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Large mode area fiber lasers and their applications

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The area of fiber lasers has undergone rapid developments in recent years. Gone are the days when fiber lasers were seen as something of an irrelevant curiosity, offering interesting performance features, but always with power levels or other performance limitations, that made them unsuitable for all but a few applications. Improvements in the area of high-power, high-brightness semiconductor pump lasers, and the development of techniques, such as cladding-pumping, have changed this viewpoint markedly. Most significantly, fiber lasers have shed the 'low power' label and it is now widely appreciated that the heat-dissipation characteristics of the fiber environment, coupled with the high efficiencies demonstrated (in excess of 80%), actually make fiber lasers a preferred candidate for many high-power applications. Moreover, major advances in fiber Bragg grating fabrication and more sophisticated fiber designs and pump coupling techniques, have at the same time improved device performance and increased the versatility, functionality and practicality of the technology; allowing the development of a broad range of robust, practical optical sources.

By far the greatest research/commercial effort over the past few years has been targeted towards achieving high continuous wave output powers. Progress has indeed been impressive with output powers in excess of 110W already achieved [1]. Clearly, there are many potential uses of multi-watt cw fiber lasers, with major applications in the industrial printing, marking, military, medical and telecommunication industries. To date little work has been performed in the area of high power pulsed fiber lasers. It should be stated at the outset that fiber lasers will never be able to compete in absolute terms with the energies and peak powers achievable with bulk laser systems. This is due to the very features that make them attractive for high average power applications specifically: the mode-confinement, (which leads to the high efficiencies and excellent spatial mode characteristics), and the extended length, (which provides the excellent thermal management characteristics). However, by appropriate fiber design fiber laser performance can be raised to a level suitable for a number of important application areas, (e.g. micro-machining and LIDAR), at which point the previously described features of compactness, efficiency and flexibility make them a highly attractive alternative to conventional solid state lasers.

The key to achieving increased pulse energies and peak powers has been to increase the mode field diameter (MFD) within the fiber. From an energy applications perspective this enables more energy to be stored within the structure before ASE, or lasing due to the ultimately unavoidable back reflections, limits the storage capacity. The energy stored scales more or less in proportion to the mode area. A large MFD is good from a pulse peak power viewpoint since it reduces the optical intensity within the core and reduces the impact of optical nonlinearities. As an illustration of the limits of conventional fibres a standard erbium doped fiber operating at 1550nm has an MFD in the range ~6-8 μm and allows energy storage of ~10-20μJ. Tolerable power levels within such a fibre might be in the range 100W-1kW, depending on the device length and the particular application in mind. Note that large core fibers are not just useful for pulsed lasers. As cw laser powers continue to increase nonlinearity and power handling will also become a major issue, pointing to the need for fiber with large mode sizes. Moreover, in cladding-pump schemes, the pump absorption length scales with the relative ratio of core and cladding area. Larger core sizes thus mean shorter device lengths- a desirable feature in almost all instances. The need for large core fibers is thus self evident, however the core size of a fiber cannot be arbitrarily increased without penalty. Single mode operation, a fundamental requirement for many applications, can only be maintained for a restricted range of core diameters. As the core diameter is further increased a fiber becomes multimode and therefore less useful from an applications perspective, unless excitation of an individual mode can be reliably obtained, and maintained.

Recently we developed low numerical aperture, large mode area (LMA-), rare earth doped fibers incorporating complex refractive index, and dopant profiling. A typical erbium-doped LMA-fiber refractive index profile is shown in Fig.1. The low NA (typically ~0.06) ensures a factor of ten increase in mode area for pure single-mode operation relative to conventional erbium doped fiber. Further increases in mode sizes using the low NA approach alone are restricted by the associated increase in bend-loss sensitivity. We have shown the anticipated ten-fold increase in output pulse energy obtained through use of such fibers in a number of (nanosecond) laser [2] and amplifier systems [3]. The improvements obtained (pulse energies up to ~0.2mJ, peak powers >100kW) are significant since they open up a range of new applications for fiber lasers and amplifiers. For example, we have shown that it is possible to directly pump parametric devices based on quasi-phase matched materials such as periodically poled lithium niobate (PPLN)[4], and silica fiber[5], allowing for efficient wavelength conversion of fiber laser output. Indeed, we recently obtained tuning in the range 0.98-4.5 microns from a ns OPO using a simple, Q-switched erbium doped fiber laser diode pumped with just 300mW of 980nm radiation [6].

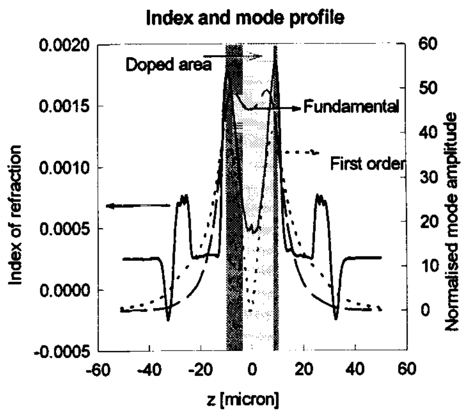

Figure 1 Refractive index profile of a typical low-NA large mode area fiber. The outer ring of raised index is included primarily to reduce the fiber bend loss, which increases rapidly with increasing mode area, and to further expand the fundamental mode. This particular erbium doped fiber is dual-moded at 1550nm. The fundamental and second order mode are plotted on the curve. The larger overlap between the fundamental mode with the rare earth doped region of the fiber provides mode selection allowing a device to operate in a single spatial mode, despite the multimode nature of the guide. The typical MFD is ~20μm for SM operation at 1550nm

The LMA design also offers benefits for short pulse lasers. For example, the reduced nonlinearity can be used to scale the output powers obtained from passively mode-locked lasers, from the pJ to the nJ regime [7]. For higher energies and powers we have developed an all-fiber chirped pulse amplifier system based on both active, and photosensitive LMA fiber components. We were able to generate ~2ps pulses with peak powers approaching 0.5 MW [8]. Far higher powers (>10MW) can be achieved with the use of a bulk grating based re-compressor [9].

As mentioned above the possibility of obtaining much larger mode sizes exists even when the core is capable of supporting a number of guided modes. This can be achieved by using a tailored dopant distribution profile to provide maximum gain for the fundamental mode (see Fig.1). The fundamental mode is thus preferentially excited and single mode operation can be achieved providing mode-coupling between the fundamental and higher order modes can be kept at a tolerable level. This can be ensured by keeping the outer dimensions of the fiber large (>200 microns)[10]. Using such an approach we were able to obtain as much as 0.5 mJ of pulse energy in a single transverse mode (MFD=34μm) from a simple Q-switched erbium doped fiber laser operating at 1550nm [11]. Pulse energies approaching 0.9mJ were obtained with a slightly degraded spatial mode (M^2=1.7) in a slightly larger pull of the fiber (MFD=40μm). In more recent experiments we have achieved pulse energies in excess of 2mJ from a cladding-pumped, Yb doped fiber laser based on this core design (MFD≈50μm), albeit in a slightly multi-moded beam (M^2=3). Average output powers of >5W, at a wavelength of 1090nm, were also obtained for mJ operation (see Fig.2)[12]. These results represent an approximate two-order of magnitude increase in pulse energy relative to those obtained with conventional core designs. These latest results show that even in the pulsed regime fiber laser are starting to compete in performance term with more conventional solid state approaches, and there still remains plenty of scope for further improvements.

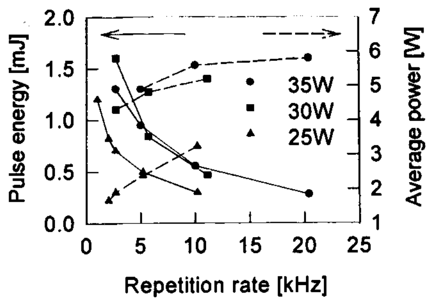

Figure 2. mJ pulse energies at multi-Watt power levels obtained from a Q-switch cladding-pumped Yb fiber laser. Pulse energies as high as 2.3mJ were obtained using a more refined cavity design

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