Advanced Optical Technology Ltd

Technical Note (13)

Use of Photonic Fibre to Deliver ACE Laser Pulses

Introduction

Technical notes (7) and (9) report the performance of short conventional fibres for delivering ACE laser pulses. The two notes deal with step-index all-silica fibres typically of length ~ 1-10m and core 25µm - 200µm diameter. These fibres are shown to allow efficient and reliable power transmission at 1064nm, 532nm and 355nm of the ~ 1ns pulses from ACE lasers, albeit with major loss of beam quality due to their multi-mode character.

In Technical note (9) we commented on the advent of photonic fibres and their (important) potential for TEMoo laser power transmission without significant beam quality loss. In the interim period (to Dec 2005) we have undertaken some initial trials with short (~ 1m) lengths of such fibres.

Solid-Core Photonic Fibre

At 1064nm, we have used an AOT-YAG-10QHP oscillator to investigate an IR all-silica photonic fibre - Crystal Fibre type LMA 25. Both end faces of this fibre had the photonic holes closed to a depth of ~ 100um (an option offered by the manufacturer) to prevent the ingress of contaminants. The fibre ends were fitted with FC connectors and had a laser-grade polish to the faces. The fibre specification included:-

- Core size: 25.2um+/-0.4um
- Mode field dia: 19.8um+/-2.0um
- NA @ 1064nm: 0.04+/-0.01
- Cladding dia: 268um+/-5um
- Attenuation @ 1064nm: < 3.5dB/km

In contrast to the conventional step-index fibres discussed in Technical Notes (7) and (9), the low NA here means that the bending radius must be kept large (ie ~ 100mm or more), and that the input beam acceptance cone for the fibre is low – max full-angle in the range 60-100mm mrad.

Based on the fibre specification limits, the product of beam acceptance angle x mode-power dia is ~ 1510-3083mrad.µm. For a perfect Gaussian beam the same product for $1/e^2$ (~ 86%) of the power is 1.27 x λ ~ 1.27 x 1.064 rads ~ 1351mrad.µm, and for 99% included power it is 1.5x this ie 2027 mrad.µm. A comparison of these latter numbers with the former indicates that achieving high power transmission through the fibre requires both; (i) a very good input TEMoo laser beam quality, and (ii) excellent mode-matching of the TEMoo beam to the fibre.

To allow experimental determination of the optimum mode-matching conditions, we used a high quality 60mm fl focusing lens to couple the YAG laser pulses into the fibre. We varied the relay magnification into the fibre core to find the optimum waist size ie that allowing the best power transmission (T%) through the fibre.

The results of this trial are shown in Fig (1). In the figure, the input power was that measured going into the AR/AR coated focusing lens. It can be seen from the figure that the peak T% was ~ 70%, which compares with a practical limit of ~ 90% (allowing for ~ 8% Fresnel loss from the uncoated end faces of the fibre and 1-2% from the lens surfaces).

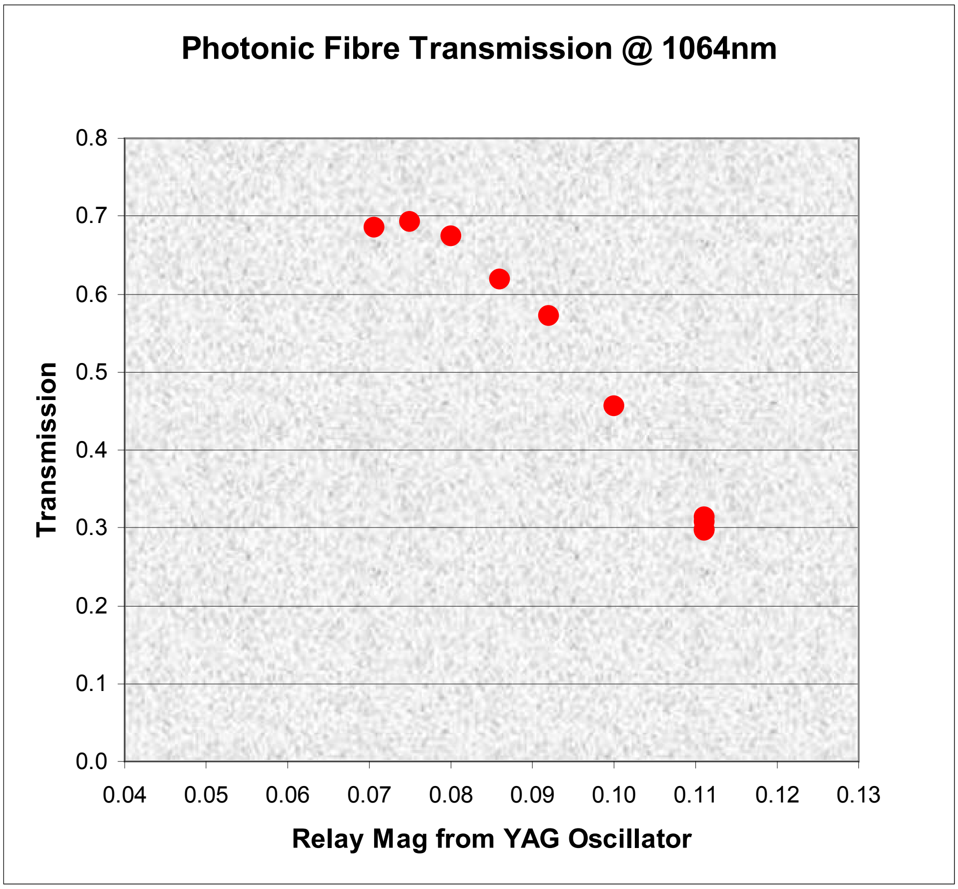

Figure (1) Transmission of 25µm core 1m long photonic fibre at 1064nm using AOT-YAG-10QHP pulses at 10kHz.

Interestingly, the power transmission with the fibre ends reversed was lower, possibly due to some degradation of the second fibre face, or to sub-surface defect(s) scattering power outside the guiding NA of the fibre core. Both ways round, the output beam from the fibre was a good TEMoo single-mode lobe.

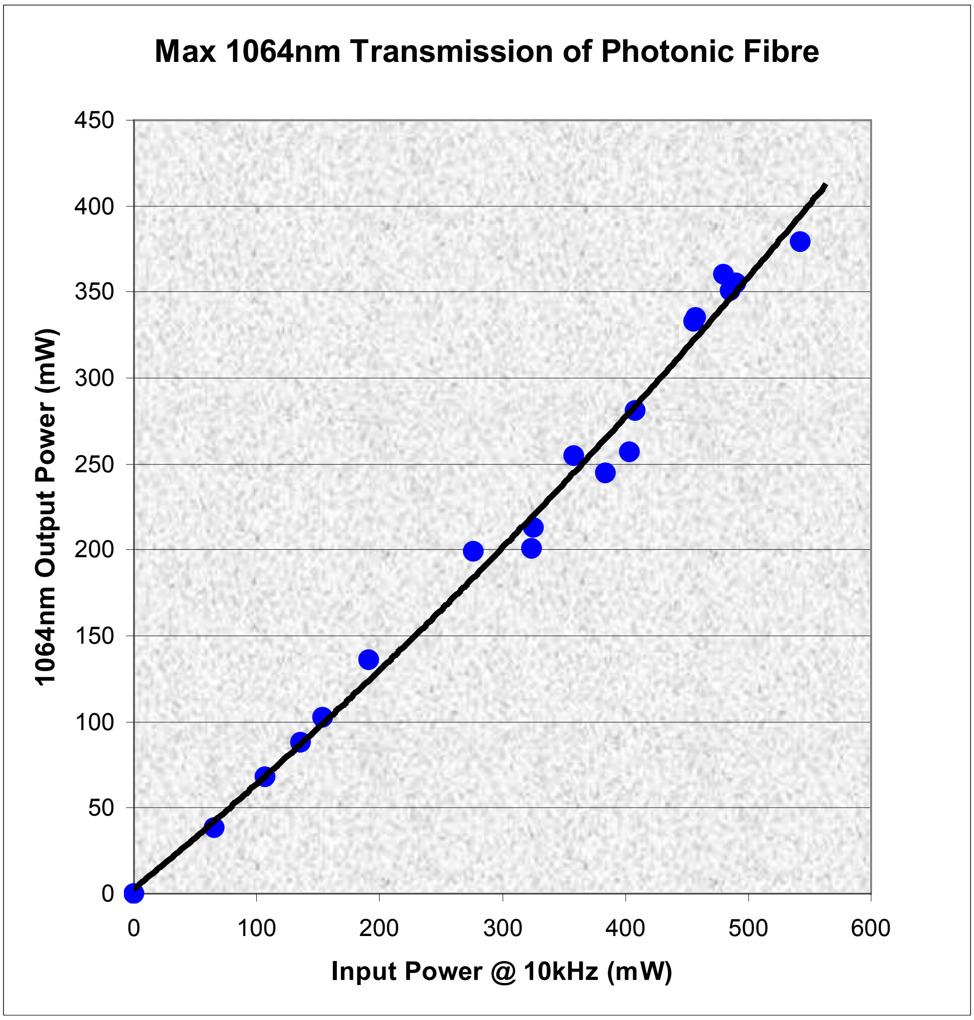

Figure (2) Power transmission of photonic fibre as a function of input power at 10kHz with optimum input beam relay magnification from the AOT-YAG-10QHP oscillator.

We have operated with this 1m fibre for a few hours at ~ 500mW input without noticeable deterioration of the fibre. We have looked at the temporal shape of the pulses IN and OUT of the fibre using a fast InGaAs (IR) diode. They were ~ 2.7ns FWHM going in and were not noticeably changed coming out. Although we did not use a monochromator to look for non-linear (eg stimulated Raman) emission, the output pulse shapes were stable and followed the input power up. These characteristics suggest that there was no significant non-linear conversion/loss developed in the fibre up to the maximum pulse power. At 500mW @ 10kHz in (50uJ/pulse) the average input fluence to the fibre was ~ 16J/cm^2, and the average power density ~ 6GW/cm^2. It can be seen from Fig (2) that the fibre allowed > 35µJ/pulse output @ 10kHz.

An observation of slight concern was that the alignment of the photonic fibre for stable high T% output was very critical. The trials showed that the input face needed to be centred on the beam to < 1µm accuracy, and the focus lens needed very careful z-axis adjustment. This is perhaps not surprising, given that the fibre mode dia is only 19.8µm and the YAG TEMoo input beam parameter is close to that of the fibre, even for a perfect TEMoo spatial beam profile. However, on the positive side, an attractive feature of the fibre is the fibre cladding size. The cladding diameter of > 250µm meant that the fibre was both robust to physical handling, and tolerant to power over-spill from the core eg due to input beam shape imperfections or modest input beam misalignment.

Hollow-Core Photonic Fibre

For visible and UV single-mode beam transmission, photonic fibres of the above design use significantly smaller core size eg for the second harmonic wavelength of 532nm the optimum core size is ~ 10-8µm diameter – an area reduction of ~ 10x over that at 1064nm. This reduction forces the consideration of hollow-core photonic fibres for high power transmission, particularly as the wavelength moves into the blue/UV region. In hollow-core fibres, > 95% of the beam power coupled in travels in air not silica which gives the potential of much higher power capability. An additional advantage is that the hollow-core design has an NA similar to a conventional fibre. This allows tight bending of the fibre without loss, but does not significantly change the requirement for good mode-matching at the input to achieve a single-lobed output beam.

We used two hollow-core photonic fibres in our trials. The first was designed for transmitting a beam ~ 1064nm (the second a beam of ~ 532nm). The fibre were cleaved with a hand tool. The specification of the fibre included:-

- Length ~ 1m, Type HC-1060-02
- Fibre NA ~ 0.12
- Core dia ~ 9.7µm
- Mode field dia ~ 6.5µm
- Cladding dia ~ 123µm
- Attenuation @ 1060nm < 100dB/km

Given the smaller core size of this acceptance angle x mode-power dia product ~ 1103mrad.µm), more significant demagnification was required to reduce the input beam to mode-match to the fibre. Four achromats of 30-45mm focal length and with BBAR coatings centred ~ 750nm were available for this task. Each was tried in turn. The transmissions achieved with the two longer fl lens are presented in Fig (3). It can be seen that the performance was not as good as that found with the lower NA larger (solid) core fibre. Even allowing for the larger (~ 5% measured) insertion loss of each focus lens, the fibre power transmission was < 50%, and this transmission was extremely sensitive to the focus lens position and alignment - even compared to the solid core photonic fibre. However, we found it notable that the fibre was able to operate to ~ 380mW input power, at least for a period of some 10s of minutes. This corresponded to a maximum input power density of ~ 24GW/cm^2 and a fluence of ~ 55J/cm^2.

The results with this hollow-core photonic fibre were a little disappointing, and we tentatively attributed them to poor optical quality of the end faces ie which were hand cleaved. In the case of the solid core fibre, the fusing of the photonic holes in the surface region allowed the manufacturer to use conventional fibre optical polishing techniques for a laser-grade polish. Without this opportunity, cleaving has to be used which can be a ‘hit and miss’ technique. Several attempts were made to re-cleave the input end of the hollow-core fibre and improve transmission, but without noticeable success.

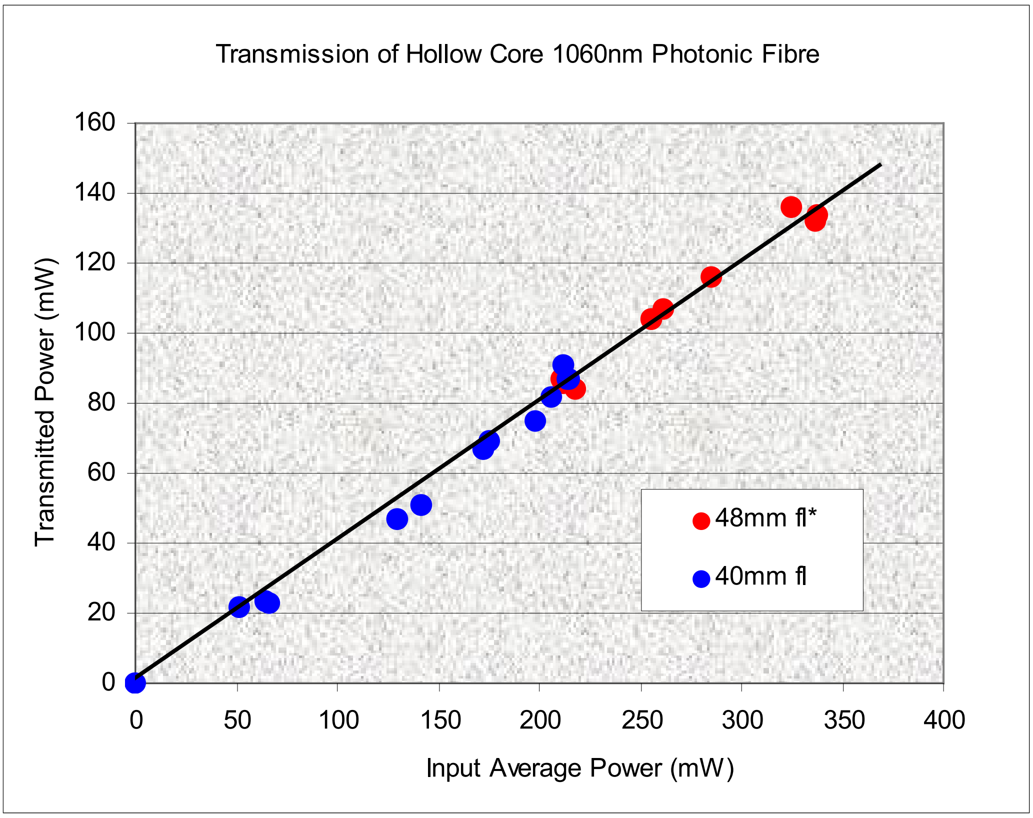

Figure (3) Best power transmission of 9.7µm diameter ~ 1m long hollow core fibre with ~ 2.7ns pulses @ ~ 10kHz

The second hollow-core fibre, designed for operation in the green part of the spectrum, was similar to the IR sample but had a core of ~ 8µm diameter and a loss given as < 400dB/km. This fibre was also hand cleaved and tested with frequency doubled pulses @ 532nm. In this case, the transmission results were even more disappointing ie T% was significantly lower than for the IR fibre.

For comparison, it is worth noting (figure 4) that in trials at 532nm with a short conventional all-silica fibre of 25µm core diameter and 0.22NA, we achieved > 90% power transmission @ 532nm i.e. close to the practical limit of 92%. In this case the fibre end faces were also hand cleaved. The input beam was focused in the range ~ 10-12µm diameter at the fibre input face. For this type of fibre, the results show that it is possible to make the input spot significantly smaller than the core, with the whole beam not only coupled-in, but guided in the fibre. All the power comes out at the distal end and is not 'lost' to the cladding/buffer region. In contrast, with a photonic fibre, the same approach can't be used. It doesn't help to make the waist of the input beam smaller than the fibre mode size to improve input coupling, for once inside the fibre, significantly more power is not guided ie is lost to the cladding/buffer region.

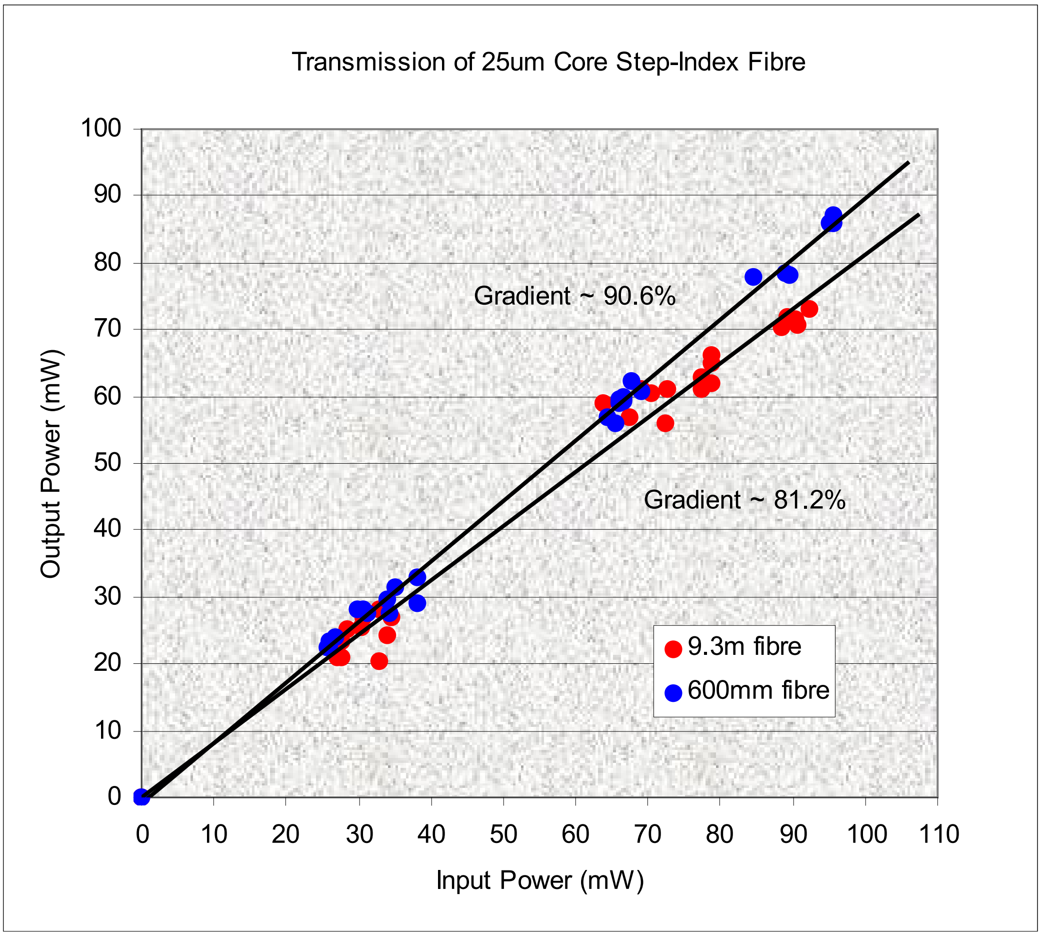

Figure (4) Transmission at 532nm of conventional low OH step-index silica fibre of 0.22NA arranged in ~ 100mm loops. Input laser pulses were of ~ 2.2ns duration at 25kHz.

This note has summarised preliminary performance results for photonic fibres designed for single mode laser beam transmission. It is clear that good power transmission can be achieved with TEMoo pulses from ACE lasers. Although efficiency is not quite comparable to that using conventional fibre, the maintenance of high beam quality is a major attraction for a number of applications.