Recent Progress of High Power Fiber Lasers for High Power and High Quality Material Processing Applications

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ABSTRACT

CO_2 and YAG lasers are routinely capable of producing cw output powers in the range of sub-W to multi-kW and as such have become the mainstay of the laser cutting and welding industry. Despite numerous advancements in their design these lasers are still typified by poor wallplug efficiencies (typically 1-10%) and/or relatively poor optical beam qualities. On the other hand recent developments in laser diode technology, fiber design and beam combining techniques have meant that cladding pumped ytterbium-doped fiber lasers have attracted growing interest as a route to highly efficient (20-40% wallplug efficiencies), high output power, high beam quality (near-diffraction limited) lasers for a vast array of material processing applications. More specifically fiber lasers have a number of distinct advantages over their more conventional alternatives including size, reliability, wavelength selectivity, heat dissipation, wall plug efficiency and operational cost. Furthermore they can be operated without the need for active cooling or optical alignment. In this paper we review the recent progress in fiber design that is facilitating the scalability of the output power of fiber-based lasers and amplifiers.

Keywords:double clad fibers (DCF), polarization maintaining (PM), fiber laser, beam combining.

1. INTRODUCTION

For certain applications, such as ranging and free-space communications, operating in the “eye-safe” 1.5-2.0micron range is preferred. In addition there are a number of sensing and medical applications that require other specific wavelengths. For such “wavelength specific” applications it becomes necessary to employ a variety of optically-active lanthanide ions, such as neodymium, thulium or codoped erbium/ytterbium. However for non-wavelength specific applications, requiring only extremely high output powers a number of unique advantages have made ytterbium the dopant-ion of choice. More specifically ytterbium-doped fibers offer high output powers tunable over a broad range of wavelengths, from around 975-1120nm (more typically from 1030nm to 1120nm). Ytterbium also has a relatively small quantum defect, that is to say because the pump wavelength (typically 915-975nm) is close to the lasing wavelength, very little energy is lost to heating. Furthermore, unlike other lanthanide ions, ytterbium has only a single excited state and thereby is not subject to complications arising from excited state absorption (ESA) and is relatively immune to self-quenching processes. Consequently high concentrations of ytterbium ions can be incorporated while maintaining excellent conversion efficiencies (typically greater than 75%).

Traditionally the achievable output power from a fiber laser was limited to the mW domain by the need to launch excitation energy directly into the core of the fiber. With the advent of double clad fiber technology in 1988 [1] this restriction was removed and demonstrated output powers were soon reported in the 100W range [2]. However it was soon recognized that the scalability of output powers was then limited by amplified spontaneous emission and nonlinear processes such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) [3]. Fortunately these limitations can be overcome by using fibers with low numerical apertures (NAs), large-mode areas (LMAs), novel index profiles and high dopant concentrations [4]. The recent availability of pump laser diodes with ever-increasing output powers and brightness, coupled with the development of these LMA fibers have led to an exponential increase in the reported output power of a single fiber lasers with near-diffraction limited output beam quality; to beyond the kW-level [5-9]. Furthermore most of these results had output powers limited not by the fiber design but rather by the availability of pump-diode power. In fact it has even been suggested that power-scaling beyond 10kW in a single-fiber configuration may be feasible [8]. It must be noted however that these results have typically been achieved in laser cavities employing bulk optic devices, such as mirrors and lenses. Clearly real-world industrial applications necessitate an “all-fiber” solution which would provide the added advantages of a more compact, robust and reliable device which would also exhibit superior optical performance due to a reduced susceptibility to misalignment. Indeed IPG has demonstrated such an "all-fiber" device using a Master Oscillator Power Amplifier (MOPA), however this device is characterised by a randomly polarised, spectrally broad output beam; of the order of 13nm [9]. For applications requiring further scaling of the output power and indeed for many applications at this or even lower output powers such characteristics are unacceptable. For example there are a number of power scaling techniques wherein the output from multiple fiber lasers is combined. These techniques include coherent beam combining, spectral beam combining and polarization beam combining and in each case operating under stable linear polarization with spectrally narrow output is a requirement [10][11]. Furthermore there a number of other material processing applications including those employing nonlinear frequency conversion, into the visible and ultraviolet regions, where such polarized and spectrally narrow outputs are required. Such requirements provide yet another layer of complexity to the fiber design but such PM-LMA fibers are now a commercial reality [12] and are facilitating the manufacture of fiber lasers with linearly polarized outputs.

2. LINEARLY POLARIZED SINGLE-MODE FIBER LASERS

Last year we reported the first completely monolithic linearly-polarized, diffraction-limited, narrow-linewidth cw fiber laser operating with more than 300W output [13]. The significant practical advantage of the demonstrated design is its ultimate simplicity: the laser cavity consists only of a PM-LMA fiber spliced to a fiber Bragg grating (FBG). Linearly polarized output is achieved due to a polarization-mode selectivity of a tightly coiled PM-LMA fiber. More recently we have been able to scale the output of this laser to in excess of 400W [14].

The fiber structure and the laser cavity design are shown in Fig. 1. The cavity consisted of a 33m length of PM-LMA fiber spliced directly to an FBG with >99% reflectivity on one end and a flat fiber cleave providing 3.5% Fresnel reflection on the other. The ytterbium-doped Panda-type PM-LMA fiber, had a 20µm 0.06NA core (V# ~ 3.5) and a 400 micron octagonally-shaped 0.46NA inner cladding. In order to eliminate both the undesired polarization-mode and higher-order transverse modes the YDF was coiled onto a 7.5cm diameter aluminum mandrel. The laser was pumped from both ends by fiber-coupled, wavelength-multiplexed diode bars at the 915nm, 940nm and 976nm. The total amount of pump power coupled into the fiber laser was around 610W.

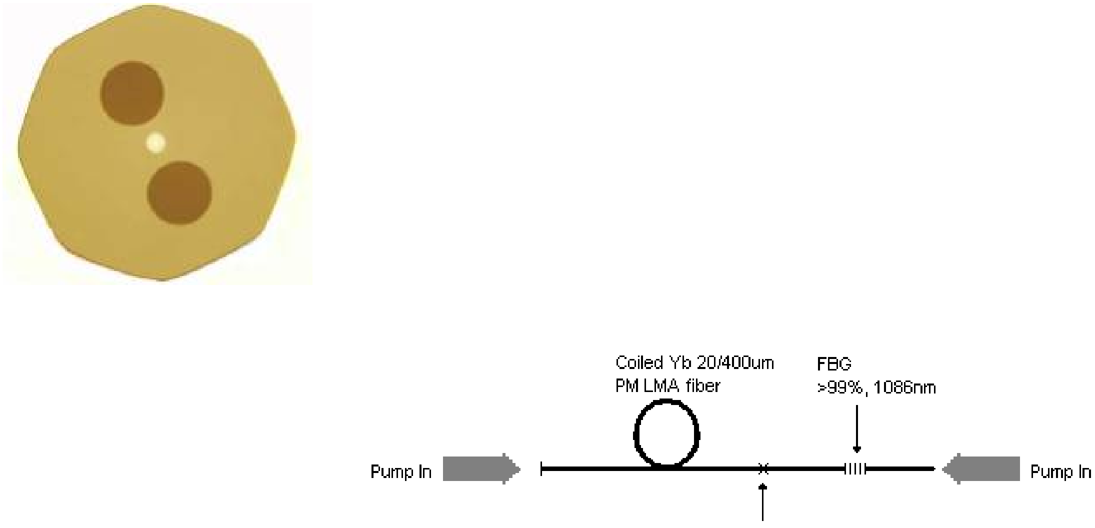

Fig. 1. An optical image of the fiber end-face and the cavity design of the all-fiber based linearly polarized fiber laser.

Fig. 2 shows the 1086nm laser output power as a function of coupled pump power. The laser exhibited a threshold of ~3W and a 66% slope efficiency; the latter comparable to other techniques of making polarized fiber lasers. The maximum laser output power was 405W. A Polarization Extinction Ration (PER) of up 18dB was measured at the output of this simple laser cavity. The laser produced a near diffraction-limited single-mode output with an M^2=1.1+/-0.1. Also presented in Fig. 2 is the measured laser linewidth. As compared with the 0.57nm linewidth previously reported [13] this laser had a relatively broad linewidth of around 2nm. It must be noted however that the spectral width was not only limited by the width of the FBG reflector but that the observed linewidth was observed to increase with laser power. Clearly the straight-cleaved end is not wavelength selective and incorporation of a wavelength selective output coupler (see Fig. 3) would help to narrow the observed output. Importantly no sign of detrimental non-linear effects, such as SRS or SBS have been observed. Furthermore theoretical analyses based upon observed values for the threshold for end-face damage of doped fibres and the Raman threshold as a function of feedback suppression in a 30m long 20micron core fiber indicates that, by minimizing feedback from stray reflections to < -45dB, it should be possible to scale the output power of this design to 2kW cw and higher.

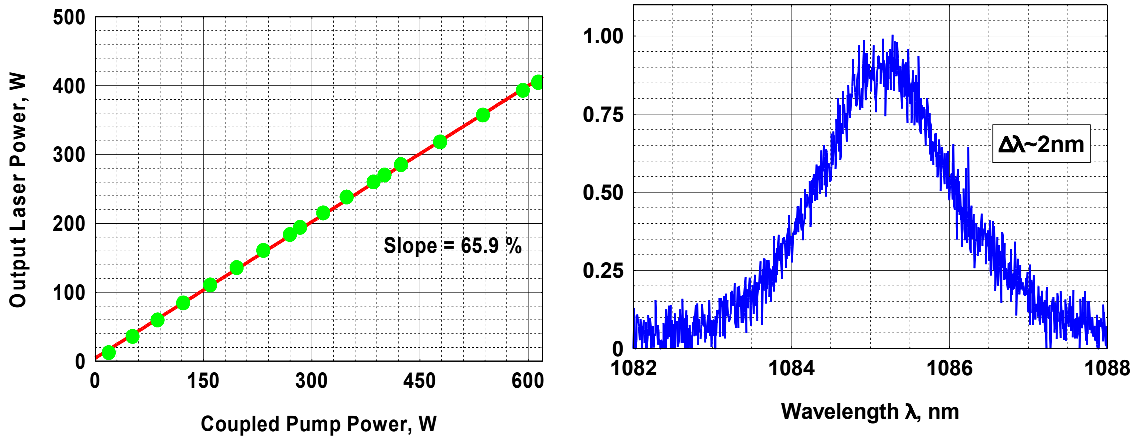

Fig. 2. Slope efficiency and spectral linewidth for the linear polarized fiber laser cavity shown.

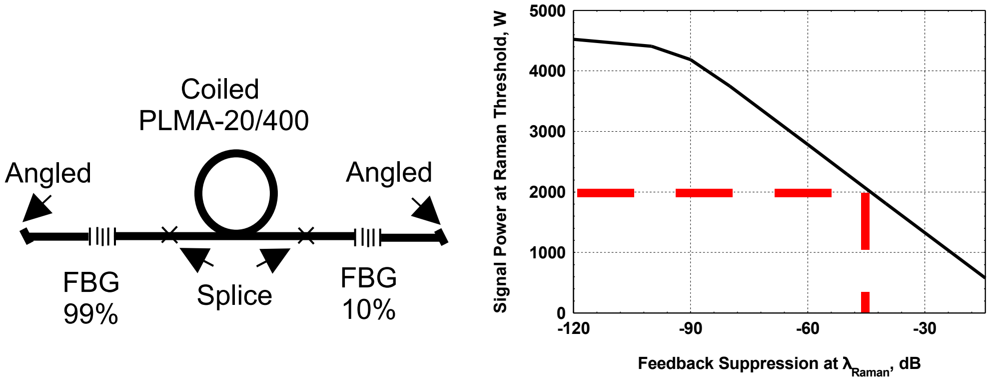

Fig. 3. Cavity design for reduced laser linewidth and theoretical analysis of the scalability of output power based on SRS.

This simple and robust all-fiber design is particularly attractive for further power scaling to >10kW using multiple-beam combining techniques, and is promising to facilitate a broad variety of practical applications requiring high-power linearly-polarized diffraction-limited laser beams. Indeed work is already underway, at a number of facilities including HRL Laboratories (see Fig. 4), to combine the output of several such fiber lasers.

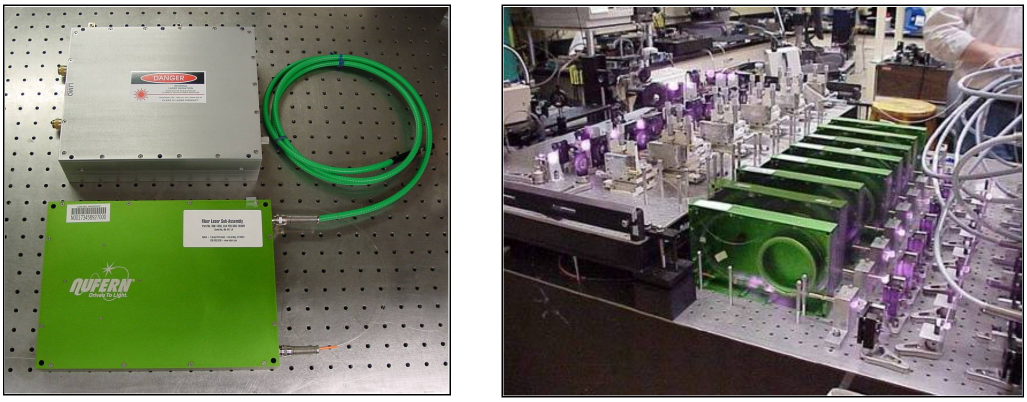

Fig. 4. Linearly polarized fiber laser and beam combining experiments (image courtesy of M. Minden, HRL Labs).

Flexibility in the choice of lasing wavelength (typically from 1030nm to 1120nm) means that it is possible to use frequency doubling crystals to generate lasing output with wavelengths from 515nm to 560nm and through further frequency conversion into the UV. Several groups have already commercialized lasers based on this technique (see Fig. 5).

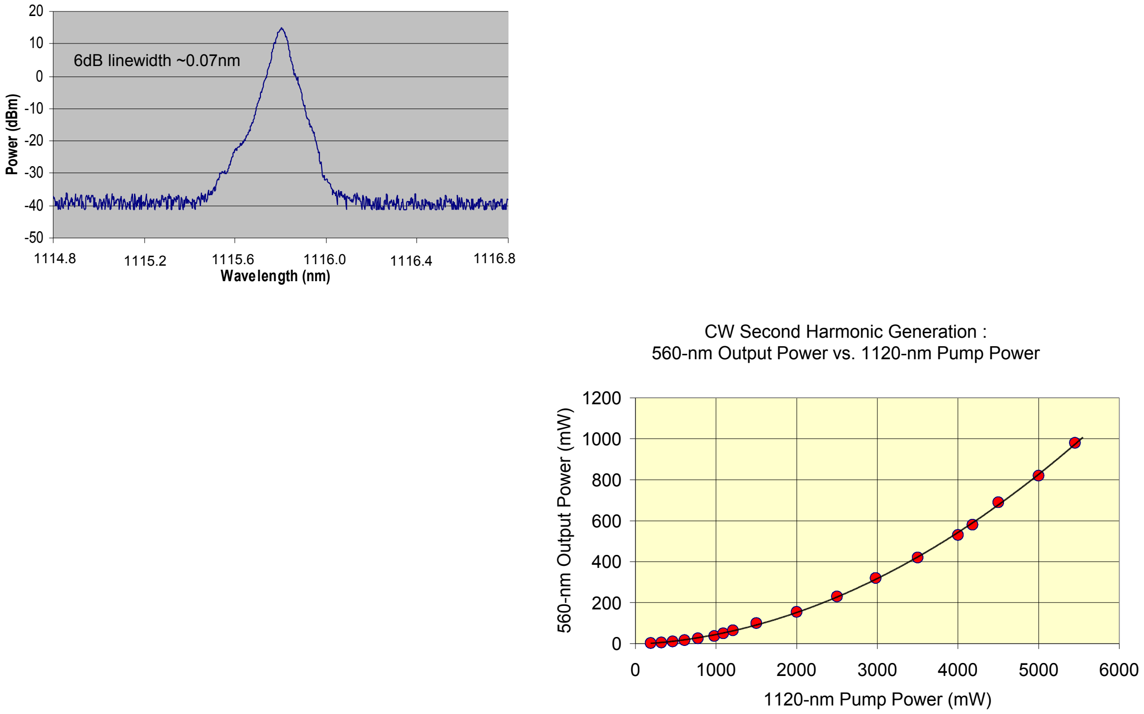

Fig. 5. Nonlinear frequency doubling of a 0.07nm narrow-linewidth 1120nm fiber laser with 17dB PER (Data courtesy V.Karpov,MPB Communications Inc).

3. CONCLUSIONS

With extremely high wallplug efficiencies and high output beam qualities from compact, rugged, reliable, passively cooled devices the ytterbium-doped fiber laser has attracted significant attention in recent times. Recent advances in pump-diode and fiber design are facilitating the development of monolithic (all-fiber) diffraction-limited, linearly polarized lasers with output powers approaching the kW-level. These devices are ideally suited to both power scaling and applications requiring frequency conversion. As a consequence fiber lasers based upon these designs are now challenging more traditional CO_2 and YAG laser systems in a range of material processing applications.

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