Next Generation Fibres for High Power Laser and Telecommunications Applications

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***Abstract* – The fundamental capacity of optical networks based on conventional fibre technology is rapidly being approached. We speculate how high power fibre laser technology developed over the past decade might be adapted and applied to help avoid the otherwise looming capacity crunch.**

I. Introduction

Driven by the exponentially growing demand for capacity, it is already apparent that the next generation of telecommunication networks will be radically different from previous implementations; coherent detection and multi-carrier techniques, along with powerful digital signal processing will be deployed to maximize the available capacity of each fibre strand within the network. However, whilst these developments are welcome, they only delay the inevitable capacity crunch as we exhaust the single fibre bandwidth. Put simply, once these techniques are deployed over the next few years, we can only increase network capacity by adding additional fibres. With a per annum growth rate of over 40% , this only delays a total capacity exhaust by a few years before new cable deployments are required (presumably at 40% of the installed base per annum!). However, the proximity of extensive deployment of new fibre cables in the next decade (2020-30) provides a unique opportunity to re-examine our choice of transmission fibre in the hope of finding a dramatic increase in per-fibre capacity. It is therefore clear that radical innovation in the basic internet infrastructure (i.e. transmission fibres and amplifiers) is now urgently required.

Unsurprisingly perhaps, many of the key issues to be faced in developing the next generation of fibres for telecommunication (e.g. nonlinearity, mode-control, and damage effects) are also critical in the context of high power fibre lasers. Consequently, we anticipate that much of the work done in this field, which has led to power scaling of fibre lasers from the 100W to the 10kW regime over the past decade, may be leveraged to good effect as we look to further capacity scale our networks. We describe some of the main opportunities below.

II. Loss and Nonlinearity Reduction

In order to maximize the data carrying capacity of a fibre it will be necessary to operate with as high a signaling spectral efficiency as possible and this dictates using as high an Optical Signal to Noise Ratios (OSNRs) as possible before the onset of the nonlinear impairments that limit the possibility of achieving efficiencies at the Shannon-limit. The reduction of fibre attenuation and nonlinearity (ideally both simultaneously) are thus primary targets for next generation transmission fibres. Nonlinearity is a major factor limiting power generation and delivery in fibre laser systems, particularly in short pulse systems where peak powers in excess of 1MW have been reported.

Hollow core Photonic Band Gap Fibres (PBGFs) represent a technology that could ultimately yield major benefits in terms of both loss and nonlinearity. PBGFs comprise an array of longitudinal wavelength-sized holes periodically arranged in the cladding to form a photonic bandgap in the transverse plane of the fibre. A central air-filled hollow defect constrains light within the air core to propagate along the fibre over a tailorable spectral range. The sub-percent fraction of optical power guided in the glass matrix means that Rayleigh scattering, the dominant source of loss for SSMFs, is negligible for PBGFs, such that these fibres have the potential to achieve significantly lower losses than conventional solid core variants [1].

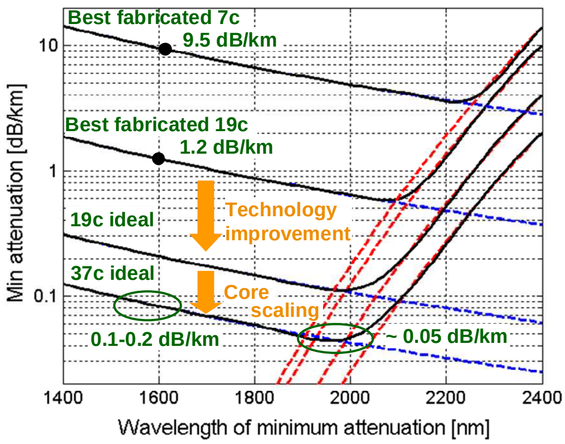

Fig. 1. Fundamental mode loss versus wavelength for different core designs and a typical hexagonal symmetry lattice with 7, 19 and 37 cell elements removed to define the core.

Losses in PBGFs are fundamentally dominated by two mechanisms: (1) surface scattering at the core glass-air interface and (2) infrared phononic absorptions in the glass matrix. The combined effect of these two loss mechanisms is to shift the wavelength region of minimum loss from 1550 nm to the 1900-2100 nm band [1]. Impressive improvements in PBGF design and fabrication techniques have reduced the loss in these fibres from several dB/m to 1.2 dB/km at 1600 nm in the space of just a few years. The potential for nonlinearity reduction relative to solid core fibres is though even more significant due to the very low nonlinearity of air and the low mode overlap with silica [2]. Indeed, fibres with around 0.1% of the nonlinearity of conventional solid fibres have already been achieved.

Our modelling indicates that through realistic technological improvements in fibre fabrication and modest changes in fibre design it might be possible to realise fundamental mode losses below 0.1 dB/km, representing up to 20 times improvement over the current 1.2 dB/km record (achieved in a 19-cell core fibre). Our estimate is based on a 4-fold reduction in surface scattering due to improvements in surface roughness (x2) and moving to a longer wavelength (x2), and a five-fold improvement resulting from the reduced field at the glass surface arising from use of a higher air fill fraction cladding (x2) and a larger core (x2.5). These fibres would have a nonlinear coefficient extremely close to that of air ($\gamma \sim 0.001\ W^{-1}km^{-1}$). The low-loss bandwidth of the fibre could exceed the bandwidth of current S+C+L band systems assuming issues associated with residual gas and water species absorptions can be eliminated. Note that in order to be able to fully exploit these fibres it will also be necessary to deal with the increased number of modes that can theoretically be supported by the larger core along with the practical issues of interconnection/cabling.

III. Extended spectral bandwidths

Both for low nonlinearity single mode PBGF fibres and fibres made from other potential low loss materials, such as Fluoride glass, the minimum loss wavelength will extend to longer wavelengths than the current third telecoms window, potentially to well beyond 2µm. The development of amplifiers capable of operating beyond the range of erbium doped fibres is thus an important technical requirement. Rare earth doped fibres based on either Thulium, or possibly Holmium, appear to represent the most attractive solutions as they offer diode-pumped solutions in the spectral regime extending from at least 1.7-2.2µm [3]. High-power Tm^{3+}-doped silica fibre lasers and amplifiers have received increasing attention over the past few years due to emerging applications in the medical, defence and security areas. So far the work has focused on realising high power, single wavelength lasers and output powers close to 1kW have now been reported. Studies on the use of these rare earth/silica systems as long wavelength amplifiers have started only relatively recently and as of yet not really with optical fibre telecommunications in mind.

IV. Spatial Multiplexing

Conceptually at least, the simplest way to increase the data carrying capacity of a fibre is to increase the number of separate information channels through some form of spatial multiplexing. One means to do this is to use multi-core (MC-) fibres with each core providing a separate single mode data channel [4]. An alternative is to use some form of Mode-Division-Multiplexing within a Multimode (MM) transmission fibre [5]. In the later case mode-mixing is a major issue which either needs to be avoided, or mitigated using means such as Multiple-Input, Multiple-Output (MIMO) signal processing. Multicore and multimode fibres provide a route to power-scaling above the single-mode, single-core, power generation limit and a significant amount of work has therefore been conducted on multicore fibre lasers and amplifiers operating with either isolated or coupled single mode cores. Significant progress has also been made in terms of exciting and managing modes in multimode fibre structures that could also be of significant use in telecommunications moving forward.

V. Improved power handling

An increased fibre capacity will obviously lead to higher average power levels within the fibre, with the consequence that we will rapidly encroach upon the ~ 1.2W fibre fuse threshold for SMF. Any new fibre technology will therefore need to be developed with this in mind. Power handling is fundamental to the realization of robust, reliable high power fibre laser systems and substantial progress has been made in the management of scattered/unconfined light and thermal effects in fibres. This knowledge, perhaps coupled with the observation that the fuse threshold can be increased though the use of microstructure within the fibre [6], should ensure that the need to use higher power levels will be a solvable problem from a cable reliability perspective. The issues of eye-safety and the associated increased electrical power requirements for submarine systems may though prove thornier problems.

VI. Conclusions

In conclusion, substantial work is now required on the development of next generation fibre infrastructure in order to accommodate societies every incredible digital demands. Photonic bandgap and multicore fibres along with novel gain media and power handling techniques studied primarily in the context of high power fibre lasers offer possible ways forward.

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