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CALCULATION OF THE INPUT LASER PULSE RADIUS IMPACT ON STIMULATED RAMAN SCATTERING UNDER SELF FOCUSING CONDITIONS

This study focuses on investigating stimulated Raman scattering under self-focusing conditions and the impact of other parameters on its efficacy. Contrary to expectations, the efficiency of stimulated Raman scattering could discontinue to increase, and may rather start to decline when the input radiation power grows, because of the "absolute saturation" effect. The paper investigates the influence of this effect under self-focusing conditions using the example of a ruby laser in toluene. Calculations are given in order to characterize the indicated phenomenon based on power and Stokes component. The approaches for mitigating the impact of the "absolute saturation" effect on the process by increasing the initial radius of the incoming laser beam are being examined. A software product was developed using the Wolfram Mathematica program to enable calculations for each unique scenario. This software helps in selecting the settings to achieve the optimal parameters to ensure the highest efficiency of Raman scattering.

Keywords: ***stimulated Raman scattering, self-focusing, "absolute saturation" effect.***

Introduction

Stimulated Raman scattering (SRS) is one of the first nonlinear phenomena that was discovered. The occurrence of this phenomena was foreseen in 1923 by the Austrian theoretical physicist Adolf Smekal, who observed that when there is additional radiation in the medium with a wavelength distinct from the incident radiation.

Moreover, in 1930, Raman was awarded the Nobel Prize in Physics for the discovery of this phenomena, which was later named in his honor. Simultaneously with Raman, Soviet physicists Mandelshtam and Landsberg had been conducting research in this field. But since it was not acknowledged at that time that the effects discovered by them are the same phenomena, this led to terminology discrepancies in the publications. The word "Raman effect" or "Raman scattering" was commonly used in English-language literature, but in Eastern European literature, the term "combination light scattering" was more prevalent (Polyak, Demegko, & Gonchar, 2018). Over the course of its extensive existence, there have been moments where this phenomena was deemed unproductive for investigation. However, today it has presented new and exciting prospects in numerous fields. Light amplifiers and laser radiation sources can be considered as one of these areas of application.

Also, according to (Fibich, & Gaeta, 2015; Ferrara, Ranjan, & Raghini 2023), imaging techniques and research based on the Raman effect continue to appear and improve. Therefore, the study of stimulated Raman scattering remains relevant to this day. This is because this effect is an important physical phenomenon that is used in numerous modern optical systems and technologies.

1. Stimulated Raman scattering under self-focusing conditions. The self-focusing condition has an important role in the occurrence of stimulated Raman scattering. This phenomenon occurs when a high-intensity laser beam enters the optical system, causing a changes in the refractive index of the medium. Such a change can lead to a decrease in the curvature radius of the wave front, consequently leading to an increase in the intensity of the beam at the focusing center (Fibich, & Gaeta, 2015).

The condition of self-focusing becomes an essential factor study of stimulated Raman scattering, since the increased intensity of the laser beam increases the probability of interaction with molecules in the medium, which leads to scattering processes. Thus, the self-focusing condition is important in the study of stimulated Raman scattering and the development of optical systems based on this phenomenon (Singh, & Keshaw, 2013, p. 6074–6080).

Also, according to (Stolen, 1973; Agrawal, 2012), it was experimentally recorded that the efficiency of stimulated Raman scattering depends on the power of the stimulated radiation. But in real cases, there are instances where the effectiveness stops to increase or may even decline as the power grows. This phenomenon was called the "absolute saturation" effect The reasons for this phenomenon are currently under research and have not yet been fully understood.

In certain cases, the development of "absolute saturation" in optical systems and technologies while applying the Raman effect might be undesirable and even harmful.

In accordance with the above consideration of additional factors affecting the stimulated Raman scattering, including the radiation spectrum, is an important stage for its implementation and application.

Therefore, this work considers the impact of various parameters, including the radius of the incoming laser beam, on stimulated Raman scattering.

2. Calculation of the impact of the initial radius under self-focusing conditions. In order to determine the impact of the "absolute saturation" phenomenon in a nonlinear guiding medium under self-focusing conditions, calculations were conducted to analyze the energy and power of the Stokes component. The calculations take into account the characteristics of the medium and the incoming laser beam.

To characterize the variation of the laser front r_x as it passes through the surrounding medium, we can use the following formula: (1) (Dudka, Ivanisik, & Borysenko, 2003).

$$r_x^2 = r_0^2 \cdot \left[\left| 1 - (x/x_f)^2 \right|^{\mu/2} + (r_f / r_0)^2 \right], \quad (1)$$

where r_0 – initial radius, x – coordinate (distance from the beginning of the environment), μ – parameter, r_f – front radius in the focal region, x_f – self-focusing length.

According to the above equation, in the focal zone, the beam radius, parameter, and self-focusing length are set according to (Ivanisik, 2015). where P_{b0} – power of the laser beam at the beginning of the medium, P_S – self-focusing power (critical power), k – wave vector, n – index of refraction of the medium.

$$x_f = \text{const.} \tag{2}$$

$$\mu = 2{,}92\tilde{P}^{-0{,}5} + 1/\tilde{P} + 1, \tag{3}$$

$$x_f = 0{,}3806nkr_0^2 \Big/ \left[\left(\sqrt{\tilde{P}} - 0{,}7703\right)^2 - 0{,}0528\right]^{1/2}, \tag{4}$$

$$\tilde{P} = P_{b0}/P_f, \tag{5}$$

where P_{b0} – power of the laser beam at the beginning of the medium, P_S – self-focusing power (critical power), k – wave vector, n – index of refraction of the medium.

To calculate the power of the laser and Stokes components P_{bx} and P_{sx} respectively at a certain random point x with a given length L at the end (outlet) of the medium P_{bL} and P_{sL}, when plane waves are approaching, the following system of equations is obtained (6–7):

$$P_{bx} + \frac{\lambda_s}{\lambda_b} P_{bx} = P_{b0}, \tag{6}$$

$$\frac{dP_{sx}}{dx} = KP_{sx}\frac{P_{bx}}{\pi r_x^2}, \tag{7}$$

where K – amplification factor, λ_s and λ_b – the wavelength of the Stokes and laser components, respectively.

To obtain numerical solutions of system (6-7), the entire length of the medium L is divided into infinitely small intervals dx.

Under the condition of pulsed pumping, the radiation energies of the component pulses E_{bL}, E_{sL}, is calculatedusing the following equations (8–9):

$$E_{bL} = \int_{-\infty}^{\infty} P_{bL}\,dt, \tag{8}$$

$$E_{sL} = \int_{-\infty}^{\infty} P_{sL}\,dt. \tag{9}$$

3. Calculation results. A software application was developed to solve the aforementioned equations and iteratively apply this strategy to determine the impact of absolute saturation for each distinct situation with varying input data.

The Wolfram Mathematica software was used to create the dependences of the power of the Stokes and laser components in the case of continuous and pulsed pumping conditions. The chosen parameters are representative of the process of reconstructing the multimode radiation of a ruby laser in toluene.

Toluene was chosen due to its characteristics that enable control over the wavelength and the ability to minimize energy expenses in an active medium.

The input data of the program according to (Dudka, Ivanisik, & Borysenko, 2003) are listed in the table 1.

Table 1

Input data

Symbol	Physical quantity	Description
P_{s0}	$1{\cdot}10^{-9}$ W	power of the Stokes component at the beginning of the medium
$\tilde{P}$	2.6	exceeding the critical power of self-focusing
r_0	114 mkm	initial radius of laser beam fragments during self-focusing
r_f	5 mkm	minimum radius of the laser beam fragments at the focal point
λ_b	694 nm	the wavelength of the ruby laser
λ_s	745,7 nm	wavelength of the Stokes component in vacuum for toluene
P_S	25 kW	critical self-focusing power in toluene
n	1,48127	refractive index in toluene
L	25 cm	the length of the cuvette
K	1,16 cm/MW	toluene combination gain coefficient

In particular, see Table 1 and Figure 1. Use the single line spacing before and after them. Figure 1 displays the obtained relationship between the powers of the Stokes and laser components and their respective coordinates, resulting from the program's running.

In the focal area of self-focusing, a nearly complete transformation of the laser component into the Stokes component is observed. Accordingly, data on the position of the self-focusing zone in relation to the environment were obtained.

The relationship parameter has the greatest influence on the character of this graph $\tilde{P}$.

To obtain a more comprehensive explanation of the self-focusing phenomenon, we can refer to the graph shown in Figure 2. The figure shows the conversion factor into the Stokes component. Based on the graph it is evident that once the self-focusing threshold is passed, there is an almost complete transition towards the Stokes component This value remains approximately at the same level until it begins to decrease with the subsequent increase in pumping power.

Using this graph, one can identify the input power values at which the phenomenon of "absolute saturation" starts and persists, as well as avoid excessive initial pump power, which leads to the stimulated Raman scattering growth stop or even decrease.

In the case of the pulse mode of operation based on (8–9), the dependence of Stokes and laser pulses was constructed, as shown in Figure 3.

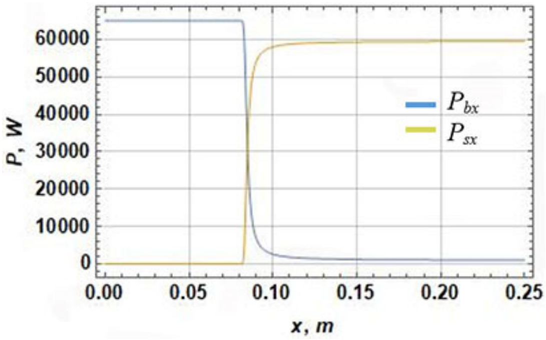

Fig. 1. Power of laser P_{bx} and Stokes P_{sx} components from coordinates

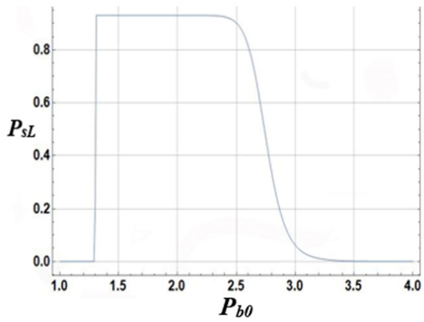

Fig. 2. Dependence between the transformation of the laser component into the Stokes component and the input power of laser radiation

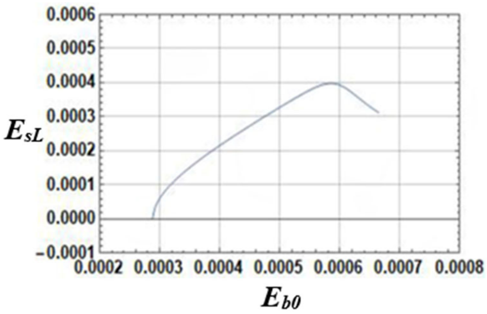

Fig. 3. Dependence of the conversion process from the laser component to the Stokes component on the input power of laser radiation

On the graph, you can observe the point of "absolute saturation" after which increasing the input pulse pumping leads to a decrease in the transformation into the Stokes component.

Accordingly, the obtained application makes it possible to calculate the effect of "absolute saturation" in order to select the optimal configuration of the input parameters in each specific case.

4. Prevention of the effect of absolute saturation at constant power. The phenomenon of "absolute saturation" is consistent with the violation of the transformation of the laser component into the Stokes component at specific values of radiation generation exceeding a certain value.

This effect does not correlate with the depletion of the pump. Sudden focusing causes the atypycal behavior, which leads to a decrease in the length of the focal region. To avoid this effect, at constant values of the initial power under self-focusing conditions, the method of increasing the initial diameter of the pumping beam can be used. As the initial diameter of the pumping beam increases, its instantaneous power is distributed over a larger area, which reduces the probability of the saturation effect.

To demonstrate this method, there were set different values of the initial radius of the beam in the created software product, for example 120 mkm and 130 mkm. These values were then compared to the input data shown in Figure 3. The comparison is shown in Figure 4.

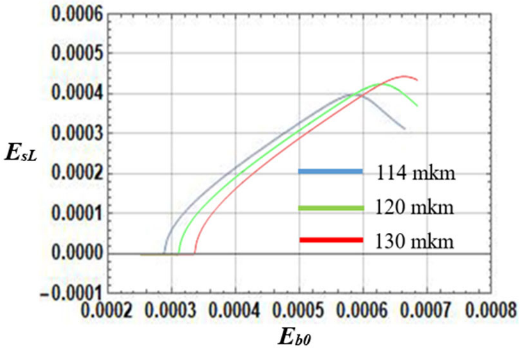

Fig. 4. Dependence between energy levels and varying initial beam radius

A shift in the critical point is observed, beyond which the efficiency of simulated Raman scattering ceases to rise. As a result, an increase in the radius of the input beam has an impact.

Discussion and conclusions

A study of stimulated Raman scattering under self-focusing conditions was conducted to determine the impact of additional factors on it, such as the effect of "absolute saturation" – the presence of a critical point after which the efficiency of the process ceases to increase. A software application was developed using the Wolfram Mathematica program to do power and Stokes component calculations for the purpose of characterizing this process.

A method based on increasing the initial radius of the input beam is proposed to increase the efficiency of stimulated Raman scattering, which has proven its effectiveness.

Authors' contribution: Oleksandr Mokhonko – conceptualization, software, empirical data collection and validation; nalysis of sources, preparation of literature review or theoretical foundations of research; Anatiliy Ivanisik – conceptualization, methodology, software, empirical data collection and validation; empirical research.

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РОЗРАХУНОК ВПЛИВУ РАДІУСА ВХІДНОГО ЛАЗЕРНОГО ІМПУЛЬСУ НА ВИМУШЕНЕ РАМАНІВСЬКЕ РОЗСІЮВАННЯ ЗА УМОВ САМОФОКУСУВАННЯ

Присвячено дослідженню вимушеного раманівського розсіювання за умов самофокусування та впливу додаткових факторів на його ефективність. Усупереч очікуванням ефективність вимушеного раманівського розсіювання може перестати зростати, та й навіть почати спадати у разі збільшення потужності вхідного випромінювання через ефект "абсолютного насичення". Досліджено вплив зазначеного ефекту за умов самофокусування на прикладі рубінового лазеру в толуолі. Наведено розрахунки для того, щоб охарактеризувати це явище на основі потужності й компоненти Стокса. Розглянуто прийоми зменшення впливу ефекту "абсолютного насичення" на процес, в основі якого лежить збільшення початкового радіусу вхідного пучка лазера. На основі пакету "Wolfram Mathematica" створено програмний продукт, що дає змогу проводити обчислення для кожного конкретного випадку з метою підбору оптимальних параметрів для забезпечення оптимальної ефективності раманівського розсіювання.

Ключові слова: ***вимушене раманівське розсіювання, самофокусування, ефект "абсолютного насичення".***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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