Power Beaming with Diode Lasers

Tobias P. Koenning, Dr. H. G. Treusch

Dilas Diode Laser Inc.
9070 South Rita Road / Suite 1500
Tucson, AZ, 85715

Improvements in the electro optical efficiency and output power of diode lasers within the last few years have made the diode laser a viable source for power beaming. Combined with a growing market of photo voltaics, the key components for power beaming applications have evolved from scientific laboratory experiments into equipment ready for deployment into the field.

The NASA sponsored Space Elevator competition is not the only, but maybe the most popular, current application for power beaming. International teams meet once a year to compete using a self designed climber on a rope, while the energy has to be supplied by power beaming from the ground. Starting with a height of 50m in 2005, the goals are increased every year to achieve a required climbing height of 1km for the 2008 contest. The first two contests (2005, 2006) were dominated by spot lights and mirrors reflecting sun light. The first lasers were introduced to the competition in 2007 where the winning team, as well as others, used industrial grade diode lasers as their power source for the 100m lift. The required height of 1km for the 2008 competition requires a sophisticated optical setup to achieve the required spot size at both the minimum and the maximum distance of the climber from the ground.

The most important criteria a power beamer is judged by is the overall efficiency. The overall efficiency is determined by the electro-optical efficiency of the source, the opto-electrical efficiency of the photo voltaic cells and the optical setup in between these two components.

Industrial grade high power diode lasers are available with electro-optical efficiencies up to 60%. Taking into account losses in the optical system, typical efficiencies for a power beamer are approximately 50%. Available wavelengths range from 800nm to 980nm. Considering atmospheric transmission, an excellent window can be found between 840nm and 890nm [1]. The transmission at 808nm, a standard high power diode laser wavelength, comes close the transmission of this window. GaAs photo voltaic cells work well at this wavelength and conversion efficiencies >50% at 25ºC were demonstrated by Olsen et al [2] at 806nm. The intensity for this experiment was 100mW/cm^2, however, efficiencies for higher intensities may be lower.

The efficiency of the optical setup is primarily determined by the spot size of the beam on the detector surface compared to the detector size itself. A beam smaller then the detector area leads to higher intensities which can increase the reflectivity of the photo voltaic cell and decrease the efficiency. A beam size larger than the detector causes immediate power loss due to clipping. Because the detector moves away from the power source in the Space Elevator competition, as well as in many other power beaming applications, an optical system with a variable focus is desirable. A common, and reasonable considering weight and sensitivity to wind, detector size in the Space Elevator competition is 1m x 1m. The power requirements are determined by the weight of the climber, the efficiency of the system (including the motor of the climber and the contact to the ribbon) and the desired climbing speed. A safety margin (S) may be considered.

With a climber weight of 25kg, 10kg payload and a minimum speed of 2m/s [3] for the contest, the required laser power can be determined with Formula 1. The efficiency values used are estimated.

$$P \approx \frac{(m_{climber} + m_{payload}) \cdot v \cdot S}{Eff_{optics} \cdot Eff_{PVcells} \cdot Eff_{motor} \cdot Eff_{mechanics}}$$

$$P \approx \frac{(25kg + 10kg) \cdot 2\frac{m}{s} \cdot 1.5}{80\% \cdot 25\% \cdot 70\% \cdot 80\%} = 9375W$$

Formula 1

Summarized the following laser parameters seem to be suitable for the 2008 Space Elevator competition:

- 10kW output power
- Desired wavelength at 808nm
- A spot size of 1m x 1m (from 50m to 1km)

Based on the parameters shown above, Dilas Diode Laser Inc. has developed a diode laser system suitable for the contest in September 2008. The laser source for the system is an industrial grade, actively cooled diode laser stack with 1250W of optical output power in the near infrared. Keeping the different needs and funding resources of the attending teams in mind, the system is designed to be modular with each building block containing two of the stacks mentioned above, thus generating 2.5kW of optical power. The housing was designed so that the modules can be arranged next to each other in two dimensions in order to achieve the desired output power.

Each diode laser stack contains multiple diode laser bars. The laser bars chosen for this application contain 19 emitters with each 100um width and 500um pitch. Using commercially available FAC (fast axis collimation) lenses, the divergence in the vertical axis can be reduced to < 4mrad (full angle $1/e^2$). The slow axis divergence can be reduced by cylindrical lens arrays. Each one lens of the array collimates one emitter of each laser bar. The typical divergence in the horizontal axis after slow axis collimation is 20mrad (full angel $1/e^2$). Due to the micro-channel coolers required to cool the laser bars, the vertical pitch between the laser bars is fixed to 1.8mm, resulting in a total beam height of 25mm. The width of the beam is 10mm. Due to the pitch of 1.8mm and the beam height of each laser bar of about 0.8mm, the fill factor of each stack is < 50%. Both stacks can be combined by a method known as interleaving [4], thus doubling the power while maintaining the beam parameters mentioned above. The resulting beam parameter products for fast axis (FA) and slow axis (SA) for the combined beam of both stacks are shown in Formula 2.

$$BPP_{FA} = \Theta \cdot D = 4mrad \cdot 25mm = 100mm \cdot mrad$$

$$BPP_{SA} = \Theta \cdot D = 20mrad \cdot 10mm = 200mm \cdot mrad$$

Formula 2

The spot size in 1km distance is mainly determined by the divergence of the beam. In order to achieve the required size of 1m x 1m in 1km distance, the divergence in both axes has to be equal to or less than 1mrad. The desired size of the beam at the laser output window is 100mm in both directions in order to allow a 2 dimensional arrangement of the modules. This requires a BPP of 100mm·mrad for both axes. Looking at the BPP in Formula 2 these parameters can be met in fast axis, but not yet in slow axis. In order to reduce the BPP in slow axis, the beam is cut in half and polarization combined with the other half, thus leading to a beam size of 5mm while maintaining the divergence of 20mrad. The resulting BPP is 100mm·mrad and meets the requirements.

The final optical components needed to achieve the desired beam parameters are anamorphotic telescopes that equalize the beam parameters in fast and slow axis direction. Each positive cylindrical lens is used to focus the beam in each direction. One aspheric lens is used to re-collimate both axes, thus building an anamorphotic keplerian telescope. The resulting beam has a similar height and width of 100mm and divergence angles of 1mrad in both directions. In order to achieve these values, near diffraction limited lenses are required. All lenses are designed with high index material (SFL57) and all three curvatures are corrected for spherical aberrations. Both cylindrical lenses are mounted on a computer controlled translation stage. By moving the lenses back and forth, the beam diameter can be matched to the detector size at every distance required for the Space Elevator contest.

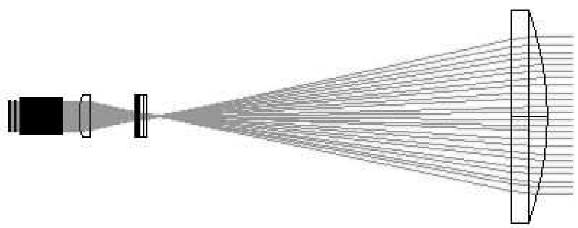

Figure 1: Side view op optical system

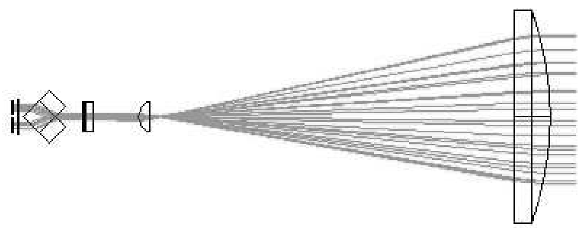

Figure 2: Top view of optical system

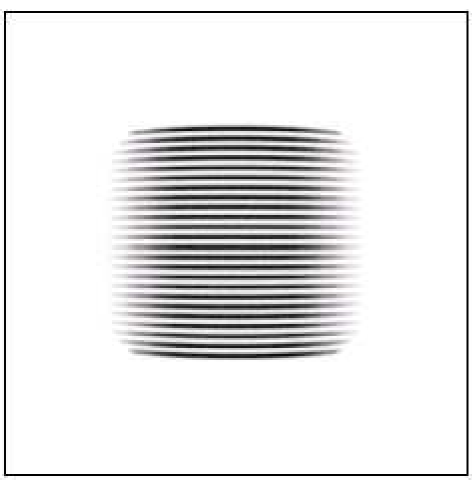

Figure 3: Simulated intensity distribution in 50m distance (2m x 2m detector)

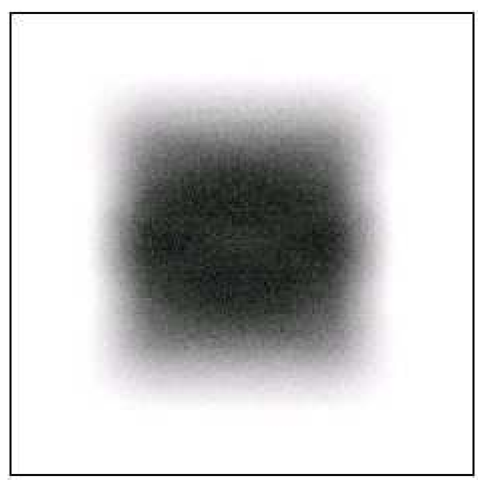

Figure 4: Simulated intensity distribution in 1km distance (2m x 2m detector)

The Space Elevator competition is only one application for power beaming with diode lasers. Based on the experience from the contest, Dilas Diode Laser Inc. can provide customized solutions for many power beaming applications. Based on key parameters (power, distance, detector size) individual systems can be designed.

References

[1] Henry W. Brandhorn, Jr., David R. Forester, *“Effects of the Atmosphere on Laser Transmission to GaAs Solar Cells”* IAC-03-R.3.08, 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Bremen, Sep. 29-3, 2003

[2] Olsen, L.C., Huber, D.A., Dunham,G., Addis, F.W.**,** and Anheier, N.A., *“High Efficiency Monochromatic GaAs Solar Cells”*, pp 419-424, 22nd IEEE Photovoltaic Specialists Conference Record, Las Vegas, NV, 1991

[3] The Spaceward Foundation, “Handbook pb2008 v0.13”

[4] Hans-Georg Treusch, Frank Leibreich, “Powering Brightness”, pp18-19,spie’s OEmagazine, Sept. 2001