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Beam Magnification and the Efficiency of Optical Trapping with 790-nm AlGaAs Laser Diodes

G. J. Escandon, Y. Liu, G. J. Sonek, *Member, IEEE*, and M. W. Berns

Abstract—The efficiency of dielectric particle confinement with 790-nm AlGaAs laser diode optical traps is investigated as a function of beam magnification and polarization state. When an anamorphic prism pair is used to correct for diode beam ellipticity, trapping efficiencies of nearly 0.37 are achieved with a magnification factor of 3X, laser powers of 4–18 mW, and an overfilled microscope objective entrance aperture. Results are compared for diodes having small (8 μm) and large (57 μm) astigmatisms, but comparable far-field divergence angles.

I. INTRODUCTION

THE single-beam gradient force optical trap [1], or optical tweezer, uses a highly focused laser beam to create optical forces that can be used for the micromanipulation and force transduction of micron and submicron-sized particles, including single cells [2] and other biological organisms [3]. As an alternative optical source to the Nd:YAG laser ($\lambda = 1060$ nm), the laser diode-based optical trap has been proposed and demonstrated, using InGaAsP (1300 nm) [4], [5] and GaAs (840 nm) laser diodes [6], where the emission wavelengths correspond to the spectral regions of minimal chromophore or water absorption in biological media. To date, however, very little data has been made available which correlates the laser diode parameters with optical trap performance. In comparison to other laser sources, laser diodes typically have lower output powers, astigmatism, non-TEM₀₀ elliptical beam profiles, and large far-field divergence angles, largely derived from the asymmetry of the diode active region. Hence, additional optics are often required to collimate, and make circular, the diode beam prior to its use with other optical components. In particular, beam magnification, the extent of aperture filling, and beam polarization state become important parameters which can dramatically affect the efficiency and performance of laser diode-based optical traps.

In this letter, we present results of optical trapping experiments with AlGaAs laser diodes emitting at 790 nm which quantify, for the first time, the effects of diode beam magnification on the efficiency of optical trapping. With laser powers in the range of 4–18 mW, the trapping efficiency can be maximized by overfilling the microscope objective used to create the optical trap, with parallel axis magnifications of

> 2X. This overfilling is, however, at the expense of the power delivered by the tweezer. No substantial difference is observed between the transverse trapping efficiencies of small and large astigmatic diodes. With the ability to tailor diode beam properties as described herein, semiconductor laser diodes would be well-suited for the development of compact and efficient optical tweezer systems in a variety of applications.

II. EXPERIMENTAL SETUP

The laser diode-based optical trapping system used in the present study is shown schematically in Fig. 1, while the measured characteristics of the two commercial stripe-geometry AlGaAs laser diodes (Sony SLD 201V-3, 203-AV) investigated are given in Table I. The two diodes have comparable emission wavelengths (~ 789 nm) and far-field divergence angles ($\theta_{\parallel} \sim 13^\circ$, $\theta_{\perp} \sim 25 - 30^\circ$), but differ in threshold current, maximum output power, and degree of astigmatism, respectively. Both small (8 μm) and large (57 μm) astigmatic, low-power (30 mW), single mode TE-polarized diodes were chosen for study. As shown in Fig. 1, the optical output from the diode, set via a current and temperature controller, is first collimated with a 5 mm f.l. lens, and then magnified, along the axis parallel to the beam polarization direction, with an anamorphic prism pair. The angle of rotation of each prism can be individually adjusted to produce the desired parallel-to-perpendicular axis beam width ratio. The beam is then focused, via a 100X, 1.25 N.A. oil immersion microscope objective having a maximum beam convergence angle of $\sim 56^\circ$, onto the particle or sample of interest to create the optical trap. The trapping process is observed and recorded by reflecting a portion of the back-reflected beam onto a video camera and monitor, respectively. The sample chamber, formed with two coverslips and a silicone gasket, contain 10 μm diameter polystyrene microspheres ($n = 1.57$) suspended in deionized water ($n = 1.33$), where n is the refractive index of the medium. The entire chamber is mounted on a linear translation stage that can be moved with velocities as small as 10 $\mu\text{m}/\text{sec}$.

In order to quantify trap performance as a function of beam magnification and input optical power, the microspheres are first confined by the optical laser trap by focusing the laser beam at a distance ~ 10 μm above the bottom coverslide, and then dragged, via the translation stage, in directions parallel (\parallel) and perpendicular (\perp) to the beam polarization axis, but transverse to the beam propagation direction. The Stoke's drag force, given by the expression $F = 6\pi r\gamma v_c$, where r is the particle radius, γ is the water viscosity (0.01 dyn-s/cm), and

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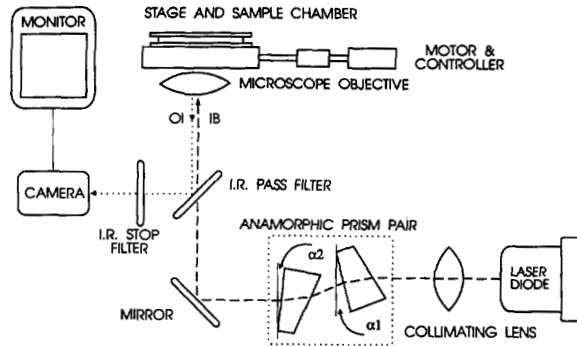


Fig. 1. The experimental setup used to study the effects of AlGaAs laser diode beam parameters on the performance of an optical tweezer system. The system incorporates an anamorphic prism pair and collimating lens for beam shaping and magnification.

TABLE I
MEASURED PARAMETERS OF THE ALGAAS LASER
DIODES USED IN THE OPTICAL TWEETZER SYSTEM

	SLD-201 V-3	SLD-203 AV
Wavelength λ (nm)	789 ± 0.1	787 ± 0.1
P_{\max} (mW)	30.0 (at 125 mA)	19.6 (at 90 mA)
I_{th} (mA)	90	55
Far-Field Divergence	30	25
θ_{\perp} (deg)	θ_{\parallel} 13	13.5
Astigmatism (μm)	57.5 ± 1.0	8.1 ± 0.1

v_c is the critical velocity at which the particle escapes the trap, is used to determine the optical transverse forces which are generated by the focused diode beam. These forces are further corrected for by an objective power transmission factor (60%), and a viscous drag factor (138%) which accounts for the location of the dragged particle with respect to the chamber coverslip. The trapping efficiency, Q , is determined from the expression $Q = (c/n)(F/P)$, where c/n is the velocity of light in the surrounding medium, F is the transverse force, and P is the applied optical power. Theoretically, the transverse efficiency is calculated by determining the positions of zero axial force, as the trapped particle is moved relative to the beam focus away from its equilibrium position [7].

III. RESULTS AND DISCUSSION

The laser diodes were tested with parallel-to-perpendicular ($\parallel - \perp$) beam width ratios $\omega_{\parallel}/\omega_{\perp}$ equal to 0.55, 1.12, and 1.54 for SLD-201, and 0.45, 1.06, and 1.39 for SLD-203, each corresponding to anamorphic prism magnification factors of 1X, 2X, and 3X, respectively. The possible combinations for beam shapes at the input aperture of the microscope objective are shown in Fig. 2, and represent the cases of an underfilled ($a_{\perp} = 0.5, 0.75, 1.0$) and overfilled ($a_{\perp} = 1.3, 1.5$) input aperture (dotted circle) with an elliptical gaussian beam (solid lines). The parameter a is the ratio of the mode beam width ω to the input aperture radius r [7], and is defined separately for ω_{\parallel} and ω_{\perp} . In Fig. 2(a), for example, a_{\parallel} is equal to $a_{\perp}/2$, and corresponds to a magnification factor, M , of 1X. Here, the beam width along the axis parallel to the diode junction plane

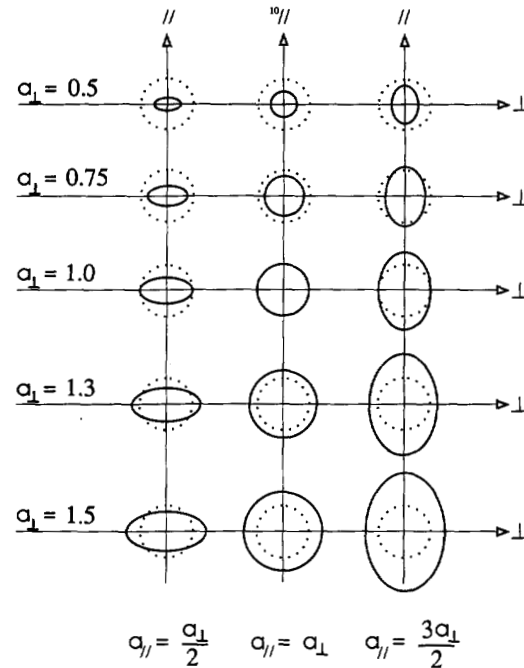


Fig. 2. Schematic of elliptical beam shapes (solid lines) relative to the input aperture of the microscope objective (dotted lines) for beam magnifications of (a) 1X, (b) 2X, and (c) 3X, respectively. \parallel and \perp refer to the beam polarization axes, defined with respect to the laser diode junction.

is taken to be half-as-large as the perpendicular beam width. For increasing a_{\perp} and constant M , the ratio of the major-to-minor axes of the ellipse is preserved. Figs. 2(b) and (c) represent beam magnifications of 2X and 3X, respectively. As both the magnification and a increase, the intensity distribution of the beam becomes more uniform over the input aperture, and trap efficiency is expected to increase [7]. For a diode of finite power, however, continuing to magnify the beam width also reduces the percentage of power transmitted through the objective lens. For example, at a magnification of 3X, nearly 48% of the input power is lost. For the two diodes considered herein, only the overfilled cases, i.e. $a_{\perp} = 1.5$ (SLD-201) and $a_{\perp} = 1.3$ (SLD-203), were examined, since the extent of aperture underfilling was difficult to control.

The results of transverse trapping force measurements are shown in Figs. 3(a) and (b), for beam magnifications of 1X, 2X, and 3X, and forces measured along axes parallel, and perpendicular, to the beam polarization direction. Over the range of output powers from 4–18 mW, as transmitted through the trapping objective, it is seen that the transverse forces scale nearly linearly with power. For diode SLD-201, in Fig. 3(a), little difference is found between the forces produced along the \parallel and \perp axes, while diode SLD-203 exhibits nearly a 37% force difference for the two polarization orientations. This latter behavior might be expected, based on ray-optic force calculations for 10 μm diameter microspheres. However, the lack of a substantial polarization dependence for diode SLD-201 is still unclear, and may be due to the diode's large astigmatism and focal characteristics. For both diodes,

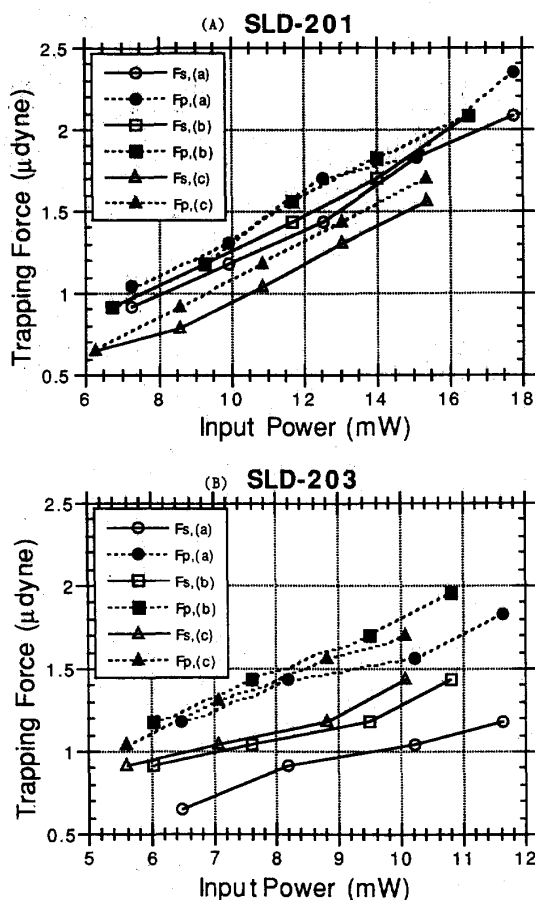


Fig. 3. Applied transverse trapping force as a function of input laser power for magnifications of 1X^(a), 2X^(b), and 3X^(c), and for diodes (a) SLD-201 and (b) SLD-203, having large and small astigmatism, respectively. *s* and *p* refer to measurements made perpendicular (\perp) and parallel (\parallel) to the beam polarization direction.

however, an increase in magnification is seen to produce an increase in optical trapping efficiency. The predicted and measured efficiencies as a function of magnification factor are summarized in Table II, where a ray-optics model using an elliptical gaussian beam intensity profile has been used to estimate the efficiency. Here, it has been assumed that the input diode beam intensity can be written as: $I(r) = I_0 \exp - 2\{(x^2/\omega_{\perp}^2) + (y^2/\omega_{\parallel}^2)\}$, where ω_{\perp} and ω_{\parallel} are the beam widths defined for the perpendicular and parallel axes, respectively. For $\omega_{\parallel} = \omega_{\perp}$, the circular gaussian (TEM₀₀) mode profile is recovered, while in the limit of a approaching ∞ , the input intensity profile becomes a constant I_0 . It is seen that, while the 1X data underestimates the efficiency by as much as 43% (SLD-201), the errors for 2X and 3X are significantly smaller ($< 20\%$). We note, in comparison, that the ray-optics model predicts nearly a constant value for Q as M is varied. The larger errors for unity magnification are attributed to the deviations in measured escape velocity at very low laser powers, and the accuracy to which power transmission measurements can be made through the trapping

TABLE II
COMPARISON OF MEASURED AND CALCULATED TRAP EFFICIENCIES

		MAGNIFICATION		
		1X	2X	3X
SLD-201	Polarization*			
Q (theory)	\parallel	0.377	0.372	0.372
	\perp	0.289	0.292	0.291
Q (measured)	\parallel	0.214 ± 0.013	0.256 ± 0.010	0.258 ± 0.010
	\perp	0.193 ± 0.010	0.248 ± 0.011	0.236 ± 0.012
SLD-203				
Q (theory)	\parallel	0.379	0.371	0.371
	\perp	0.277	0.290	0.293
Q (measured)	\parallel	0.241 ± 0.020	0.304 ± 0.010	0.375 ± 0.020
	\perp	0.150 ± 0.010	0.223 ± 0.020	0.306 ± 0.030

* Scan direction, measured with respect to the polarization state of the laser beam.

microscope objective. The effects of astigmatism were also accounted for in the ray-optics theory by assuming that a spatial separation between the points of origin of the θ_{\parallel} and θ_{\perp} diode beams corresponds, after beam propagation through collimation and high N.A. focusing objective lenses, to a change in the axial positions of the focused beams with respect to the center of the microsphere or, alternatively, a change in the maximum beam convergence angle. Displacements of the focal point in the axial direction are expected to have a greater influence on the resulting axial trapping forces than the transverse forces. For diode astigmatism of 8 and 57 μm , it is estimated that axial Q 's vary from $\sim 5\%$ to 26%, while transverse Q 's vary by less than 8%, based upon focal point displacements of ~ 3.5 and 25 μm , respectively.

Hence, as the beam profile becomes circularized, or proceeds to overfill the aperture with a more uniform intensity distribution, the experimental efficiency improves, regardless of whether the diode has a small or large amount of astigmatism. There is a trade-off, however, between the amount of power lost due to overfilling, and the increased magnification required to improve trap efficiency. This trade-off is less critical for high-power laser diodes, where an ample power margin is available for beam shaping and magnification power losses. In the limit of a uniformly filled input aperture, the Q 's transverse to the direction of beam propagation are expected to achieve their maximum values [7]. In the present case, overfilling the input aperture with an elliptical gaussian beam appears to confirm this result, as shown in the data of Fig. 3 and Table II.

IV. CONCLUSION

Using an anamorphic prism pair to correct for laser diode beam ellipticity and adjust the ratio of parallel to perpendicular beam widths, trapping efficiencies of nearly 0.37 have been achieved with low (4–18 mW) laser powers. The ability to confine and manipulate micron-sized test particles with laser diodes, along with the knowledge of diode parametric dependences as presented herein, should provide a basis for future work in the development of diode-based optical microscopy and tweezer systems at other operating wavelengths.

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