Advanced Optical Technology Ltd

Technical Note (9)

Delivering High Brightness UV Laser Pulses by Fibre

The advent of photonic fibres and their current rapid development has led us to examine the performance of conventional fibres and to try and understand whether they will be superseded soon by the new technology, particularly for UV laser pulse transmission

Since the early 1980s the quest has been on to deliver high intensity pulsed beams through flexible fibres and maintain beam brightness. Our Q-switched lasers operate in TEM_{00} mode with pulses down to ~ 0.5ns so we are most interested in this prospect. The best conventional fibres (all-silica with pure silica core) are widely available and we have been studying their use. Our main aim has been to check practical performance, particularly in the UV at 355nm, and look to see what advantages might be gained in the future with the realization of photonic fibres – featuring widely in the news at this time.

All-silica conventional fibre is available for single mode use with core size of a few microns, or typically at ~ 50um diameter (or above) for multi-mode use. Although small core size and low NA give the best chance of beam quality preservation, the former option is restricted by fibre damage and the latter by transmission loss occasioned by bends, etc. Since standard fibre is available with either ~ 0.2NA or ~ 0.1NA we first looked at low NA fibres.

Low NA Fibre. In Figure (1) the losses of ~ 10m long samples of the two types of fibre are compared under the same input conditions ie input cone ~ 50mrad (full angle) and ~ 25um diameter beam. The low NA fibre was found to introduce a significant loss (even for small angle bends) and one that increased with number of fibre loops. In contrast, the higher NA fibre had a low loss insensitive to the number of fibre loops.

This test was conducted under quite severe bending conditions to accentuate the bending effects ie with the fibres bent into 12mm diameter coils. To complement these results, Figure (2) shows the relationship we measured between fibre transmission and bend radius for the same two fibres. Here, the fibre comprised 7-loops at the given radius. It is clear from the figure that the transmission of the 0.12NA fibre began to drop (rapidly) once the coil radius was reduced to ~ 15mm, whereas the 0.22NA fibre showed little change in transmission (to our surprise) even down to ~ 2mm radius.

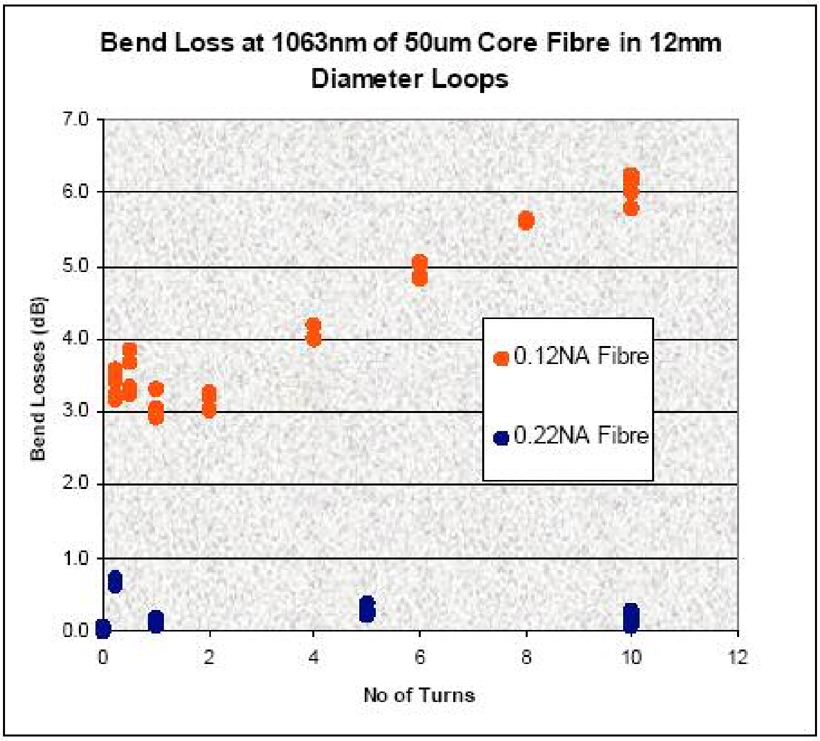

Figure (1)
Effect on transmission loss of coiling standard and low NA fibre to loops of ~ 12mm diameter. In the two cases, the input TEMoo laser beam cone (full) angle was ~ 50mrad.

The case for considering using a fibre with lower NA rests mainly on the presumption of achieving a higher output beam quality ie a lower output beam cone angle. In the trials resulting in Figure (2), we measured the output beam cone angles from the two fibres and noted the changes with loop radius. In the case of the 0.22NA fibre, the cone (full) angle increased only very modestly from ~ 160mrad for large loops (~ 100mm diameter) to ~ 175mrad for small loops (~ 4mm diameter). However, the cone angle from the 0.12NA fibre was measured as ~ 200mrad (similar to that set by the fibre NA) across the full range of fibre loop sizes.

This comparison of fibre performance was a bit surprising and suggests little to commend use of low NA fibre for delivery of the laser pulses, at least for applications where only short fibre lengths (few metres) are required.

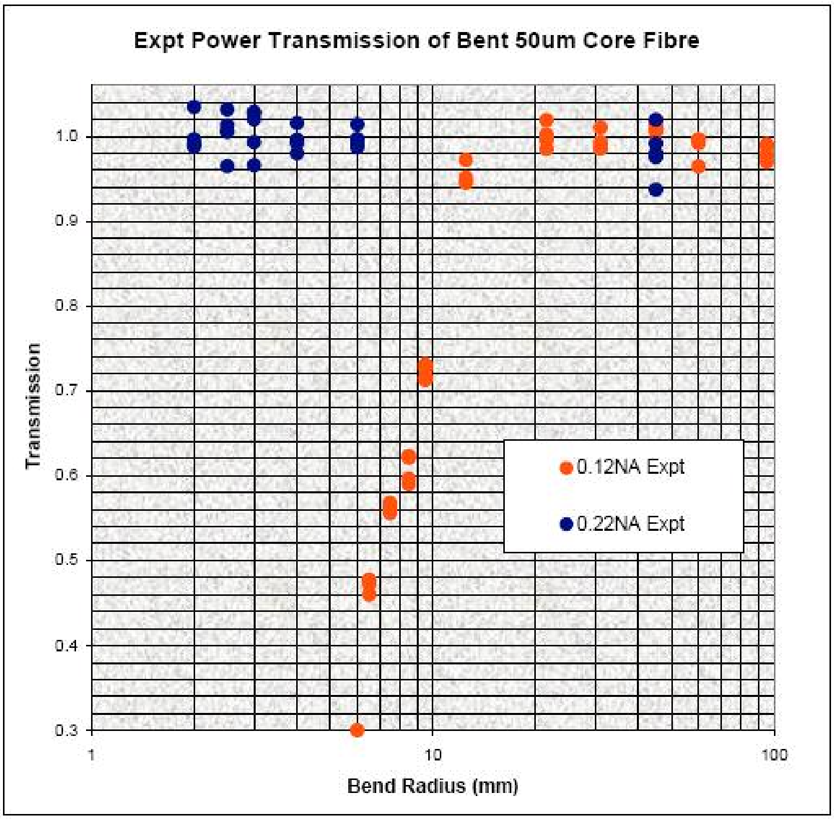

Figure (2)
Effect of bend radius on transmission of 50um diameter core fibre in coil of ~ 7 loops. In the two cases, the input TEMoo laser beam cone (full) angle was ~ 50mrad.

Standard NA Fibre. We followed-up the above trials with numerous experiments using small core (~50-200um diameter) fibres of 0.22NA with our ~ 1ns laser pulses. These have covered operation at 1063nm, 532nm, 355nm and 266nm wavelengths. Of most applications interest for us currently is performance at 355nm. For operation at this wavelength, we used high OH all-silica fibre as recommended by suppliers so as to minimise fibre absorption and transmission losses.

Conducting trials involving long and short lengths of fibre it is possible to estimate the UV loss in the fibre. Figure (3) shows results at 355nm using two 50um diameter core fibres, of ~ 9.3m and ~ 0.5m length, respectively, arranged in coils with large (~100mm diameter) loops with low bend loss.

The results in Figure (3) suggest that the fibre loss was ~ 100dB/km at 355nm, which compares with a nominal value of ~ 50dB/km stated by the fibre manufacturers. The figure also shows that the transmitted power can be > 75% for short fibre lengths.

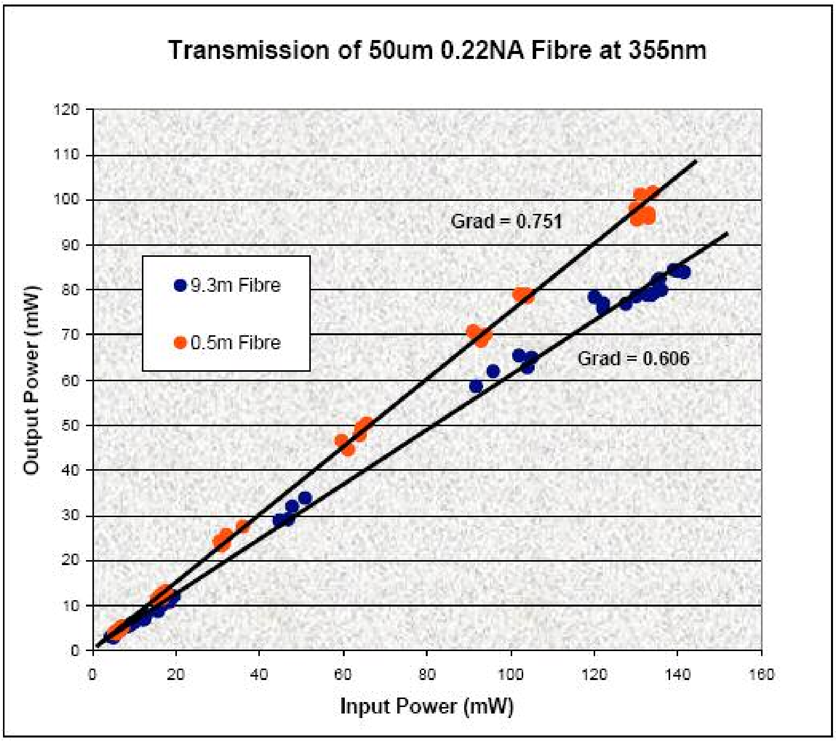

Figure (3)
Input/output power at 355nm for two lengths of 50um core diameter fibre using ~ 1.5ns duration TEM_{00} pulse at 25kHz.

In these trials at 355nm, the input TEM_{00} beam size was limited to ~ 10um diameter to achieve high input coupling efficiency and low power overspill into the cladding. At the maximum input average power, the pulse energy was > 5uJ, and the energy density on the fibre input face > $5J/cm^2$. The cleaved fibre faces survived this exposure without any problems throughout the trials. However, it is known that this energy density is not very far from the damage level of fused silica under pulsed 355nm irradiation.

As with the earlier trials (where operation was at 1063nm) measurement was made of the 355nm beam from the fibre with it subject to being coiled at different diameters. The power distribution from fibre coils of 4mm, 7.5mm and 90mm diameter were recorded, and the data normalized to show the change in shape/width of the angular distribution with coil diameter. The results are plotted in Figure (4) and show that the distribution was fairly insensitive to coil diameter and that the full angle (to the ~ 10% power points) was ~ 200mrad. Further measurement showed that the background power (power outside the main lobe and within the fibre full NA) was not more that 10% of the total even in the case of the tightest fibre coil. We concluded that short lengths of fibre (9.3m in this case) can be used, even with the fibre subject to tight loops, without the full NA becoming filled at the output of the fibre. If this had happened, it would have resulted in an output beam of ~ 440mrads full angle.

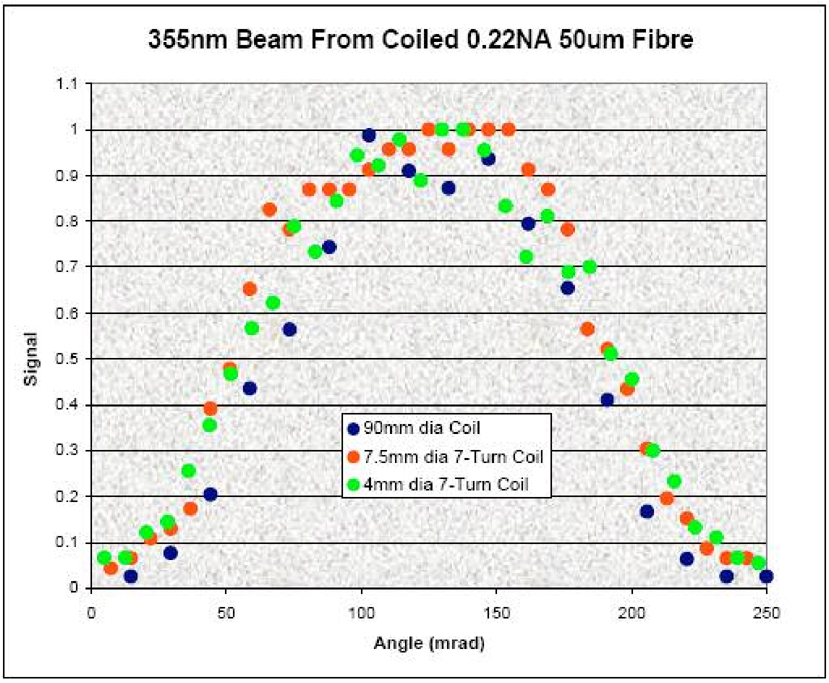

Figure (4)
Output beam angle at 355nm from ~ 9.3m long 50um core diameter 0.22NA fibre, with fibre at 3 different coil diameters. Results taken with photodiode behind a small (0.5mm) diameter pinhole scanned across the beam at ~ 100mm. The input beam cone full angle was ~ 50mrad.

It is interesting to note that the cone angle of ~ 200mrads for the 355nm output beam of the 0.22NA fibre under tight coiled conditions was similar to that for the 0.12NA fibre, BUT without the severe transmission loss which resulted using the latter type fibre (shown in Figure 2). This again supports the view that, at least for small core diameter multimode fibres in the range of a few metres length, there is not a clear advantage in using low NA fibre for transmitting high brightness pulses.

Photonic Fibres. The trials outlined above suggest the feasibility of using even smaller core conventional all-silica fibres for transmission of our short, high peak power pulses at 355nm. We have worked to an energy density limit of ~ 5J/cm^2 in an input beam of ~ 10um diameter, and it might also be possible to operate at this level reliably using a ~ 15-20um diameter fibre i.e. without further increase in the energy density. However, even if successful, such performance is likely to still result in a degradation of the TEM$_{00}$ input beam quality by a factor x10 or more. This is a materials (optical damage) problem and, in principle, might be overcome by using air rather than silica as the main medium guiding the laser power in a smaller core fibre, since clean air has a very high dielectric strength.

This switch in fibre core medium is becoming a reality, following recent developments in the field of photonic crystal fibres. Early examples comprised all-silica holey fibre with a solid core in which the beam was guided. Such designs allow the opportunity of single mode performance with a larger effective core size compared to conventional fibre, but it is achieved with a low NA and the associated high bending losses of conventional fibres. In contrast, the most recent developments concern hollow-core (bandgap) photonic fibres which not only have air as the core medium (allowing high power transmission), but are reported to have negligible bend loss, even when coiled to ~ 3mm radius loops.

Potential hurdles to be overcome with the new designs are formidable as operation moves from the IR through the visible to the UV. Notably, as with conventional fibres, the core and the rest of the guiding holey structure needs to shrink at shortening wavelengths to maintain single-mode performance, and this also leads to a tightening of the tolerance to defects. Despite these difficulties, we note that hollow-core photonic fibre is beginning to be offered with losses quoted at acceptable levels for many applications i.e. < 100dB/km in the IR, < 1000dB/km in the green, and < 2000dB/km in the blue. These results give good optimism that photonic fibres delivering single-mode power in the UV at 355nm with useful efficiency are not far off.

This is an exciting prospect for us as a laser supplier as we believe that flexible delivery of high power, high brightness UV pulses will find many users. No-doubt, the continued commitment of R&D resources applied to the new fibre technology will also facilitate future progress to even shorter wavelengths. Today, we find that the best conventional all-silica fibres are of marginal performance at 266nm. They have losses of ~ 1000db/km (which corresponds to 70% transmission over 1m), low damage thresholds and have solarization as a long-term concern. A hollow guide for the UV without these limitations would be a major breakthrough.

Useful References

1) ‘Bend Loss in Large Core Multimode Optical Fibre Beam Delivery Systems’, Boechat AAP et al, Applied Optics, Vol 30, No 3, pp321-7, (1991)

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