and Recommendations.

Owing to that the harmonic intensity generated is proportional to the square of the fundamental intensity. And if, the beam cross sectional area is kept constant, as well as by the assuming of the laser power are not variation during the second harmonics generation, i.e. without any temperature tuning and walk-off rays inside the coherent length of the nonlinear LiNbO3 , therefore still the normalized intensity varied with angle title around the phase matching the most effective factor on this types operation .

as can be estimated from figure (3), the value of the tuning angle to varied the minimum to maximum intensities around the phase matching condition was only 2.5^o,which is giving reliability efforts to obtained the suitable condition for the generated the intensive harmonics generation for SHG within this our model.

Because of the conversion efficiency is the most influential factor on the performance of the harmonics generation.In addition it is satisfactory production for these nonlinear operations, SHG or not, in subchapter 3.2 focuses on the investigated the dependence of the conversion efficiency depending on the outside effective factors such as the fundamental power and length of the crystal with conditions of the phase matching as shown in figures(4-5-6-7-8-10),the limitations of the fundamental power to be input in this case were the withstand damaged of this types nonlinear LiNbO3 crystals . and must be carefully to chosen the length of this sample must around the 8 mm in order to avoided the increasing on differences types losses inside the material by the temperatures fluctuations and the ray walking-off. The conversion of the second harmonics configuration with these studies conditions was about 69% as shown in figures (10), this efficiency percentage is high enough for the inside cavity arrangement, such as the proposal configuration of this studied sample on the other hand the conversion efficiency can be impossible to exceeded the percentage of 45%, it will be in the range of (23-45%) for the outside cavity configuration, this is owing to the many problems associated with higher reflection,scattering and the absorptions.these effective conversion for both the side and outside cavity configurations will be decreasing as the increasing in harmonics ranks this is owing to the decreasing in the intensities of the beams with the increasing of the higher harmonics operations. In the case of goals of this work only until third harmonics can be regard to be achieved, the decreasing in the conversion from the second to third was estimated more than 2.5 times and the intensity of the third fundamental beam become not enough to generate the further fourth harmonic by this our proposal sample.

This results were reproved by sketching shown in figures (4,5,6,7,8) , which are represented that the dependence of the conversion efficiency on the length of the crystal and the input pumping power, the shortenings in coherence length must be regard to avoided the damaging in the crystal samples , in this work must be no more than 10 mm with laser power more than 500 watt .

The increasing of requirement coherence interaction distance in the long configuration of the nonlinear crystal can be limited by the following:-

- *walk-off* and make the pumping, harmonics(2^{nd} & 3^{rd}) pulses out of the same group velocities (mismatching), this cause to minimized the waves overlapping distance inside the nonlinear material with the direction of the length. This is dramatically decreasing the conversion efficiency percentage for both the harmonics generation . Owing to the higher intensive power requirement, this effect expected to be stronger limited with the second harmonics generation(SHG) than higher harmonics.
- Thermal influences which are caused by the temperatures fluctuation inside the nonlinear material, this also can be leads to decreasing the conversion efficiency in the both of these types nonlinear operations. Exceeding the limitations of this effect may destroying the nonlinear crystals material.

Therefore, the suggesting for any experimental in this such works, to get the production of the harmonics generation with sufficed efficiency of conversion, must be attention to chosen the proper length with the selective types of the nonlinear material and with regarding to make any used any facility or method to prevent or at least minimizing the temperatures fluctuations as possible as possible.

Finally for the applications purposes ,the efficiency for this operations can significant improved by using the following :-

- higher power density with the limitation of withstand applied crystal type and dimensions.
- long interaction length with regarding to save the overlapping the beams.
- material with greater effective coefficients or smaller index refraction i.e. , with higher value of the ratio, ($d_{eff}^{\ 2} / n^3$) .

5- References

[1] Boyd. G.D. and kleinman. D.A.J.AppL .phys.39.3597. .(1968).

[2] Manley J. M and Rowe, H. E., "Some General Properties of Nonlinear Elements – Part I: General Energy Relations", Proceedings of the IRE, July, p. 904 – 913. 1956

[3] Fundamental of photonics ,B. E, A, Saleh ,m.c. Teich, wiley – interscience , 1991.

[4] Photonics , Linear and nonlinear Interactions of laser Light and matter , R.menzel . springer verlag , 2001.

[5] Lei Shi, Linghao Tian, and Xianfeng Chen Electro-optic chirality control in MgO:PPLN Published by the American Institute of Physics. JOURNAL OF APPLIED PHYSICS 112, 073103 (2012).

[6] Jacopo Parravicini, Jassem Safioui, Vittorio Degiorgio, Paolo Minzioni, and Mathieu Chauvet. JOURNAL OF APPLIED PHYSICS 109, 033106 _ Published by the American Institute of Physics.2011

[7] W. Sellmeier, Zur Erklärung Refractive index and dispersion. Schott technical information document TIE-29 (2007).

[8] R.Sh. R.Sh.Alnayli university of AL- Qadisiya investigation of second – harmonic generation in KH_2PO_4(KDP) crystal supplement Al-Kufa Journal ,2007,vol.8,No.2 , AL- Qadisiya ,Iraq 2007 .

[9] Gilat, Amos. MATLAB: An Introduction with Applications 2nd Edition. John Wiley & Sons. ISBN 978-0-471-69420-5.. (2004).

[10] V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, L. Maleki, *Phys. Rev. Lett.* **92**, 043903 (2004).

[11] C. Moser, G. Steckman, *Photonics Spectra*, pages 82-86. June 2005.