Quasi-Bessel Beams for use in Laser Power Beaming

Tristan Hadley, Gavin Conibeer

School of Photovoltaics and Renewable Energy Eng., UNSW Sydney, NSW 2052 Australia

Introduction

Rising interest in space-based activity for lunar and other off-earth applications has brought off-Earth resource extraction into focus. One possible resource is the water ice discovered in the dark and hence bases of lunar polar craters. The very fact that they are dark, or permanently shadowed, means it is not obvious how the abundant solar power on the surface can be used to power prospecting rovers in the base of the crater. However, transfer of power from surface solar arrays to the rovers can be provided by high power density focussed lasers with reasonable efficiency - up to or even exceeding 50%. One limiting factor is the dispersion of the laser beams over the several kilometres required, which would require very large receiving on the prospecting rovers to collect all the transmitted power. The power from the lasers is collected by high efficiency single bandgap photovoltaic solar cells, which must be made large enough to capture the full beam to avoid wasting energy in an environment which demands optimal efficiency and heavy costs for resource delivery. This paper investigates the viability and feasibility of the use of non-divergent quasi-Bessel beams in place of lasers with a conventional Gaussian beam profile. Simulations and practical experimentation indicate that a Gaussian laser can be transformed into a quasi-Bessel beam over a limited distance when passed through an Axicon lens. These beams were shown to have a non-divergent profile that can concentrate the energy from the initial laser into a diameter as small as 6% of the original beamwidth, providing significantly higher intensities for power transfer over these limited distances. It was calculated that these limited distances can practically exceed 10km, and that within this range the lasers are just as effective at delivering power to a photovoltaic cell as their Gaussian counterparts. Any loss of energy in the beam by attenuation through the Axicon lens was shown to be negligibly small for optical materials at less than 9% per Sm^{-1} conductivity which realistically equates to a negligible amount due to the low conductivities within optical lens materials. Quasi-Bessel beams were thus confirmed as a highly viable method to improve the efficiency of laser powered beaming for extra-terrestrial mining.

Laser power beaming concept

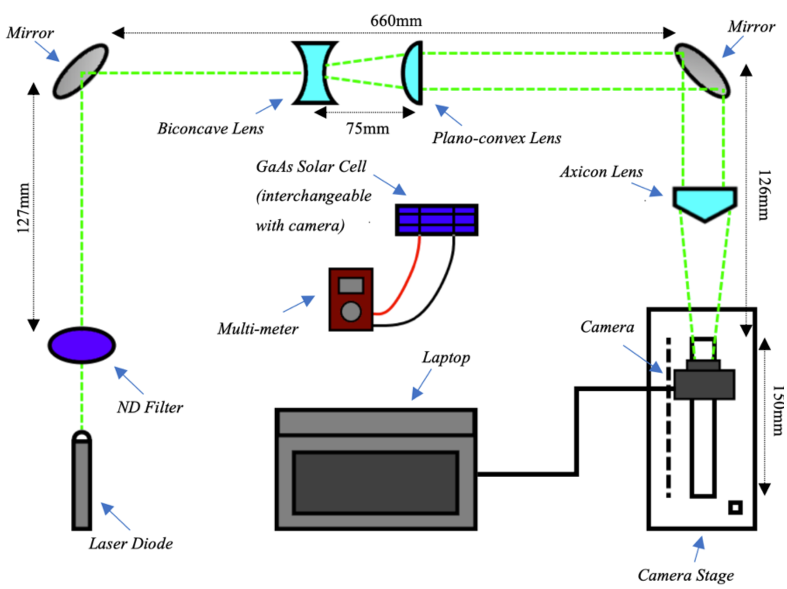

Fig. 1: Laser power transfer: This illustrates both the concept and the experimental set-up for a laser power transfer experiment.

Fig. 1 shows the experimental set-up for laser power transfer experiments. It also illustrates the concept of power being transferred from the green laser on the right, through a system of lenses to shape the beam to a receiving camera or solar cell on a travelling stage that could be at an arbitrary distance. The receiving solar cell, which ideally has a bandgap at slightly lower energy than the laser energy, converts the laser light back into electricity at the point of use. This can be used to transfer power across either difficult terrain, across a barrier, through space, or between two mutually moving platforms. It is thus a flexible, wireless means of transferring power that can have power transfer efficiencies as high as 69% experimentally for GaAs solar cell receivers [2].

Theory of Bessel beams
Bessel beams are electromagnetic waves with an electric field amplitude given by the Bessel function of the first kind. Bessel beams have the desirable property for LPB in that they are non-diffractive and thus do not experience divergence [1]. Bessel beams arise as solutions to the Helmholtz equation.

Bessel functions solutions ($y(x)$) to Bessel's differential equation:

$$x^2 \frac{d^2y}{dx^2} + x\frac{dy}{dx} + (x^2 - \alpha^2)y = 0$$

where α is the order of the Bessel function and is some arbitrary complex number. Bessel functions of the first kind are where α is a positive integer.

A beam with the properties of a Bessel beam over a limited distance, a quasi-Bessel beam (QBB) can be generated by propagating a Gaussian beam through a conical Axicon lens. The initial disruption of the Gaussian beam profile results in a downstream reconstruction of the conical wavefronts to give the quasi-Bessel region, over which there is zero beam divergence.

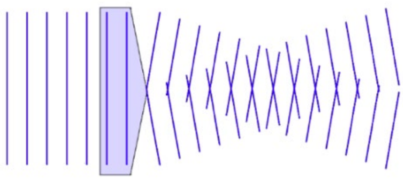

Fig. 2: Two-dimensional wavefront diagram showing generation of a quasi-Bessel beam using an axicon lens [1].

FDTD simulation [4]
The finite-difference time-domain (FDTD) method is used to simulate the propagation of Gaussian beams using Python. For 2D simulations EM wave propagation is in the *xy*-plane, in either the transverse magnetic (TM) mode, with the electric field vector in the *z*-direction, or the transverse electric (TE) mode, in which *z* is the direction of the magnetic field vector. Wavelengths in the *mm* range are chosen to reduce computational intensity, see Fig. 3.

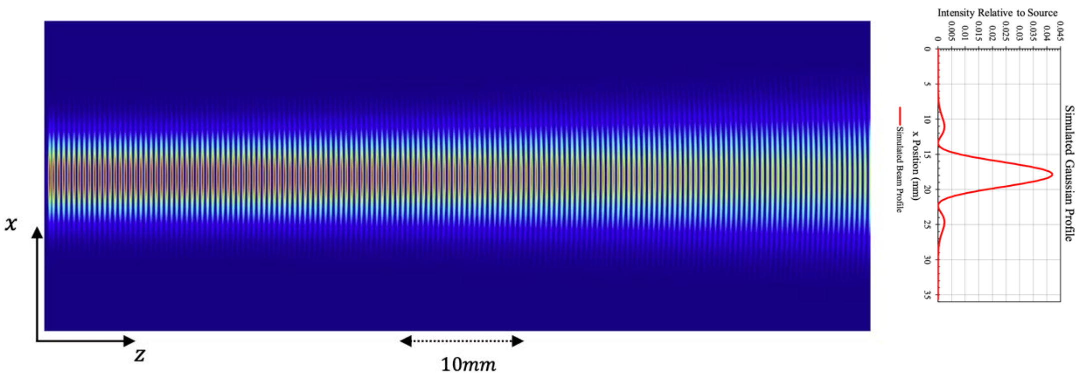

Fig. 3: Relative intensity map in 2D (left) and the simulated intensity profile (right) for a Gaussian beam with λ = $1mm$ through free space.

The intensity profile shows a reasonable Gaussian beam shape with very small side lobes, but this results in a divergence of the beam, albeit with a small angle of divergence. If propagated over several kilometres this would result in a significant decrease in beam intensity and the need for a large collecting solar cell.

The introduction of a conical Axicon lens (in red on the LHS of Fig. 3) disrupts the Gaussian beam in such a way that the downstream reconstruction of conical wave sections results in a quasi-Bessel region extending over a few *mm* to *cm* in which the beam is perfectly parallel with zero beam divergence, see Fig. 4. The intensity profile of the quasi-Bessel beam indicates rings of decreasing intensity concentric with the highest intensity central beam. If this quasi-Bessel region can be extended over metres or even kilometres with very small Axicon lens angles and shorter wavelengths, beams of much higher intensity and smaller beam s[potts could be delivered at a distant receiving solar cell.

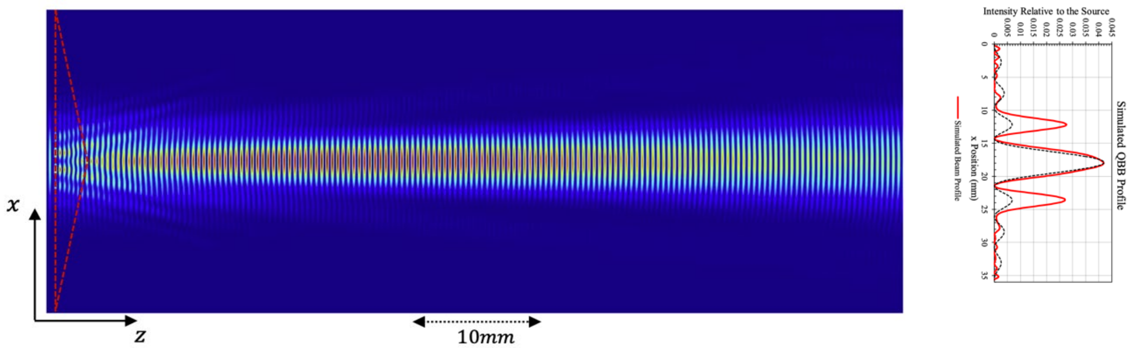

Fig. 4: Relative intensity map of a 2D Quasi-Bessel Beam (QBB) propagating to the right (left) and the cross-section of the simulated intensity profile (right) with $\lambda = 1mm$.

These quasi-Bessel regions are limited to a few *cm* for the results in Fig. 4, but by extrapolating these results for an initial Gaussian beam of 500*mm* diameter (which can be achieved with a Galilean beam expander [3]) the quasi-Bessel region can be extended to 10*km*! This being sufficient to transfer power in the lunar crater applications considered. This estimation assumes an Axicon angle of 0.5° and index of refraction of 1.4 and that the optimal laser wavelength for GaAs solar cells is used of ~$1um$. The estimation does require further validation.

Experimental validation [4]

The experimental set-up shown in Fig. 1 was used to measure both the beam profile and the power transferred to a GaAs cell, for Gaussian beams and quasi-Bessel beams processed through one of two Axicon lenses with opening angles of 0.5° or 2°. The concentric rings of decreasing intensity of the quasi-Bessel beam through the 0.5° Axicon lens captured by the CCD camera 500mm after the lens are shown in Fig. 5 (left). And the the experimental cross section of the beam profile compared to the modelled Bessel beam profile are shown in Fig. 5 (right). These show quite good agreement and thus indicate formation of quite a reasonable quasi-Bessel beam.

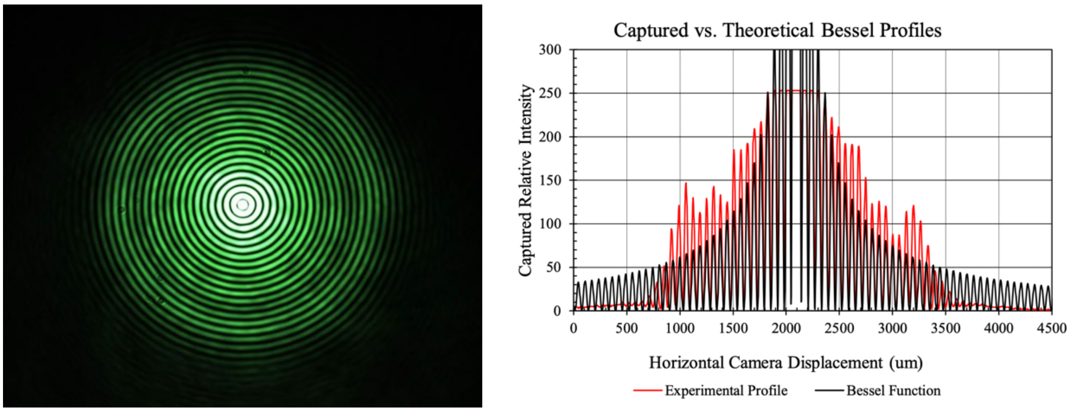

Fig. 5: Captured QBB profile of 7.0mm expanded laser through the half-degree axion, 500*mm* from the lens (left) and comparison between the experimental beam profile and the Bessel function (right).

The data in Table 1 show the I_{SC} and V_{OC} measured in the GaAs solar cell illuminated in the power transfer set-up. There is only a slight decrease in these parameters for both Axicon lenses and for a Gaussian beam at initial beam diameters of 3.5*mm* and 7*mm*. (The latter controlled by the strength of lenses in the Galilean beam expander in Fig. 2.)

Table 1	2.0° Axicon		0.5° Axicon		No Axicon (Gaussian beam)	
Beam Width (mm)	**3.5**	**7.0**	**3.5**	**7.0**	**3.5**	**7**
I_{sc} (μA)	254.7	213.8	254.2	210.6	260	216
V_{oc} (mV)	590	576	589	575	590	577

The values show almost exactly the same V_{OC} with and without the Axicon and a very small (~2%) decrease in the I_{SC} for the Bessel rather than the Gaussian beam. This small loss can be attributed to the small attenuation of the beam passing through the extra Axicon lens, which would only be a minor loss in practice. The full I-V curve and hence power and efficiency were not measured with the current set-up and will be the subject of further work. However, the advantage of the non-divergent region of the quasi-Bessel beam is not likely to be manifest until beaming over significant distances, such that the expanding Gaussian beam no longer fits wholly within the receiving solar cell.

Conclusions

The potential of a quasi-Bessel beam to overcome the problems of Gaussian laser beam divergence over long laser power transfer distances is investigated. Simulations indicate that quasi-Bessel beams generated by a conical Axicon lens can have regions several *cms* long that have zero divergence. It is indicated that these regions can be extended to several *kms* under large enough initial beam diameters. Experimental demonstration of quasi-Bessel beam formation has been demonstrated with Axicon lenses in a laboratory laser power transfer arrangement and the V_{OC} and I_{SC} of a receiving GaAs solar cell are seen to differ very little from a Gaussian beam, indicating that quasi-Bessel beams are feasible to use in a power transfer set-up and may offer significant advantages for beaming over distances of *kms*.

References

[1] McGloin, D. & Dholakia, K. (2005). Bessel beams: diffraction in a new light. *Contemporary Physics, 46*(1), 15-28.
[2] Fraunhofer ISE (2021) Efficiency of 68.9% for GaAs with laser light: https://www.ise.fraunhofer.de
[3] Edmund Optics (2021) Beam Expanders: https://www.edmundoptics.com
[4] Hadley, T, "The Viability of Quasi-Bessel Beams for use in Laser Power Beaming", 4th year thesis, SPREE UNSW (2022).