Computation of The Efficiency of Harmonic Generation Using Cascading Configuration.

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Abstract

In the present work theoretical relations are derived for the efficiency evaluation for the generation of the third and the fourth harmonics using crystal cascading configuration. These relations can be applied to a wide class of nonlinear optical materials. Calculations are made for beta barium borate (BBO) crystal with ruby laser λ=694.3 nm . The case study involves producing the third harmonics at λ =231.4 nm of the fundamental beam. The formula of efficiency involves many parameters, which can be changed to enhance the efficiency. The results showed that the behavior of the efficiency is not linear with the crystal length. It is found that the efficiency increases when the input power increases. The walk-off length is calculated for different spot sizes. It is found that when the spot size increases , the walk-off length increases too.

Introduction

Within less than one year after the publication of Maiman famous paper on pulsed optical masers [1], Frankan et al published for the first time a paper on the generation of optical harmonics [2]. They stated the theoretical background for the generation of the second harmonic and higher order harmonics from the fundamental laser beam. They experimentally were able to produce the 347.2 nm second harmonic from the 694.3 nm Ruby laser fundamental beam. The production of the second harmonic was made by focusing three joules, one msec pulsed laser output pumped inside crystalline quartz crystal sample [3]. Nonlinear effects are essential for the modification of the laser output. Variety of nonlinear processes including harmonic generation, parametric down conversion and stimulated Raman effect extend the range for coherent sources throughout the infrared and into the vacuum ultraviolet [4]. Nonlinear optical processes are essential in many applications in chemistry, biology, medicine, materials technology. Some of these effects are used in optical communications systems for obtaining ultra- short pulses [5]. Non resonant interactions are most useful for wavelength conversion of laser light, wave mixing and optical phase conjugation. The nonlinear interactions are based on the nonlinear modulation of the refractive index of the material by incident light

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as a result of the strong force effect [6]. The cascading technology is employed to achieve higher beam efficiencies. The present work is concerned with the computation of efficiencies as function of crystal length for different spot sizes at different powers. The result obtained may be of interest in selecting the optimum of the parameter nonlinear crystal employed to obtain the higher order output.

Theory and computation

The amplitude for three waves mixing generated by a crystal is given by the equation [7];

$$A_3(L) = \frac{\gamma_3 A_1 A_2^*(\exp(i\Delta KL)-1)}{\Delta KL} = \gamma_3 A_1 A_2^* L \operatorname{sinc}\left(\frac{\Delta KL}{2}\right)$$
-----(1)

where

A_i : is the amplitude of the wave of the i^{th} order.

L: is the crystal length.

$$\gamma_i = \frac{(\omega_i d_{eff})}{c}$$

where

ω_i : is the frequency of the wave of the respective order.

d_{eff}: is the nonlinear effective.

c: is the speed of light.

$$\Delta K = K_i - K_j$$

where

K_i and K_j : are the wave vector for i^{th} and j^{th} order respectively. The general form of the intensity of light is given by [8]:

$$I_i = 2n\left(\frac{\varepsilon_o}{\mu_o}\right)^{\frac{1}{2}} |A_i|^2 \text{-----(2)}$$

where

n: is the refractive index.

ε_o : is the relative vacuum permittivity.

μ_o : is the vacuum permeability.

The intensity of three wave mixing may be written in the form[3]:

$$I_3 = \gamma_3^2 I_1 I_2 f_1 f_2 L^2 \operatorname{sinc}^2\left(\frac{\Delta KL}{2}\right) \text{-----(3)}$$

where

f : is the transmission factor and

$$\gamma_3^2 = \frac{8\pi^2}{\epsilon_o c n_1 n_2 n_3 \lambda_s^2}$$

where

λ_s : is the vacuum wavelength of the generated wave. The efficiency of the second harmonic generation with respect to the fundamental beam may be expressed by:

$$\eta_{SHG} = \frac{8\pi^2 d_{eff}^2 I_2 L^2 f_1 f_2 \operatorname{sinc}^2\left(\frac{\Delta KL}{2}\right)}{\epsilon_o c n_1 n_2 n_3 \lambda_s^2}$$
-----(4)

In terms of power the efficiency takes the following form;

$$\eta_{SHG} = \frac{8\pi^2 d_{eff}^2 P_2 L^2 f_1 f_2 \operatorname{sinc}^2\left(\frac{\Delta KL}{2}\right)}{\epsilon_o c n_1 n_2 n_3 \lambda_s^2 S} \text{-----(5)}$$

where

S: is the spot size of the pumping beam.

At phase matching $\Delta K = 0$ the power generated of the third order is given by:

$$P_3 = \frac{8\pi^2 d_{eff}^2 P_1 P_2 L^2 f_1 f_2}{\epsilon_o c n_1 n_2 n_3 \lambda_3^2 S} \text{-----(6)}$$

The efficiency of the third harmonic generation with respect to the fundamental beam may be written by:

$$\eta_3 = \frac{8\pi^2 d_{eff}^2 \eta_2 (1-\eta_2) P_1 L^2 f_1 f_2}{\epsilon_o c n_1 n_2 n_3 \lambda_3^2 S} \text{-----}$$
(7)

Applying the same procedure, the efficiency of the fourth harmonic generation from the fundamental beam may be obtained as;

$$\eta_4 = \frac{8\pi^2 d_{eff}^2 P_3 L^2 f_1 f_2}{\epsilon_o c n_1 n_2 n_3 \lambda_4^2 S} \text{-----(8)}$$

Figure (1) shows the arrangement for the harmonics generation from the fundamental beam and from mixing of other different orders. It is possible with these configuration to obtain the third harmonics figure (1-a) and the fourth harmonics figure (1-b) and figure (1-c).

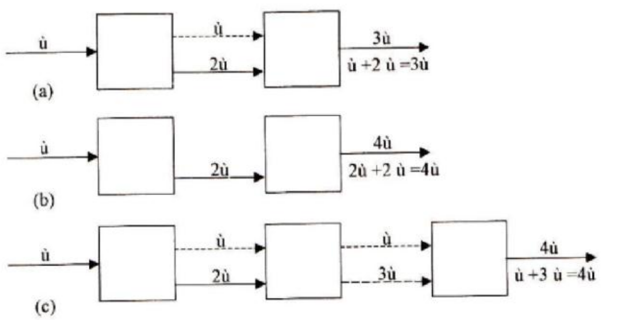

Figure (1) Schematic diagram for the third and fourth harmonic generation.
(a) Third harmonic from the residue of the fundamental beam (ù) and the second harmonic (2ù)
(b) Fourth harmonic from second harmonics (2ù)
(c) Fourth harmonic from the residue of the fundamental beam (ù) and the third harmonic (3ù)

The formula of the walk-off length is given by [8]:

$$Z = L \tan\rho$$

where

ρ: is the walk-off angle which can be given by:

$$\tan\rho = \frac{\left(\frac{n_o^2}{n_e^2} - 1\right)\tan\theta}{1 + \frac{n_o^2}{n_e^2}\tan^2\theta}$$

where

n_o: is the ordinary refractive index of the generated beam.

n_e: is the extraordinary refractive index of the generated beam.

θ: is the phase matching angle in the crystal.

Results and Discussion

In the present work, the beta-barium borate (BBO) crystal parameters are employed in the calculate to find the efficiency for third harmonic generation of ruby laser λ λ λ=231.4 nm when it interacts whit this nonlinear crystal. Figure (2) is a plot of the behavior of the calculated efficiency of the third harmonic generation as a function of the crystal length for different spot sizes at 0.5 W input powers. It is clear from these curves that the behavior is not linear in all cases. The efficiency assume different values for different spot sizes for a given crystal length. Also this figure shows that when the spot size increases the efficiency decreases. This may interpreted on the fact that the decrease in the power density leads to lower interaction.

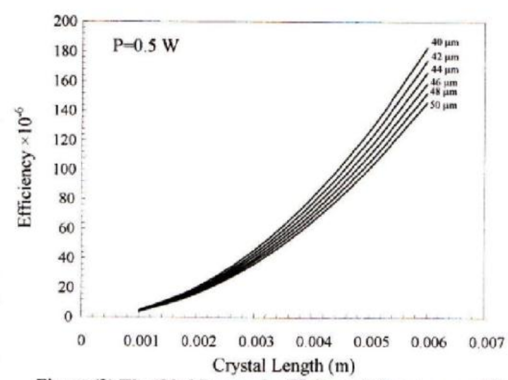

Figure (2) The third harmonic efficiency (η_3) versus crystal length (L) for different spot sizes (40, 42, 44, 46, 48 and 50 μm) at 0.5 W input power.

The decrease in the power density of course is a result of the increase of the irradiacal area for a give energy. Figure (3) represents the behavior of the efficiency as a function of the crystal length for different spot sizes and input power of 1.5 W using BBO nonlinear crystal. The interpretation is the same at that mentioned in the 0.5W case.

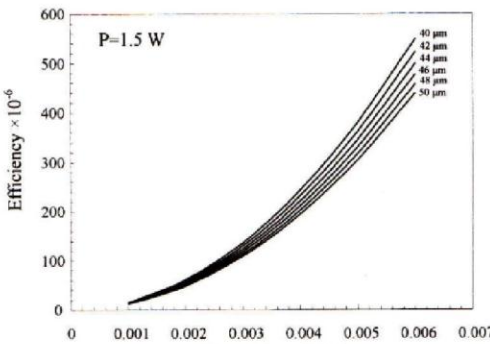

Figure (3) The third harmonic efficiency (ς_3) versus crystal length (L) for different spot sizes (40, 42, 44, 46, 48 and 50 μm) at 1.5 W input power.

Similar curves are produced to the account for the efficiency of third harmonic generation at 2.5, 3.5 and 4.5 W Figures (4), (5) and (6) respectively are plots for these cases.

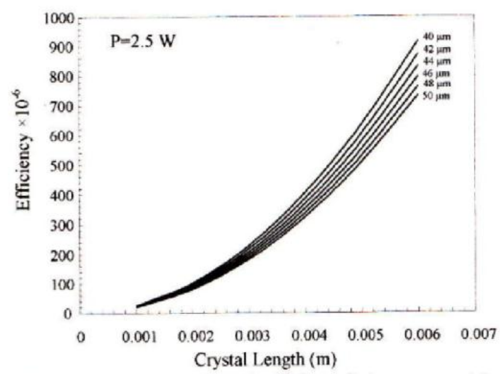

Figure (4) The third harmonic efficiency (ς_3) versus crystal length (L) for different spot sizes (40, 42, 44, 46, 48 and 50 μm) at 2.5 W input power.

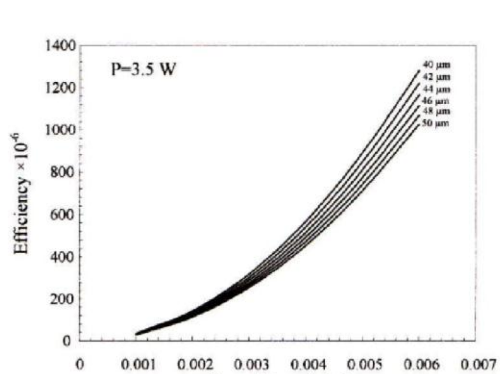

Figure (5) The third harmonic efficiency (ς_3) versus crystal length (L) for different spot sizes (40, 42, 44, 46, 48 and 50 μm) at 3.5 W input power.

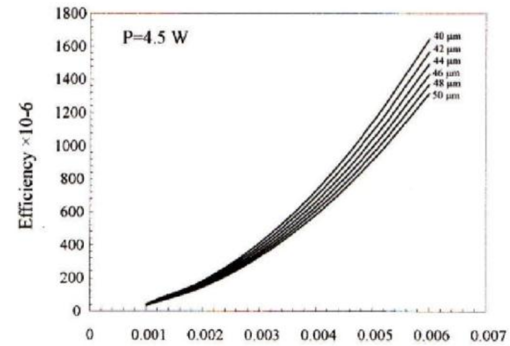

Figure (6) The third harmonic efficiency (ς_3) versus crystal length (L) for different spot sizes (40, 42, 44, 46, 48 and 50 μm) at 4.5 W input power.

Table (1) lists the calculated Walk-off length for different spot sizes of third harmonic generation.

Walk-off length (mm)	Spot size (μm)
1.1253	40
1.1816	42
1.2378	44
1.2941	46
1.3504	48
1.4066	50

Table (1) The walk-off length and the corresponding spot size for third harmonic generation.

The relation between the third harmonic efficiency and input power at 40 μm spot size and 0.001 m the crystal length is illustrated in figure (7). In this work the fundamental power may be converted to third harmonic power [9]. In conclusion the efficiency of third harmonic generation of ruby laser increases when pumping power increases and spot size decreases.

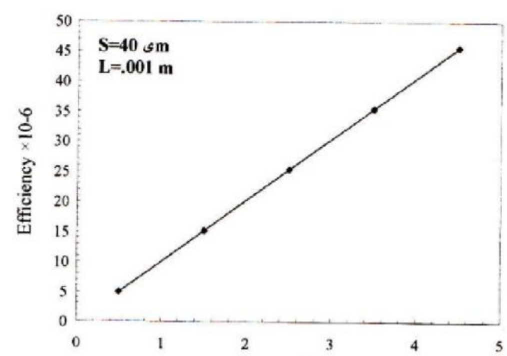

Figure (7) The third harmonic efficiency (ς_3) **versus input power for 40 μm spot size and 0.001 m crystal length.**

Conclusion

In conclusion we thank that the results presented in this work can be of interest to design a certain configuration to obtain coherent radiant at short wave length down is to the UV reign.

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الكفاءة لتولد التوافقيات باستخدام الترتيب المتتالي للبلورات غير الخطية

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الخلاصة

يتضمن العمل اشتقاق العلاقات النظرية لتقدير الكفاءة المتولدة للتوافقيات الثالثة و الرابعة باستخدام الترتيب المتتالي. هذه العلاقات يمكن تطبيقها باصناف واسعة للمواد البصرية غير الخطية. تمت الحسابات باستخدام بلورة (BBO) مع ليزر الياقوت. تشمل الدراسة حالة تولد التوافقية الثالثة عند الطول الموجي e λ=231.4 nm للحزمة الاساسية لليزر الياقوت ذو الطول الموجي λ=694.3 nm ان صيغة الكفاءة تتضمن عدة معلمات والتي يمكن بواسطة تغيرها زيادة الكفاءة. تشير النتائج ان سلوك الكفاءة مع طول البلورة يكون غير خطي. وقد وجد ان الكفاءة تزداد بزيادة القدرة الداخلة. تم حساب طول الـ Walk-off لاحجام مختلفة ووجد ان زيادة الحجم Spot size يقود الى زيادة الطول المذكور اعلاه.