

# High-Power Single Mode Fibre Coupling

High-power Single-Mode (SM) fibre coupling of continuous wave (cw) lasers in the visible range is shown at different wavelengths with coupling efficiencies as high as 80%. Whilst this value is easily achievable when laser light is coupled into multimode fibres, for single-mode fibres, 80% efficiency is close to the theoretical limit, and presents a number of significant challenges, especially at powers higher than a few 100 mW. This paper describes work undertaken by Novanta where a 2.4 W output from a SM fibre with 3 W input is achieved at 532nm.

## Overview

In 2009, Charles K. Kao received the Nobel Prize in Physics for his ground-breaking theoretical work on single-mode optical fibres, performed in the 1960s at STL in Harlow, UK. The small core diameter of only a few  $\mu\text{m}$  makes Single-Mode and also Polarization-Maintaining fibre coupling (SM/PM fibre coupling) much more challenging than simple multimode fibre coupling. The main difference between both fibre types is the area or volume which is really guiding the light. In a SM fibre, only one single transverse mode, the 'fundamental transverse mode' typically labeled as the  $\text{TEM}_{00}$  mode, can propagate in form of a Gaussian beam. In contrast, in a multimode fibre, many modes exist and propagate simultaneously. Crucial parameters for SM fibre coupling are the Numerical Aperture (NA), the Mode Field Diameter (MFD) and the cut-off wavelength ( $\lambda_0$ ). While the NA describes the ability of a fibre to gather light, the MFD is the diameter of the Gaussian intensity profile within the fibre. Only light above the cut-off wavelength is guided in single Gaussian mode through the fibre.

During this development, Novanta worked closely with Schäfter + Kirchhoff (Hamburg, Germany); a well-known supplier of advanced fibre optics who provided a series of wavelength matched fibres and fibre couplers optimized to Novanta's **gem** and **opus** lasers. Both the **gem** and **opus** are high power lasers available across the visible and infrared spectrum, delivering perfect beam quality in a very small form factor. For safe laser operation, the fibre coupler can be directly attached to the laser head, eliminating any open, free space beam. Furthermore, no optical isolator is necessary for stable laser operation. Figure 1 illustrates a basic configuration, consisting of a **gem** laser at 532 nm coupled into a SM fibre with a 1 m fibre cable. The **gem** laser was set to 1.25 W, resulting in an output of 1 W output from the fibre. This achieved coupling efficiency of 80% is close to the theoretically achievable results of such a high-power configuration, with a ceiling of 85% achieved with low power lasers in the 10 mW range. The reflectivity losses from the fibre end facets are 4% each, so the additional losses cause by all other imperfections only amount to around 10%.

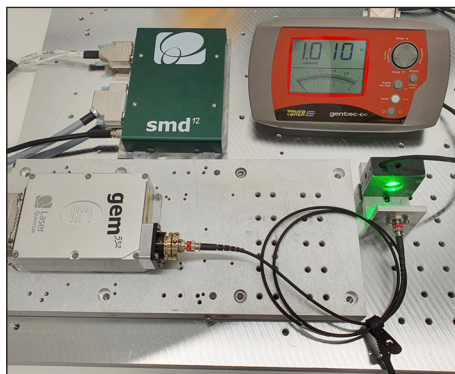


Fig. 1: SM-fibre coupled **gem** 532 laser with a 1 m fibre.  
The fibre output is directed to the thermal head of a power meter.

Many applications especially in the field of microscopy require an almost perfect beam with  $TEM_{00}$  beam profile for either sophisticated beam manipulation or tight focusing. Multimode fibre-coupled systems do not provide a solution, since after the fibre no  $TEM_{00}$  beam exists. Figure 2 shows the beam profile after the fibre output from the Novanta SM fibre coupling. The already near-perfect beam from the laser with a  $M^2 < 1.2$  ( $M^2 < 1.1$  for 532 nm systems) is further improved by the fibre as it makes the laser beam even more symmetrical and removes residual astigmatism. In effect, a SM fibre acts as a mode filter even for input beams with inferior beam quality.

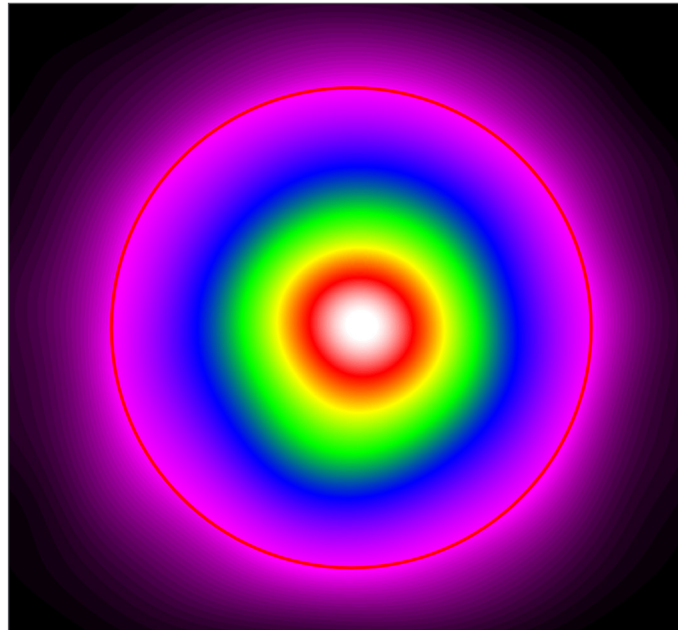


Fig. 2: Measured and filtered beam profile from the fibre output showing an almost “perfect” beam. The red ring indicates the  $1/e^2$  beam diameter.

## Single Mode (SM) Fiber Coupling Benefits

SM fibre coupling makes the utilization of lasers much easier; it enables “plug & play” laser light without the need for mirror realignment or other guiding optics. Furthermore, a fibre coupled system is also highly advantageous from a laser safety perspective. Beside these obvious advantages, SM fibre coupled systems also help when beam pointing variations caused by temperature changes are an issue. The **gem** and **opus** laser family offer exceptional beam pointing stability which results in consistent fibre coupling efficiency across a large portion of the power curve and across the operating temperature range (see Fig. 3). Delivering the light

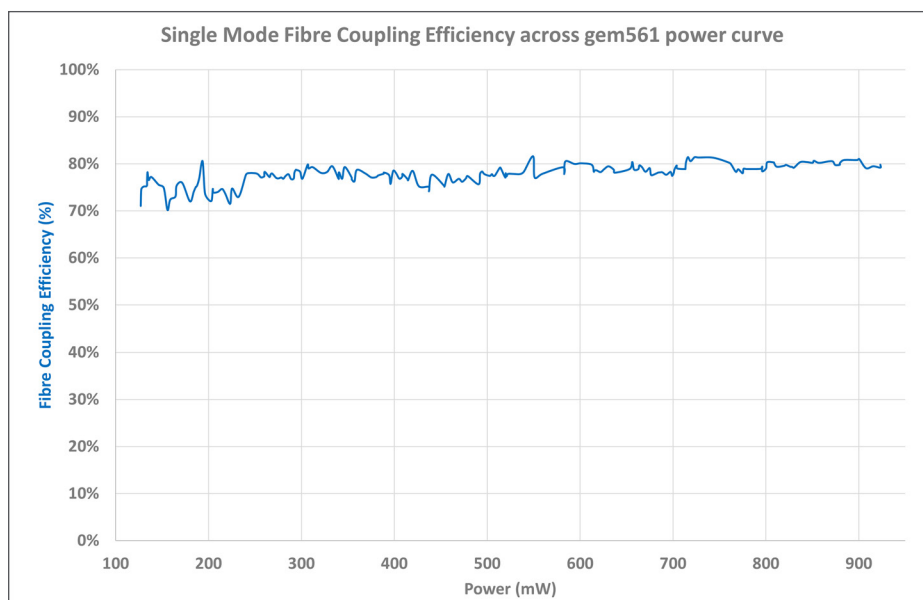


Fig. 3: Coupling efficiency of a **gem** laser at 561 nm over the output power at constant temperature.

through a SM fibre further improves beam pointing stability by eliminating any minor drift with changing temperatures or power levels since the fibre coupler with the attached fibre will follow the movement in any direction as it is subjected to the same external variation.

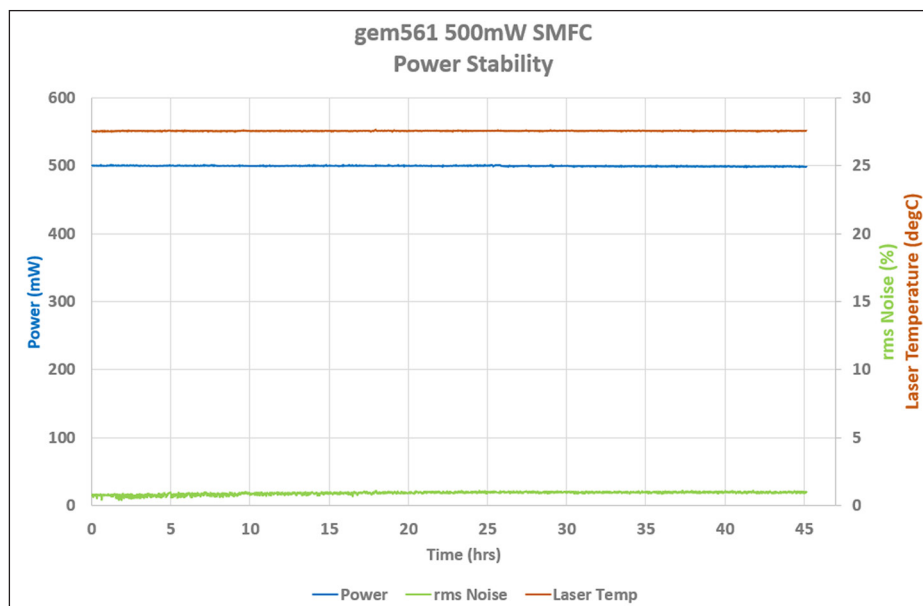


Fig. 4: Long term coupling efficiency over 45 hours at constant temperature.

In another test, long-term coupling efficiency over an extended 45-hour period was measured at constant temperature (see Fig. 4). No fluctuations were visible, demonstrating that the laser and fibre coupler arrangement is also extremely mechanically stable. Mechanical stability was further proven in a 30-minute vibration test, where the laser was subjected to a maximum acceleration of 4.9 g RMS in one direction. The coupling efficiency was measured before and after the test with no change in performance being observed.

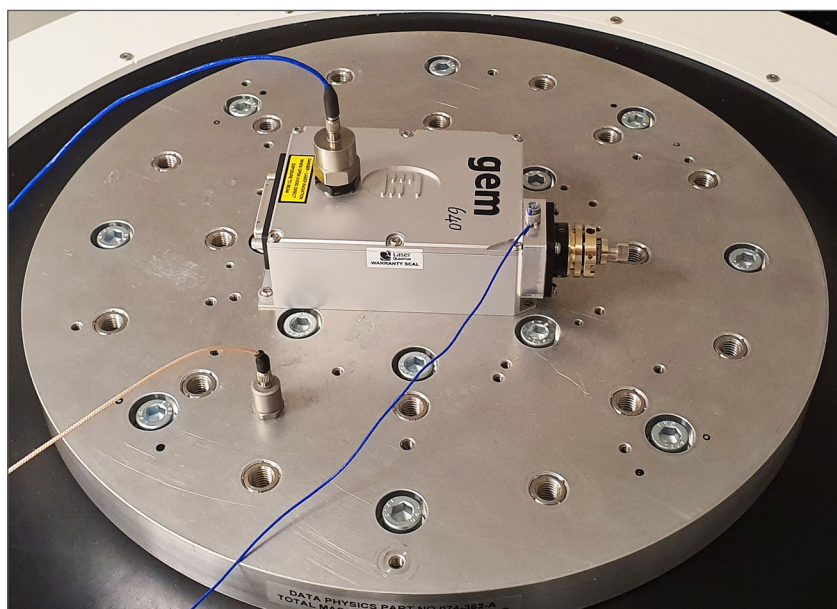


Fig. 5: **gem** laser with attached fibre on a vibration test plate.

Finally, the effect on the coupling efficiency with changing laser temperature was investigated. In this arrangement, the **gem** laser was placed on a temperature-controlled plate while the laser was operating in constant power mode. The output power from the fibre was compared against the internal power monitor reading each time after the laser temperature had settled. By comparing the two powers, both the internal reading from the laser and the external reading from the fibre, the coupling efficiency could be determined each time for each new temperature. The fitted results are shown in figure 6 and show that over the 16 degrees Celsius range

observed, the coupling efficiency remained above 75% and was repeatable across successive runs and always returned to its peak efficiency of 81% at the originally aligned temperature. This supports the statement that the laser coupling is highly mechanically stable and repeatable.

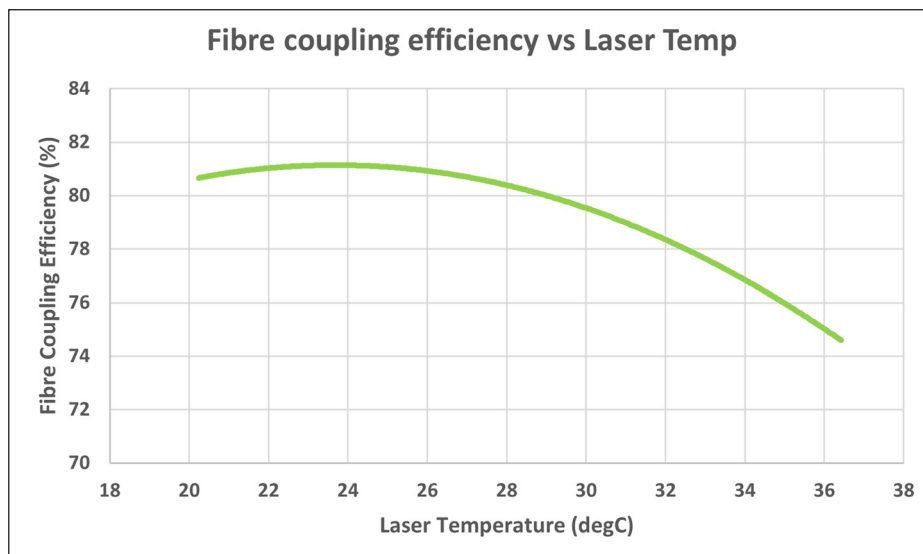


Fig. 6: Coupling efficiency of a **gem** laser when the laser head temperature is varied.

High-power single-mode fibre coupling enables solutions in many optical applications. In super-resolution microscopy for example, SM fibre-coupled laser sub-systems in the multi-Watt regime are now possible, thanks to the excellent optical engineering and beam quality now available. Taking these advances further, the fast modulation of the output power with the help of Acousto-Optic-Modulators (AOM) or Acousto-Optic Tunable Filters (AOTF) is also possible, as fibre coupled devices achieve much higher switching speeds. This is important in the field of quantum sensing or, more precisely, in the excitation of nitrogen-vacancy centres (NV-centres) in diamond. On the other hand, applications that are very sensitive to beam pointing variations benefit from efficient SM fibre coupling since any minor drift with changing temperatures or power levels is eliminated due to the fact the fibre coupler with the attached fibre will follow the move in any direction.

Novanta is now able to offer a robust solution to the previously challenging task of achieving high efficiency fibre coupling of high-power lasers. This solution is now available across all Novanta's DPSS laser wavelengths (473, 532, 561, 640, 660, 671, 1064 nm) where up to 3 W power can be coupled to single-mode or polarization maintaining fibres with a guaranteed coupling efficiency exceeding 70%.

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