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بررسی تاثیر ویژگی‌های پرتو دمش و کریستال لیزر بر تولید مدل گرمایی پرتو بسل-گاوس

رضا فلاح[۱]، حمید نادگران[۲]

[۱] گروه فیزیک، دانشگاه بیرجند، بیرجند، ایران

[۲] گروه فیزیک، دانشگاه شیراز، شیراز، ایران

چکیده – تولید پرتوهای خانواده هلمهولتز-گاوس از جمله پرتو بسل-گاوس می‌تواند شدیدا تحت تاثیر اثرات گرمایی القایی قرار گیرد. در این مقاله، پرتو خروجی یک لیزر حالت جامد، بسل-گاوسی که از یک سیستم اپتیکی ABCD می‌گذرد در نظر گرفته شده است. محاسبات تحلیلی نشان می دهد که گرمای ایجاد شده در کریستال لیزر به توان دمش، کمر پرتو دمش، رسانندگی گرمایی و ضریب جذب کریستال بستگی دارد. به منظور بررسی اثرات گرمایی، توزیع شدت مدل گرمایی پرتو خروجی بسل-گاوس بر حسب فاصله شعاعی برای توان دمش، کمر پرتو دمش، ضریب جذب و رسانندگی گرمایی مختلف شبیه‌سازی شده است. نتایج نشان می‌دهد در حالتی که دمش با توان بالا صورت گرفته و کمر پرتو دمشی باریک است، گرمای تولید شده در محیط فعال به شدت بر پرتو خروجی لیزر تاثیرگذار است به طوریکه شناسایی پرتو بسل-گاوس به آسانی ممکن نیست ولی با افزایش کمر پرتو دمش و رسانندگی گرمایی کریستال، اثرات گرمایی بر پرتو خروجی کاهش یافته و سیستم لیزری مشابه سیستم مدل بدون گرما رفتار می‌کند. نتایج این پژوهش می‌تواند کمک خوبی به محققین در تشخیص و شناسایی صحیح پرتوهای خروجی لیزر باشد.

کلید واژه- لیزر حالت جامد، اثرات گرمایی، پرتو بسل-گاوس، عدسی گرمایی، توصیف پرتو لیزر

Investigation of influence of properties of the laser's pump beam and laser crystal on the generation of thermally-affected Bessel-Gauss beam

R. Fallah [1], H. Nadgaran [2]

[1] Physics Department, University of Birjand, Birjand, Iran

[2] Physics Department, Shiraz University, Shiraz, Iran

Abstract- The generation of Helmholtz–Gauss beam families such as Bessel–Gauss (BG) beam can be dramatically suffered from thermal-induced effects. İn this work, The output BG beams of a solid-state laser were assumed to pass through an ABCD optical system matrix. The analytical solutions show that the induced heat in the crystal depends on pump power, pump beam wasit, thermal conductivity and absorption coefficient of laser crystal. İn order to investigate the thermal effects, the intensity distributions of the BG beams against radial distance under various pump power, pump beam waist, absorption coefficient and thermal conductivity have been simulated. The results show that for high pump-power values and small values of pump waist, the thermal-induced effects are so dramatic and the beam intensity distribution profile is so altered that the identification of BG beams is not easily possible, but large pump waist and high thermal conductivity can eventually make the laser output similar to nonthermal case despite high pumping power is received. The results of this work are a valuable aid to experimenters for beam identification.

Keywords: Solid-state laser; Thermal effects; Bessel-Gaussian beam; Thermal lens; Laser beam characterization

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1 Introduction

In solid-state lasers, special attention has been paid to heat load in the gain medium as the pump energy is partly converted to laser output and most of the pump energy is lost in the form of heat. The induced heat is dispersed within the crystal and causes thermal expansion of the material leading to crystal deformation and to the so-called thermal lens effect. Since almost principal parameters of laser beam is directly affected by induced heat, therefore the most serious problems are then the beam distortion and degradation due to thermal lensing and depolarization loss due to stress birefringence [1-3].The propagation characteristics of beams under severe induced heat is essential for designers to have a true insight to the laser output power, its efficiency and designing a suitable power of laser cooling systems. Bessel beams are considered as a nondiffracting solution to the scalar wave equation in circular cylindrical coordinates [4-5]. The Bessel-Gaussian (BG) beams which are Bessel beams apodized by a Gaussian transmittance, which carry a finite amount of energy and power is introduced by Gori et al. [6]. The BG beams are nearly nondiffracting because they can propagate over a large range without significant divergence. The propagation of BG beam has been investigated in free space and paraxial optical systems characterized by ABCD transfer matrices [5-6]. Recently, the existence of the BG beams was theoretically and experimentally presented [7-8]. The main purpose of this study is to investigate the generation of thermally-affected BG beams. By calculating the ABCD matrix of laser medium, we can observe the BG beam suffered by induced thermal load.

2 Thermal model and beam transformation in lens-like medium

We consider that the first-order BG beam is generated by a solid-state laser pumped by a super-Gaussian (SGP) pump profile. For this purpose, it is assumed that the variation of heat-induced refractive index can cause the gain medium is changed to an inhomogeneous graded index (GRIN) medium. Therefore assuming the GRIN medium as an ABCD thermally-affected medium, one has to calculate the element of the ABCD matrix of the GRIN medium for its full characterization. To do this, solution of the following heat equation should be obtained:

$$K\nabla^2 T = -S(\rho, z) \tag{1}$$

Where S(ρ, z) is the heat source density and K is the crystal thermal conductivity. We can write the heat source term as:

$$S_{SG}(\rho, z) = Q_\circ \, exp\left(-\frac{\rho^4}{\delta_P{}^4}\right)\exp(-\alpha z) \tag{2}$$

where α is the absorption coefficient of crystal, δ_p is pump waist and $Q_\circ$ is constant term as:

$$Q_\circ = \frac{\sqrt{2}\eta_q \eta_{abs} \alpha P_p}{\pi^{\frac{3}{2}} \delta_P{}^2 \left(1-e^{-\alpha l}\right)\mathrm{erf}\left(\sqrt{2}\frac{a^2}{\delta_P{}^2}\right)} \tag{3}$$

where P_p is the pumping power, η_q is the fraction of pump power converting to heat, η_{abs} is the fraction of absorbed pump beam and l is the laser crystal length. The accurate solution of Equation (1) has been derived by Usievich et al. [9] as:

$$T(\rho, z) = \sum_{i=1}^{\infty} t_i(z) J_\circ(v_i \rho) + T_\circ \tag{4}$$

Where $t_i(z)$ is a function dependent on the z-coordinate that satisfy the faces boundary conditions and v_i are the positive roots of equation $hJ_\circ(v_i) - KJ_1(v_i) = 0$. A change in the temperature results in a change in refractive index and causes the laser medium act as a convergent lens. The focal length of a lens-like medium is achieved by

$$f_{th} = \frac{2n_\circ}{\left(\frac{\partial n}{\partial T} + (n_0 - 1)(1+\nu)\alpha_T\right)\sum_{i=0}^{\infty}\int_\circ^l t_i(z) v_i^2 \, dz} \tag{5}$$

In addition, the expression for the refractive index of GRIN medium is obtained by expanding the Bessel functions and using paraxial ray approximation [10]:

$$n(\rho, z) = n_0\left(1 - \rho^2 \frac{\gamma(z)^2}{2}\right] \tag{6}$$

Where

$$\gamma(z) = \sqrt{\frac{1}{2n_\circ}\left[\frac{\partial n}{\partial T} + (n_\circ - 1)(1+\nu)\alpha_T\right]\sum_{i=1}^{\infty} t_i(z) v_i{}^2} \tag{7}$$

The ABCD transfer matrix is given as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \times [GRIN] \tag{8}$$

where L is the cavity free length. The GRIN transfer matrix, above equation represents the

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effects of induced-heat load on the laser medium and its detail calculation has been obtained by Sabaeian et al. [10].

3 Results and discussion

A cylindrical Nd: YAG crystal with l=5mm and radius of α=1.5mm was assumed. The laser was longitudinally pumped at wavelength of λ_p= 808 nm. The BG beam was generated with waist of δ_l=300 μm, λ_l=1064nm and κ =22144 m^{-1}. By using the assumed laser parameters, the thermally-affected and nonthermal beam profiles are simulated.

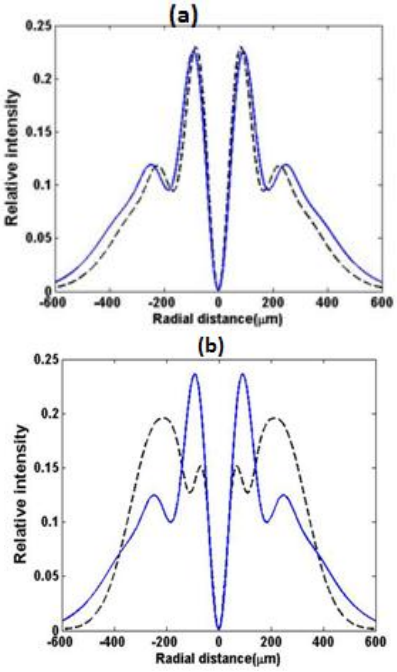


Figure 1: Intensity distributions of BG (J_1) beams versus radial distance for z=10 cm from the laser aperture for p=5W, α= 720 m^{-1}, K=10.5$\frac{W}{K.m}$ and $\delta_p = 200\,\mu m$ for **a)** p=1W **b)** p=5W. Solid plots represent the nonthermal BG beam, dashed plots shows thermally-affected BG beam.

Figure 1 shows the transverse intensity profiles of first-order BG beam versus radial distance for pumping powers of 1 and 5W, respectively. This figure and analytical results show that by increasing pump power, the intensity distribution of BG beam gradually changes. For pump power of 1W, the corresponding focal length of the induced thermal lens is 190 cm, that is very weak thermal lens is built up. There can be seen no considerable intensity profile changes under induced heat. The non-thermal model of intensity profile almost coincides with the thermal ones under 1 W pump power. For pump power of p=5 W, significant deviation from the nonthermal intensity distribution can be seen showing that the gain medium is much influenced by the thermal lens whose focal length is calculated to be about 12 cm. This means that the induced heat load has severely affected the BG beam generation.

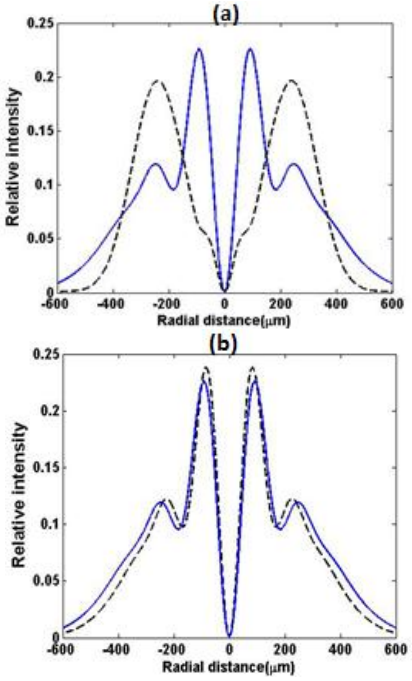


Figure 2: Intensity distributions of first-order BG(J_1) beams versus radial distance for z=10 cm for p=5W, K=10.5$\frac{W}{K.m}$ and **a)** $\delta_p = 100\,\mu m$ **b)** $\delta_p = 300\,\mu m$.

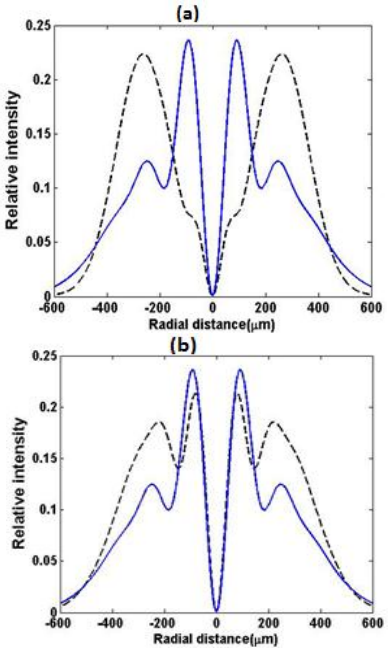


Figure 3: Intensity distributions of BG (J_1) beams versus radial distance for z=10 cm for p=5W, α= 720 m^{-1} and $\delta_p = 200\,\mu m$ for **a)** K=9 $\frac{W}{K.m}$ **b)** K=12 $\frac{W}{K.m}$.

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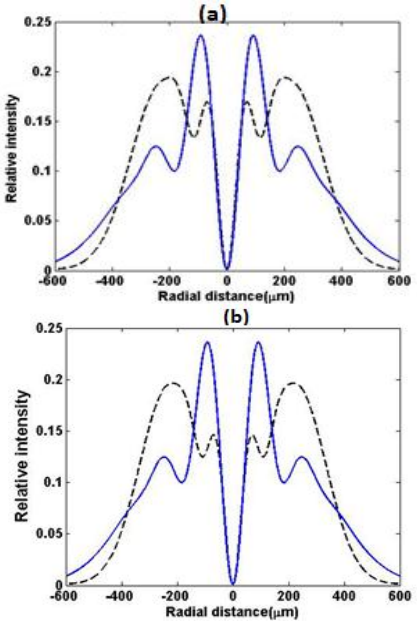


Figure 4: Intensity distributions of BG beams versus radial distance for z=10 cm for p=5W, $K = 10.5 \frac{W}{K.m}$ and $\delta_p = 200\,\mu m$ **a)** α= 520 m^{-1} **b)** α= 920 m^{-1}.

Figure 2 shows the intensity profiles of BG beams for pump waists of 100 and 300 μm. This figure clearly shows that the thermal effects diminish with increasing the pump waist. For pump waist of 100 μm and p=5 W, severe deviation from the non–thermal intensity profile can be realized showing that the laser media is considerably affected by the induced thermal lens whose focal lens is calculated to be 5.4 cm, one can say for z=10 cm, the BG profile is near the focal point of the thermal lens making much deviations of the corresponding non-thermal intensity profile. Our calculations show that the focal length of the induced thermal lens is 167 cm for pump waist of 300 μm. In this case, the beams behave as though no heat effect, even for large delivered powers is present. In figure 3 we have simulated the intensity profile of the first-order BG beams versus radial distance at 10 cm for thermal conductivities (K) of 9 and 12, respectively. The focal lengths of the thermal lens are calculated 15.6 and 21.2 cm for thermal conductivities (K) of 9 and 12 $\frac{W}{K.m}$, respectively showing weaker thermal lens by increasing thermal conductivity as expected. Therefore from figure 3, it is seen that upon increasing the thermal conductivity K, the strength of the heat-induced effects is gradually diminished. Figure 4 shows the transverse intensity distribution of first-order BG beams for thermal absorption coefficients of 520 and 920 m^{-1}, respectively. From this figure, there can be observed no considerable change in intensity distribution profiles as the absorption coefficient increases. This is because the temperature gradient causes thermal lensing in crystal does not change considerably by increasing the absorption coefficient.

4 Conclusion

This study is devoted to various impacts of pump power, pump waist, thermal conductivity and thermal coefficient absorption on the generation of first-order BG beam which are transverse eigenmodes of stable resonators. A comparison between the thermal and non-thermal BG beams not only reveals the important role of pump power, pump waist and thermal conductivity on the generation of the BG beams, but also shows how the intensity distributions are suffering from the induced thermal load. The results show that for powerful narrow pump beam, severe deviation from the non-thermal profiles can be realized showing that the gain medium is significant influenced by the thermal lens, but it can been observed that as the pump waist and thermal conductivity increases, the thermal effects diminish emphasizing that the experimenter should be aware of the extent of thermal effects in generating the special types of beams and a comprehensive thermal model is needed to accounted for heat-induced effects, otherwise everyone may be confused to identify true beam.

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