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Improving Diode Pumped Alkali Laser (DPAL) Beam Quality by Inducing Refractive Index Gradients

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14. ABSTRACT
We have recently predicted that large radial gradients of the refractive index induced by the pump beam in the heated gain medium of diode pumped alkali lasers (DPALs) could lead to improved DPAL beam quality. This effect depends on the composition of the buffer gas in the cell. We verified this counterintuitive finding by careful measurements of the beam quality factor M2 in static Cs DPALs with different compositions of the buffer gases. Computations of M2 in Cs DPALs with different He/hydrocarbon ratios using wave optics model coupled to gas dynamics code and comparison of the calculated and experimental results were also performed. The results of the present study were published in R. Luzon, et. al, “Improving the beam quality of DPALs by refractive index gradients induced by the pump beam in the heated gain medium: experimental verification of the theoretical prediction", J. Opt. Soc. Am. B 38, 550-
552 (2021). It is suggested that further work on the modeling of multi-mode diode pumped lasers interaction with hydrocarbons should be carried out, aiming at getting better agreement with the experimental results.

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I. Summary

We have recently predicted [1] that large radial gradients of the refractive index induced by the pump beam in the heated gain medium of diode pumped alkali lasers (DPALs) could lead to improved DPAL beam quality. This effect depends on the composition of the buffer gas in the cell. We verified this counterintuitive finding by careful measurements of the beam quality factor M^2 in static Cs DPALs with different compositions of the buffer gases. Computations of M^2 in Cs DPALs with different He/hydrocarbon ratios using wave optics model coupled to gasdynamics code and comparison of the calculated and experimental results were also performed. The results of the present study were published in [2]. It is suggested that further work on the modeling should be carried out, aiming at getting better agreement with the experimental results.

II. Introduction

Cs diode pumped alkali lasers (DPALs) have been extensively studied during the last years [3,4]. Recently, studies of their beam quality have been reported [5-7]. The gain medium of DPALs operating in CW mode absorbs appreciable amount of heat from the pump beam which must be dissipated. The thermal load concentrated along the optical axis of static Cs DPAL cell results in large radial gradients of temperature, gas density and hence of the refractive index near the optical axis. The refractive index gradients in the laser cell result in wave-front aberrations, such as defocusing, similar to thermal lensing in solid state lasers. However, unlike most solid-state lasers where positive thermal lens is formed [8], in DPALs the thermal lens in the pumped volume is negative [9].

Wave-front distortion of the laser beam affects the beam quality and the potential to be focused to very small spots without excessive divergence. The output laser beam quality can be quantified by different parameters such as the beam quality factor M^2, Strehl ratio, brightness and power in the bucket [10,11]. For lasers with stable resonators and bell-shaped laser beams close to Gaussian beams, the most common and convenient parameter is M^2, which represents the degree of variation of the beam from an ideal Gaussian beam [10]. Combining wave optics model and gasdynamic code we have recently predicted [1] that large radial gradients of the refractive index in the heated gain medium of DPALs could lead, counterintuitively, to improvement of M^2.

This behavior of M^2 can be explained as follows [1]. Gas heating by a Gaussian pump beam leads to lower temperature and hence to higher density and refractive index with increasing distance from the optical axis of the laser. As a result, a negative lens is formed in the gas, which leads to an increase in the sizes of the transverse laser modes of a stable resonator, and, consequently (for a given size of the pump beam) to a decrease in the number of oscillating transverse modes. The latter, in turn, leads to a decrease in M^2 in comparison with the case of a uniform refractive index in the gas [1]. The verification of this conclusion carried out in the present work is extremely important, as it may lead to a new, unexpected way to improve the quality of the DPAL beam and thus reduce the spot size of the far-field laser beam.

III. Methods, Assumptions and Procedures

In this work we measured the dependence of M^2 on the pump power of a static Cs DPAL with a stable plano-concave optical resonator for various buffer gas compositions. The static Cs DPAL was similar to that described in detail in [6,7]. Therefore, here we summarize very briefly the design and the experimental procedure for measuring M^2. Schematic of the experimental setup is shown in Fig. 1. A circular pump beam from the diode laser (Shark Laser System, OptiGrate, Inc) producing linearly polarized output beam with maximum power of 65 W, spectral bandwidth of ~ 0.05 nm and central wavelength of 852.1 nm was focused into a Cs cell by a spherical lens with 100 mm focal length. The pump beam waist diameter at the focal plane was ~3 mm and M^2 ~ 500. A cylindrical quartz Cs cell of 1” diameter and 2 cm length with two quartz windows at the ends, contained 600 Torr (at room temperature) mixture of He with hydrocarbons (methane or ethane) with different ratios of hydrocarbon/He. Cs metal was stored in a stem connected to the Cs laser cell that was placed inside a temperature controlled aluminum oven heated to ~ 100 C. To avoid excessive heating of the Cs cell to temperatures >120 C, the pump beam passed through an optical chopper with a duty cycle of 0.5 and frequency of 20 Hz.

The optical axis of a stable resonator of the laser coincided with the pump beam axis in the cell. The resonator output coupler was a flat mirror with 50% reflectivity at the laser wavelength, whereas the back mirror was a concave high reflector with reflectivity > 99% and radius of curvature R of 100 cm. The distance between the mirrors L was 90 cm and the center of the Cs laser cell was 40 cm from the back mirror. The values of R and L were chosen so that the diameter of the fundamental transverse mode of the empty cavity (~ 2.3

mm) was somewhat smaller than the diameter of the pump beam in the cavity (~ 3 mm). In this case only low-order modes took part in the laser oscillation at low laser power, and the M^2 values were small ~1-3.

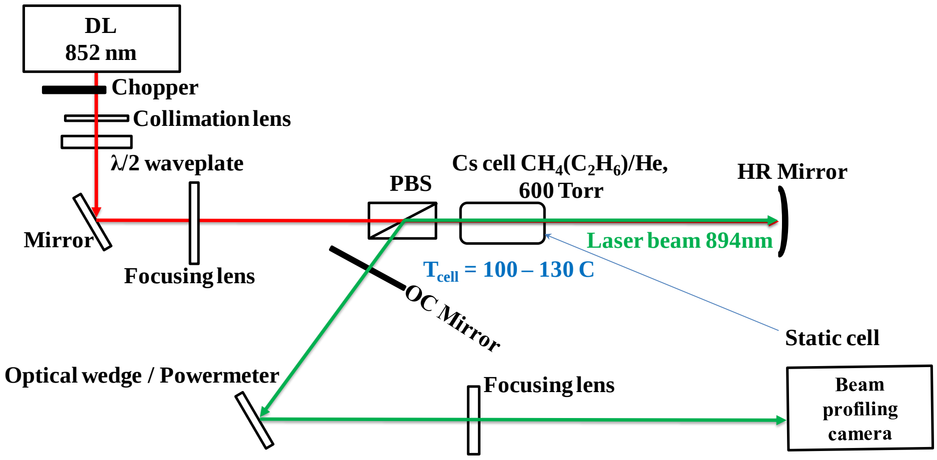


Fig. 1. Schematic of the experimental setup.

To find M^2 of the output beam reflected from the optical wedge it was focused by a spherical converging lens with 150 mm focal length and the beam radius was measured at different distances from the focal plane using Spiricon SP928 beam profiling camera (Ophir Photonics, LLC) as explained in detail in [7]. The camera software determined the beam quality factors $M^2_{x,y}$ in each of the lateral *x*–*y* directions and the average M^2 was calculated as $M^2 = M_x M_y$. Due to the circular symmetry of the laser beam, the values of M_x, M_y and M were close to each other. The optical wedge reflected ~1% of the laser power in order to avoid damaging of the camera. The camera was synchronized with the optical chopper. It was found that variations of the chopper rotation frequency did not affect the measured values of M^2. For the power measurements the optical wedge was replaced by powermeter (Ophir FL250A-BB-50).

The wave optics model coupled to gasdynamic code developed in [1] was applied to calculations of the laser power and M^2 for experimentally studied static Cs DPAL. The gasdynamic code was based on a three-dimensional, time-dependent computational fluid dynamics (3D CFD) model. The gas flow conservation equations in the DPAL cell were coupled to fast-Fourier-transform algorithm for the laser beam transverse mode propagation. Using the CFD and beam propagation models, the gas flow pattern and spatial distributions of the pump and laser intensities and the laser beam phase in a plano-concave resonator are calculated for end-pumped Cs DPAL.

IV. Results and Discussion

Figure 2 shows the dependence of the measured output power on the pump power for different compositions of the buffer gas. The output power increased with increasing pump power, but its maximum values were rather low and did not exceed several watts. In this case, as explained above, only low order transverse modes participated in the lasing, leading to low values of M^2.

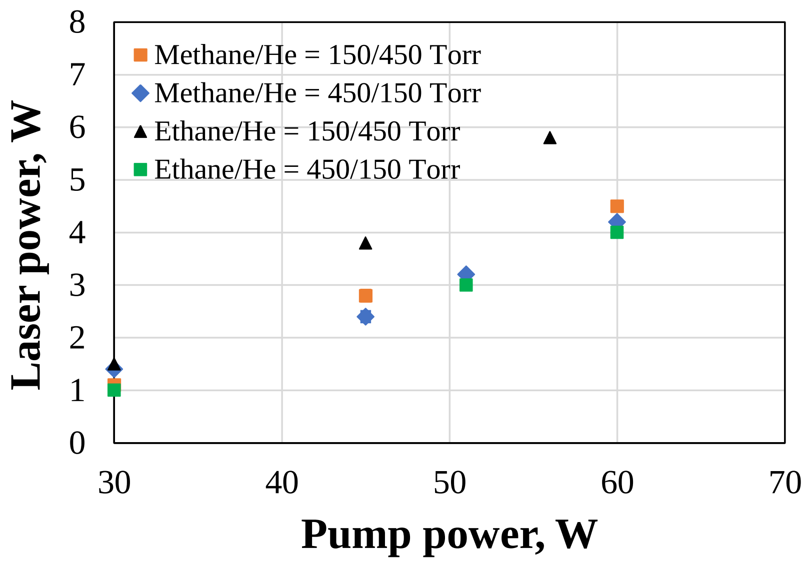
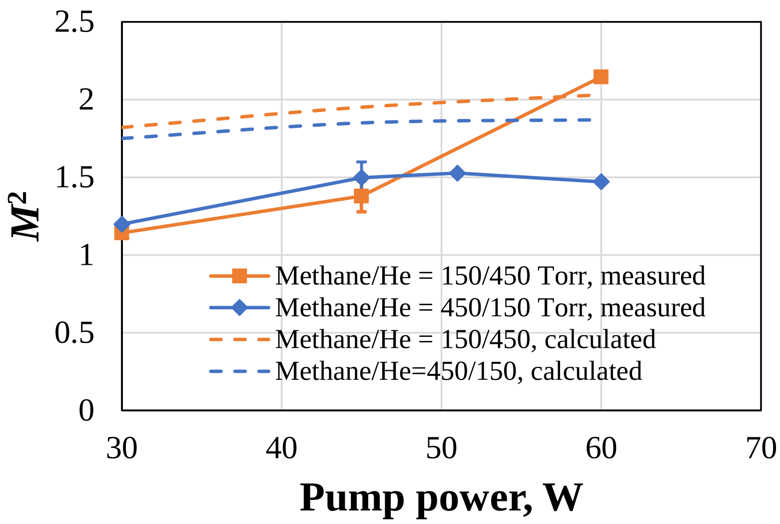


Fig. 2. Measured output laser power as a function of pump power in Cs static DPAL with different compositions of the buffer gas.

Figs. 3a and b show the measured and calculated dependence of M^2 on the pump power for two compositions of the buffer gas: a mixture of CH_4 (Fig. 3a) and of C_2H_6 (Fig. 3b) with He. For each buffer gas composition, the measurements were repeated three times and the error bars were found from the scatter of M^2 values in these experiments. For low pump power (~ 30-40 W for CH_4/He and ~30 W for C_2H_6/He mixtures) when the gas heating and hence the refractive index gradients are small, the values of M^2 for low and high molar fractions of methane and ethane are almost the same. However, at higher pump powers, M^2 for higher hydrocarbon mole fractions (corresponding to higher temperatures and refractive index gradients) is smaller than for lower hydrocarbon mole fractions. These results support our counterintuitive theoretical prediction that large radial refractive index gradients in static DPALs result in improved output beam quality.

Note that for a buffer gas with a low hydrocarbon mole fraction and therefore low refractive index gradients, M^2 increases with increasing pump power. The reason for this is that high pump power leads to the excitation of high-order transverse modes [6]. For high molar fractions of hydrocarbons, as explained above, defocusing suppresses high-order mode oscillations, which leads to a decrease in M^2.



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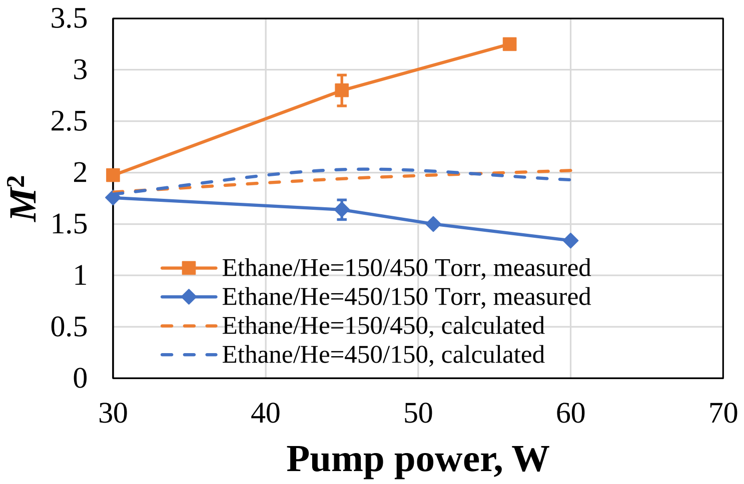

b

Fig. 3. Measured and calculated beam quality factor M^2 as a function of pump power in Cs static DPAL with high and low molar fractions of methane or ethane in the buffer gas: (a) CH_4/He=450/150 Torr and CH_4/He=150 /450 Torr; (b) C_2H_6/He=450/150 Torr and C_2H_6/He =150 /450 Torr.

Fig. 4 compares the dependence of the measured M^2 on the pump power for buffer gases with high molar fractions of methane to that of ethane. It can be seen that for methane M^2 weakly depends on the pump power, while for ethane M^2 decreases with increasing pump power. The reason for this difference is that, as shown in [1], for ethane the refractive index gradients and hence the defocusing effects are much larger than for methane. Consequently, increasing the pump power in DPALs with ethane/helium buffer gas at high ethane content can lead to a significant improvement in the output beam quality.

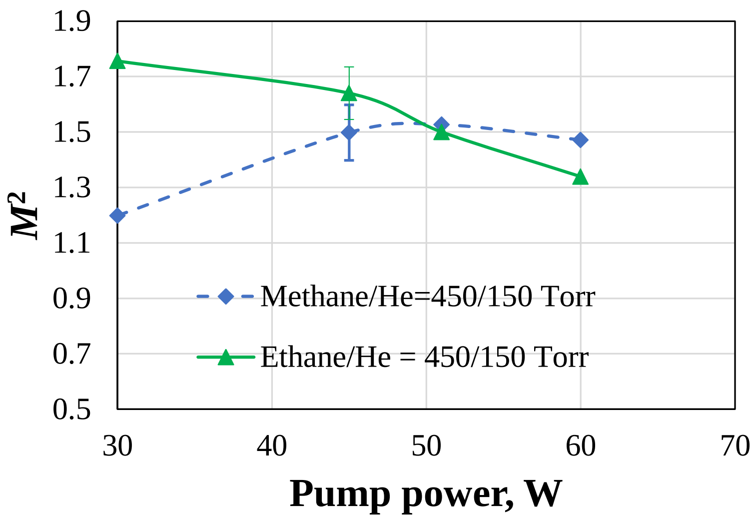

Fig.4. Measured beam quality factor M^2 as a function of pump power in Cs static DPAL with high molar fractions of methane and ethane in the buffer gas.

The calculated M^2, presented in Figs. 3a and b, differ from the measured values and are almost independent of both the pump power and hydrocarbon molar fraction. In particular, for a buffer gas with a low molar fraction of hydrocarbons and, therefore, weak defocusing, the calculated value of M^2 increases with increasing pump power much more slowly than the measured value. There are two possible reasons for the difference. One of them are inaccurate values of the input parameters in the calculations, such as the pump beam shape, Cs density and the gas refractive index. Another reason is that the wave optics model assumed that the laser beam in the cavity is coherent, and the phase of the electric field is practically uniform in the cross section of the beam. As a result, the calculated distribution of the electric field was almost single-mode, which led to low values of M^2.

V. Conclusions

It has been experimentally found that high pump power may result in radial gradients of the refractive index and in M^2 decrease in static DPALs. M^2 for high molar fractions of hydrocarbons in the buffer gas is smaller than for lower molar fractions where the gradients are small. These experiments support our counterintuitive theoretical prediction that large radial refractive index gradients in static DPALs result in improved M^2. Increasing the pump power in a DPAL with ethane/helium buffer gas at high ethane content can lead to a significant decrease in M^2, namely, to improved output beam quality. The calculated values of M^2 found using the wave optics model coupled to gasdynamic code [1], are not in agreement with the experimental results. In particular, for a buffer gas with a low molar fraction of hydrocarbons the calculated value of M^2 increases with increasing pump power much more slowly than the measured value. The reasons for these discrepancies are, apparently, inaccurate values of the input parameters of the model and the inability of the model to describe the operation of a multimode laser.

It is suggested that further work on the modeling should be carried out, aiming at getting better agreement with the experimental results. The wave optics model [1] should be combined with the intensity-based model [6], and as a result the calculated electric field in the laser beam (at a low molar fraction of hydrocarbons) will contain a larger number of transverse cavity modes, which should lead to an increase in M^2 and to a better agreement with the experimental results. The calculated M^2 value for high hydrocarbon fractions will also change and is expected to be closer to the measured values.

VI. References (works supported by the U.S. Air Force Office of Scientific Research are marked with *)

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