Investigating the Modal Dependencies of Beam Quality
Via Spectrally-resolved Imaging of the Mode Structure in Diode Lasers

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Abstract: Laser beam quality is an important factor for free-space communication and other high power applications. To achieve the power requirements for such applications, there is a trade-off with the M^2 Beam Quality factor. While direct diode lasers offer higher efficiency in a smaller footprint compared to solid-state and fiber laser systems, beam quality is poor due to multi-mode operation. M^2 measurements compliant with ISO 11146 standards require numerous measurements, especially for multimode lasers. It is possible to use faster, modal decomposition methods for measuring M^2 by employing a spectrometer to spatially separate the modes of a laser. This work presents a custom Echelle Grating Spectrometer for spatially separating laser modes. This tool provides the basis for an alternative method of M^2 measurements via Modal Power Distribution analysis.

1 MOTIVATION

With improvements to spatial and spectral brightness, diode lasers continue to gain interest in fiber pumping and industrial cutting. Single emitter broad-area laser (BAL) diodes have become a core part of many fiber laser modules due to continued improvements in reliability and efficiency (Kanskar et al, 2013). However, limitations in brightness and beam quality have prevented diode lasers from being directly used in many applications, such as free space optical communication. Mode-control of tapered diode lasers has enabled increased spatial brightness using a Master-Oscillator Power-Amplifier (MOPA) structure, seen in Fig. 1, to achieve high power without a highly multimodal beam degrading M^2 (Kelemen et al, 2009). However, the tapered profile degrades the beam quality with an astigmatic beam indicated by the virtual waist in Fig. 1. Comparing the changes in mode structure and M^2 would enable engineers to improve their understanding of multimode operation on beam quality. Improving beam quality in multimode operation of diode lasers is advantageous due to their superior wall-plug efficiency, optical power, and footprint size. Spatially examining the impact of multimode operation on beam quality provides a novel approach that can procure more information to improve diode lasers for industrial and pumping applications.

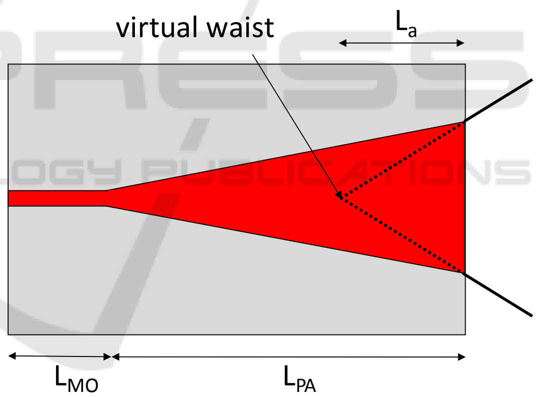

Figure 1: MOPA structure with ridge length (L_{MO}), tapered length (L_{PA}), and astigmatism (L_a).

2 EXPERIMENT

Three diode lasers were examined to investigate the relationship between mode structure and beam quality—a BAL, an offset BAL, and a tapered laser. The BAL and offset BAL have a specified emitter width of 95 μm with a 1.5 mm cavity length. The "offset" BAL is labelled as such due to non-uniform current injection – current is injected along one edge of the back side of the chip only, resulting in a non-uniform gain distribution in the lateral direction. The tapered laser uses a MOPA structure with a 1.5 mm

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ridge length and a 4.5 mm tapered region at a full aperture angle of 6° leading to a 450 µm emitter. A light-current-voltage (LIV) and spectral analysis were performed on the lasers to compare wall-plug efficiency, slope efficiency, and thermal wavelength drift. For the tapered laser, beam waist measurements were also performed to characterize the astigmatism. The beam quality of the lasers was characterized using the moving slit technique based on the ISO 11146 standard. Beam quality was measured with respect to current, illustrating the trends in the beam quality of the fast and slow axis. The lasers were also examined using spectrally-dispersed mode imaging with a custom Echelle spectrometer to demonstrate the viability of using this tool for modal power distribution analysis.

2.1 LIV and Spectrum

The LIV measurements were performed with a thermopile and a digital multimeter; spectral measurements were performed by fiber coupling light into an optical spectrum analyser. Spectral measurements were recorded after the LIV data in order to measure the spectrum at the operating conditions for peak wall-plug efficiency. To obtain an estimate of the thermal wavelength drift, the spectrum was measured at 20°C and 25°C.

2.2 Beam Profiler

In order to measure the M^2 value of the lasers and the astigmatism in the tapered laser, the beam was collimated with an 8 mm focal length asphere and focused with a f = 40 mm plano-convex lens. To minimize lens aberrations, the curved sides of the lens were facing the collimated region of the beam. A reflective neutral density (ND) filter was also placed in the collimated region and an absorptive ND filter was placed after the lens to reduce the intensity at the detector, preventing saturation. Figure 2 shows the diagram of the system and the experimental setup used for measurements. When using the system to measure the beam caustic, the 40 mm focal length lens was swapped out for a f = 75 mm lens to provide a higher magnification. The astigmatism of the laser can be measured with greater precision at high magnification because the distance between the focal points increase with the magnification squared. Equation 1 expresses the relation between beam caustic (Δz) and astigmatism (ΔL) based on the moving beam profiler method (Sun, 1997).

$$\Delta L = \Delta z \left(\frac{f_1}{f_2}\right)^2 \quad (1)$$

When using the beam profiler for M^2 measurements, the 4σ beam waist was measure at more than 10 points. The M^2 value was determined by fitting Eq. 2 to the measured data (Crist and Nelson, 2012).

$$w(z) = w_0 \sqrt{M^2 + M^2 \left(\frac{\lambda z}{\pi w_0^2}\right)^2} \quad (2)$$

To ensure an accurate fit with the data, measurements were taken near the minimum beam waist and in the linear region of propagation.

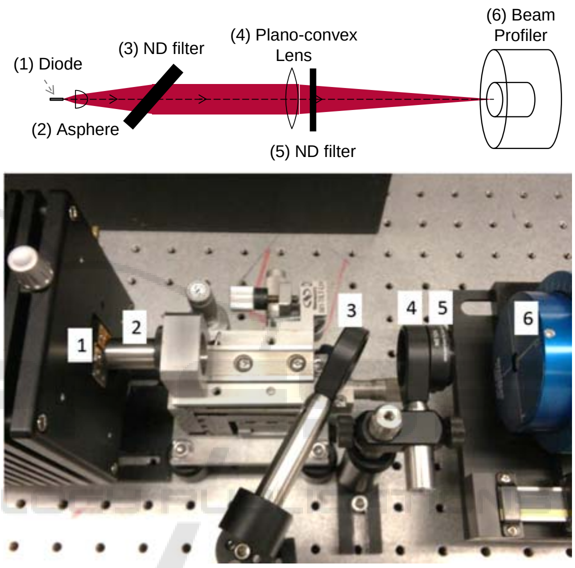

Figure 2: System design diagram of the beam quality measurement system and overhead view of the experimental setup with labelled parts.

2.3 Custom Echelle Spectrometer

A custom Echelle spectrometer shown in Fig. 3 was used to image the spectrally-resolved modes of the diode lasers. The first section of the spectrometer focuses the beam through an f = 13.86 mm asphere and reimages it with 10 times magnification using an f = 100 mm best form lens. For high power lasers, a plate beam splitter is place in the region between the apshere and best form lens. The second part of the system reimages the beam 1:1 with spectrally dispersed modes. The f = 500 mm lens collimates the beam and acts as the lens for 1:1 imaging. In collimated space, the beam double passes the Echelle grating using a dielectric mirror with 99% reflectivity from 980 - 1025 nm to reflect the single pass back to the grating with minimal aberrations. To achieve high

Table 1: Laser Wavelength and Power Characteristics.

Laser	Wavelength at peak efficiency	Peak Wall-Plug Efficiency	Turn-on Current	Slope Efficiency	Power at peak efficiency	Thermal Wavelength Drift
BAL	972 nm	62.4%	0.29 A	1.02 W/A	2.29 W	~0.7 nm/K
Offset BAL	813 nm	52.9%	0.41 A	1.14 W/A	2.76 W	~0.3 nm/K
Taper	979 nm	33.8%	1.65 A	0.85 W/A	5.74 W	~0.1 nm/K

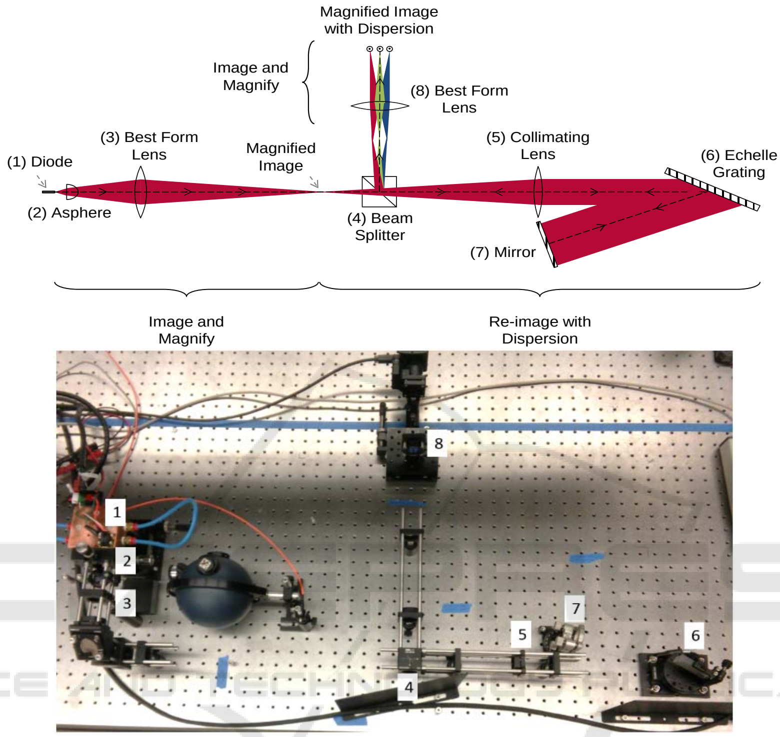

Figure 3: System design diagram of the custom Echelle spectrometer and overhead view of the experimental setup with labelled parts.

dispersion in the Littrow configuration, the grating operates with peak intensity in the 6th diffraction order with 316 lines/mm and a blaze angle of 63°. To achieve an optimum magnification for image clarity and size, an f = 50 mm best form lens magnifies the dispersed mode image by a factor of four.

3 EXPERIMENTAL RESULTS

LIV and spectral analysis were in good agreement with results from BAL and tapered laser diode measurements in prior work by Kelemen et al, showing that tapered lasers offer higher maximum output power at lower efficiency. M^2 increased with current as expected for multimode diode lasers (Kelemen et al, 2004). The images from the Echelle Spectrometer illustrated the cause of the increasing M^2 with higher order modes lasing as the current increased.

3.1 Basic Laser Characteristics

The results of the LIV and spectral measurements are shown in Table 1 and Fig. 4 – 5 to compare the characteristics of the three diode lasers. These results are typical of tapered and broad area lasers. BAL have higher slope efficiency than tapered lasers due to additional losses and higher internal laser temperature (Kelemen et al, 2004). While efficiency is lower in tapered lasers, higher powers are achievable from a single emitter. The tapered laser used in this work is rated to 6 W at a 300 mA ridge current and a 10 Amp taper current. The tapered laser also has a smaller spectral bandwidth compared to the BAL and the offset BAL. For the offset BAL, its wall-plug efficiency is lower than the BAL, but it yields more power and a higher slope efficiency.

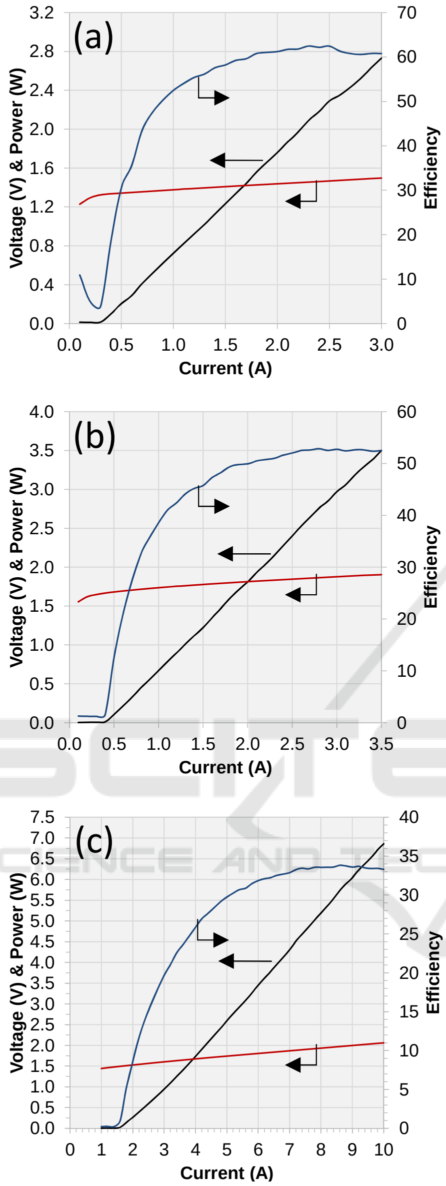

Figure 4: LIV measurements for the (a) BAL, (b) offset BAL, and (c) tapered laser diodes.

Figure 6 depicts the astigmatism in the tapered laser diode which followed the expected increasing trend at higher operating currents based on prior work by Kelemen et al 2004. The increasing astigmatism occurs as a result of Snell's law and the changing refractive index of the laser due to temperature variations with increasing current. As the current heats the tapered region, the distance increases between the output facet and the virtual waist with the astigmatism inversely proportional to the effective refractive index (Kelemen et al, 2004).

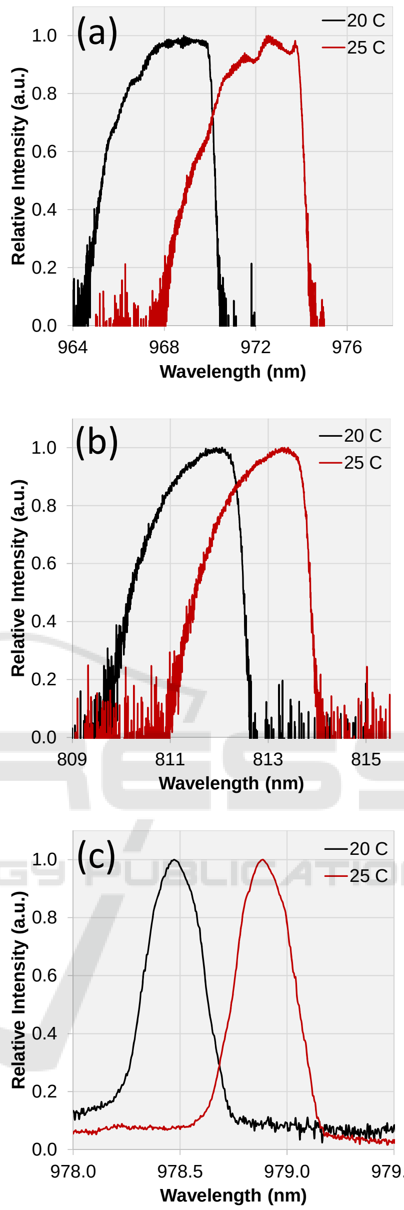

Figure 5: Spectral measurements for the (a) BAL, (b) offset BAL, and (c) tapered laser diodes using fiber coupled light into an OSA with 0.02 nm resolution.

3.2 Laser M^2 Beam Quality Factor

Beam propagation theory predicts that for multimode lasers, the presence of higher order modes will cause the M^2 beam quality factor to increase as the modes are larger than the diffraction limited beam. In this sense, M^2 serves as a "times diffraction limited" factor (Siegman, 1993). Figures 7 and 8 detail the

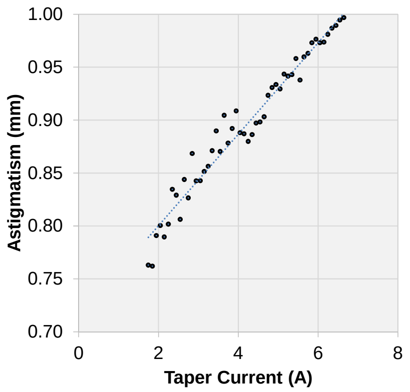

Figure 6: Tapered laser astigmatism measurements recorded using the beam profiler setup.

increasing trend in M^2 as a function of current for the two broad-area lasers. We expect from theory that the M^2 value increases with high drive currents due to the additional lasing modes. The measurements appear to follow a linear trend which suggests that the modal power distribution is non-uniform at these lower current values based on Eq. 3 (Siegman and Townsend, 1993). For constant normalized power coefficients ($c_{n,m}$) and mode indices (n), M^2 is proportional to n^2 when adding more modes at higher current. Based on this equation, the M^2 value for the beam can be measured if the modes of the laser can be isolated for modal power distribution analysis.

$$M_x^2 = \sum_{n,m} |c_{n,m}|^2 \times (2n+1) \tag{3}$$

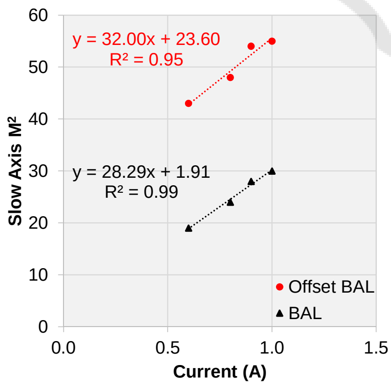

Figure 7: Slow axis M^2 measurements for the BAL and Offset BAL with increasing drive current.

3.3 Spectrally-Resolved Modes

The mode structure images (Fig. 9 – 11) from the spectrometer confirm the additional higher order modes with increasing current from 0.9 - 1.0 amps. Variations in the irradiance of individual lateral modes is observed at the camera, so the non-uniform power distribution is plausible theory. The images shown below are a small section of the full mode structure visible on the camera. The BAL modes have the same structure as those observed in previous work with repeating groups of longitudinal modes, each with several lateral modes (Stelmakh, 2009) (Crump et al, 2012). Figure 9 demonstrates the viability for the spectrometer system to measure M^2 via the modal power distribution method because the lateral modes are spatially separated enough to use image analysis for determining the normalized power coefficients.

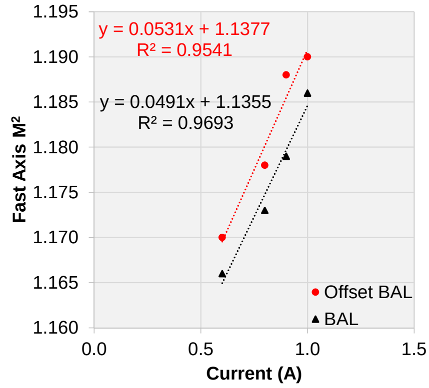

Figure 8: Fast axis M^2 measurements for the BAL and Offset BAL with increasing drive current.

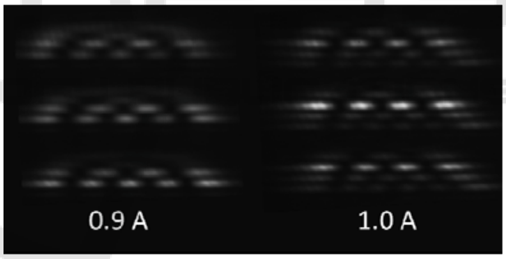

Figure 9: Spectrally-resolved modes of the BAL.

The longitudinal modes of the tapered laser were resolved with a ridge current of 100 mA and a tapered amplifier current of 3.25 amps, but the astigmatism in the laser prevented simultaneous focus in both axes. A cross-cylinder pair could be added to correct this issue in future work. Based on the separation between the modes in Fig. 10, the modal power distribution method for M^2 appears feasible with the addition of optics to correct the astigmatism.

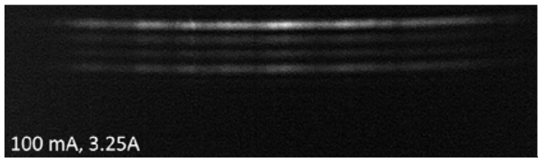

Figure 10: Spectrally resolved modes of the tapered laser.

For the offset BAL, the mode structure in Fig. 11 resembles the modes of the standard BAL, but individual lateral modes are not able to be resolved. The blurred mode profile could result from the non-uniform current injection. The indistinct quality of the modes demonstrates the limitations for isolating lateral modes. Lasers with irregular mode structures and mode spacing smaller than 3 pm cannot be properly resolved with this spectrometer, limited by the resolution of the Echelle grating (Misak, 2015).

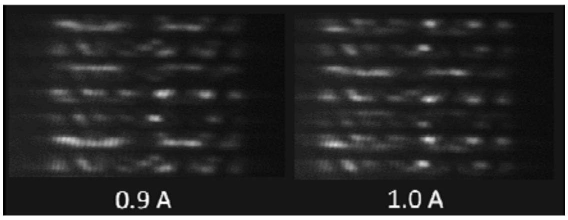

Figure 11: Spectrally dispersed modes of the offset BAL.

4 MODAL DECOMPOSITION

While using a scanning beam profile to determine M^2 via the ISO standard method produces reliable and consistent results, other methods exist that provide accurate measurements in less time. Schmidt et al demonstrated a system that measures the modal amplitudes to measure the beam quality in real-time while maintaining agreement with ISO11146 beam quality measurements. In order to acquire the modal amplitudes, the system employed computer generated holograms and complex analysis (Schmidt et al, 2011). With the Echelle spectrometer shown in this work, similar measurements of the modal power can be made, provided that the mode separation is large enough to spatially isolate the modes on the camera. With the appropriate numerical analysis, BALs and tapered lasers with similar characteristics to those in this work can be used for modal decomposition M^2 measurements with the spectrometer. Multimode VCSELs have also been shown to have enough spatial separation in previous work (Misak, 2015).

5 CONCLUSIONS

Beam quality remains an important factor in many high power applications. With more in-depth analysis of the multimode structures and the impact of higher order modes on beam quality, engineers can develop new techniques to improve the performance of high power laser diodes. Further analysis can be performed by utilizing the spatial separation between modes with the Echelle spectrometer described in this work. This tool provides as basis for additional research into the impact mode power distribution on the beam quality of diode lasers.

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REFERENCES

Crist, J. and Nelson, C. (2012) ‘Predicting laser beam characteristics’, *Laser Technik Journal*, Vol. 9, No. 1, Available from: doi.org/ 10.1002/latj.201290006.

Crump, P. et al. (2012) ‘Experimental and theoretical analysis of the dominant lateral waveguiding mechanism in 975 nm high power broad area diode lasers’, *Semiconductor Science and Technology*, Vol. 27, No. 4, Available from: doi.org/10.1088/0268-1242/27/4/045001.

International Organization for Standardization 2005, *Lasers and laser-related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part 1: Stigmatic and simple astigmatic beams*, ISO 11146-1:2005, International Organization for Standardization, Geneva.

Kanskar, M. et al. (2013) ‘High Reliability of High Power and High Brightness Diode Lasers’, *nLight Corporation*, Available from: http://www.nlight.net/news/technical-papers.

Kelemen, M. T. et al. (2009) ‘High-Power High-Brightness Lasers’, *m2k-laser GmbH*, Available from: http://www.optosolutions.com/doc/TaperedLaser_intro_070209.pdf (Accessed 08 August 2016).

Kelemen, M. T. et al. (2004) ‘Astigmatism and Beam Quality of High-brightness Tapered Laser Diodes’, *Semiconductor Lasers and Laser Dynamics*, Strasbourg, France, SPIE, Vol. 5452, No. 233. Available from: doi.org/10.1117/12.545221.

Misak, S. M. et al. (2015) ‘Spectrally Resolved Imaging of the transverse modes in multimode VCSELs’, *Vertical-Cavity Surface Emitting Lasers*, San Francisco, CA, SPIE, Vol. 9381, No. 93810L. Available from: doi.org/10.1117/12.2076629.

Schmidt, O. A. et al. (2011) ‘Real-time determination of laser beam quality by modal decomposition’, *Optics Express*, Vol. 19, No. 7, pp. 6741-6748. Available from: doi.org/10.1364/OE.19.006741.

Siegman, A. E. (1993) ‘Defining, measuring, and optimizing laser beam quality,’ *Laser Resonators and Coherent Optics*, Los Angeles, CA, SPIE, Vol. 1868, No 2. Available from: doi.org/10.1117/12.150601.

Siegman, A. E. and Townsend S. (1993) ‘Output beam propagation and beam quality from a multimode stabecavity laser', *IEEE Journal of Quantum Electronics*, Vol. 29, No. 4, pp. 1212-1217. Available from: doi.org/10.1109/3.214507.

Stelmakh, N. (2009) 'External-to-cavity lateral-mode harnessing devices for high-brightness broad-area laser diodes: concept, realizations, and perspectives' *Novel In-Place Semiconductor Lasers*, San Jose, CA, SPIE, Vol. 7230, No. 72301B. Available from: doi.org/10.1117/12.808681.

Sun, H. (1997) 'Measurement of laser diode astigmatism', *Opt. Eng.*, Vol. 36, No. 4, pp. 1082-1087 Available from: doi.org/10.1117/1.601147.