DIODE PUMP REQUIREMENTS FOR HIGH POWER FIBER LASERS

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Introduction

The single most important factor in the recent power scaling of CW fiber lasers has been the continuing improvement in fiber coupled, high brightness pump diodes. As the available power/brightness per module has increased, the cost associated with pumping a fiber laser has decreased and in turn the available CW power from a single fiber laser has increased exponentially over the last five or so years. Here we review some of the unique requirements associated with pumping high power fiber lasers in various architectures, the roadmap on power scaling and wavelength requirements for next generation eye-safe fiber lasers.

Pump wavelengths

Ytterbium

Ytterbium-doped fiber lasers dominate the industrial fiber laser market, mainly due to their excellent efficiency, long term stability and maturity of technology. At present, commercial systems are available with up to 3kW single-mode and 50kW multimode [1].

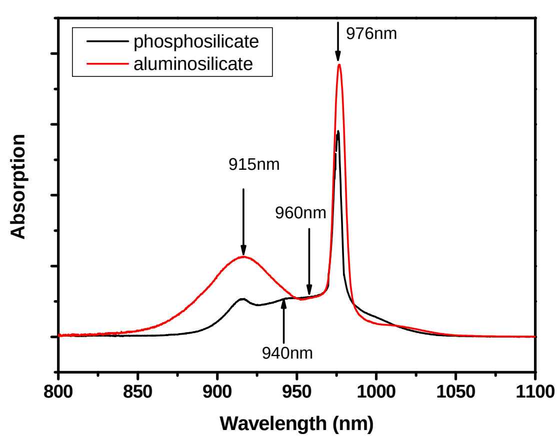

Fig. 1. Absorption for aluminosilicate and phosphosilicate Yb-doped fibers.

To aid the solubility of Yb_2O_3 in silica, two common co-dopants, Al_2O_3 and P_2O_5 are commonly incorporated into the fiber core. Each separate co-dopant influences the spectroscopic properties of the fiber as shown in Fig. 1. We can see that the peak absorption at ~976nm is approximately 3 times higher than at 915nm in aluminosilicate fibers and 5 times in phosphosilicate fibers.

Pumping at 976nm has two distinct advantages over other pump wavelengths. Due to the lower quantum defect than at shorter wavelengths, higher efficiencies may be obtained by pumping at 976nm. More significantly, shorter fiber lengths are used, key to limiting deleterious non-linear effects. The main drawback to pumping this narrow absorption peak is the tight wavelength tolerance placed upon pump diodes.

By pumping at other wavelengths (generally 915, 940 and 960nm) these tight tolerances may be significantly reduced; useful for applications such as air-cooled systems where diode temperatures, and hence wavelengths may fluctuate. Pumping at alternative wavelengths can also be useful in controlling inversion, which has been shown to be an influential factor in reducing the rate of photodegradation [2].

Erbium

980nm core-pumped Er-doped fiber amplifiers (EDFAs) have been employed extensively in the telecommunications industry for years however their output powers are limited to the availability of high power, single-mode pump sources. Original interest in wavelengths around 1.55µm arose from the low attenuation in silica making it a suitable wavelength for long-haul communications systems. Wavelengths greater than 1.4µm are considered eye-safe, therefore Er-doped devices became of interest for many more applications such as range finding and LIDAR.

The 980nm absorption peak of Er is generally too weak to exhibit sufficient gain in cladding pumped devices. By incorporating high concentrations of Yb as a sensitizer (Fig 2), this problem may be overcome. To achieve efficient energy transfer from Yb to Er, high concentrations of phosphorous must be incorporated [3] and as such, the absorption profile of Er:Yb fibers are similar to that of the phosphosilicate Yb fiber shown in Fig. 1.

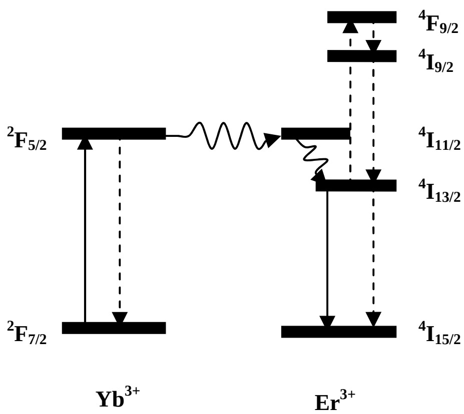

Fig. 2. Energy transfer from Yb^{3+} to Er^{3+}.

Thulium

Thulium exhibits extremely broad emission making it suitable for operation from below 1.8µm to over 2.1µm.

Most current commercial available systems utilize resonant pumping at 1.56µm from an Er:Yb laser. To date, the maximum power demonstrated from a resonant-pumped Tm laser was 415W. However the total optical-to-optical efficiency of such a scheme is typically limited to ~25% resulting in maximum power point efficiencies of ~12% [4].

To achieve higher efficiencies, pumping at ~790nm may be employed to take advantage of the cross-relaxation or two-for-one phenomenon shown in Fig. 3. Using free-space optics, the highest power that has been published from a Tm-doped laser pumped at 795nm was 301W with 61% slope efficiency [5]. When pumping at ~790nm, excited state absorption (ESA) resulting in visible light generation associated with photodarkening can be a concern [6]. Mitigation of these effects has been achieved through careful optimization of fiber composition, fiber thermal management and cavity design. We have presented some preliminary reliability data [7] and anticipate publishing more comprehensive results in the near future.

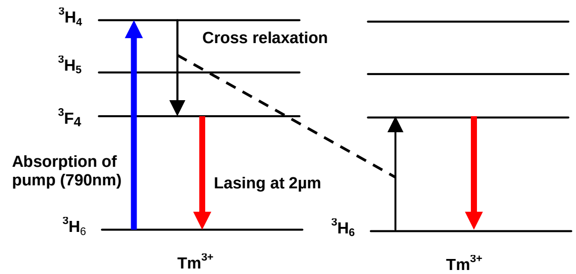

Fig. 3. Cross-relaxation mechanism between Tm^{3+}

Recently we demonstrated a monolithic 790nm-pumped Tm-doped laser producing >100W at 2050nm [8]. The wall-plug efficiency was 17% being largely limited by the efficiency of the bar source which had an E-O efficiency of only 31%. We believe that with development of single emitters at 790nm, we could demonstrate up to 25% wall-plug efficiency; twice that of currently available Er:Yb pumped systems.

Wavelength stabilization

Pump diode wavelength stabilization is common place for low-power telecommunications diodes. We are beginning to see similar technology becoming available for high power pump sources. For high power diodes, methods such as placing volume phase gratings in front of laser diodes [9] or writing Bragg gratings directly into the diode semiconductor substrate [10] are effective in both reducing emission spectral linewidth and reducing thermal wavelength shift.

The additional cost of wavelength stabilized diodes tends to exclude them from all but the most demanding applications. In the next section we show that with appropriate pump wavelength selection and thermal control, wavelength stabilization is not necessary.

Choosing bars or single emitters

There are a number of factors that influence the decision to choose either single emitters or fiber-coupled bars. In this section we discuss some of these deciding factors.

Brightness

The brightness achievable from fiber-coupled bars is generally much greater than single emitters. Using fiber-coupled bars we recently demonstrated 1kW pump power injected into one end of a monolithic fiber amplifier [11]. Six 180W 976nm diodes with

200µm 0.22NA fiber were chosen for their compatibility with the input legs of available high power tapered fiber bundle (TFB) coupler technology (Fig 4). The pump modules were spliced to the 6 input pump legs of the coupler using commercially available splicers, with typical measured splice losses of less than 0.1dB. It is important to note that significantly higher splice loss is measured when high amounts of cladding light are present in the diode delivery fiber.

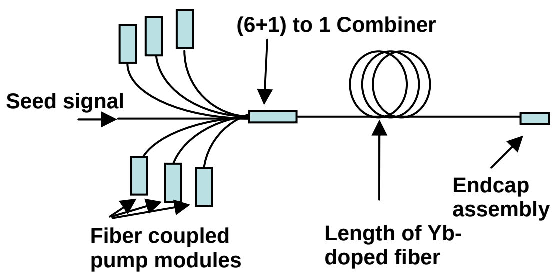

Fig. 4. 860W monolithic amplifier employing high brightness fiber-coupled bars

Of critical importance to the operation of the coupler approaching kW power levels is the pump insertion loss. In the coupler as tested, the typical pump losses are around ~0.05dB corresponding to around 10W of pump power dissipated within the coupler package.

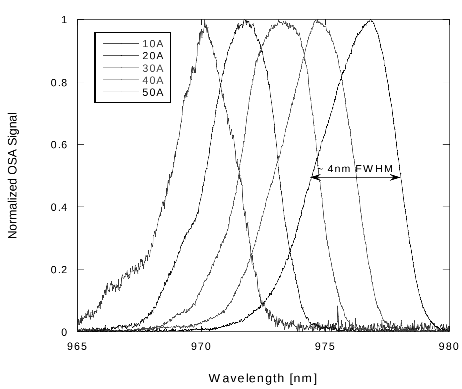

Fig. 5. Combined spectra of six 180W diode bars at various diode currents

Despite the strict water purity requirements of pump sources employing micro-channel cooled diodes, the benefits with respect to wavelength stability are shown here. Fig. 5 demonstrates their effectiveness in minimizing thermal wavelength shift. We observed that from just above threshold to full power (180W) the wavelength shift was only ~7nm which led to very constant pump absorption, evident from the highly linear slope efficiency as shown in Fig. 6. With a seed power of 4W, an output power of 860W with 85% slope was achieved.

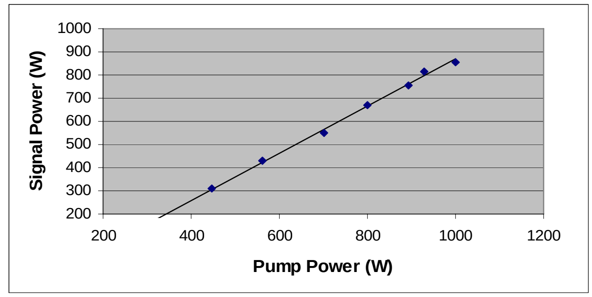

Fig. 6. Slope efficiency for amplifier

Efficiency

For applications where efficiency is of primary concern, single emitter diodes are usually chosen. Typically for single emitters we observe electrical to optical efficiencies ranging from 45~50%. Fiber-coupled bars on the other hand tend to operate with lower efficiencies, typically in the range of 30~35%. However with improvements to micro-optics and diode technology, products approaching 40% are becoming available.

Cooling and device reliability

Because of their higher efficiency and resulting reduced heat load, single emitters are much more preferable for air-cooled systems. Often single emitter diodes exceed predicted mean time to failure (MTTF) figures of 500khours. Fig. 7 below shows the degradation of a 200W Yb-doped MOPA device pumped by single emitters. After initial settling, the linear degradation rate at constant diode current was shown to be <5% per 10,000 hours.

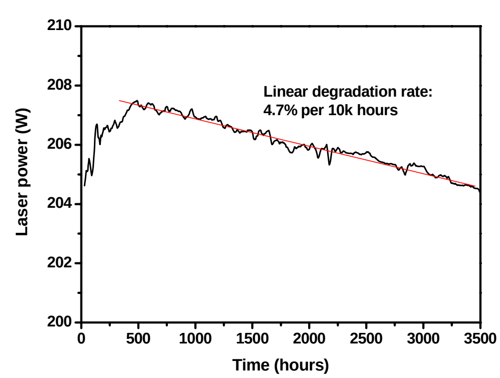

Fig. 7. 3500 hour life test data of single emitter pumped 200W Yb-doped MOPA system

Where water cooling is available, bars offer more simplified system design over single emitters. As we have shown in this paper, water cooling can achieve excellent thermal wavelength shift. In contrast, single emitters may exhibit as much as 20nm shift from threshold to full power [12].

Electrical drive requirements

For applications where fast modulation of the pump diodes is required, single emitters have a significant advantage over bar diodes. This is due to the fact that single emitter diodes may be connected in series to raise the effective dynamic resistance of the load rather than the parallel junctions of a bar.

To illustrate this, Fig. 8 below is representative of two sources; one is a fiber-coupled bar diode source and the other is an ensemble of 19 single emitter diodes. Both sources are 915nm, have a maximum output power of 110W and have similar brightness. The single emitter diodes are spliced to a tapered fiber bundle with a Ø200µm 0.48NA output fiber and the bar diode source has a Ø400µm 0.22NA delivery fiber.

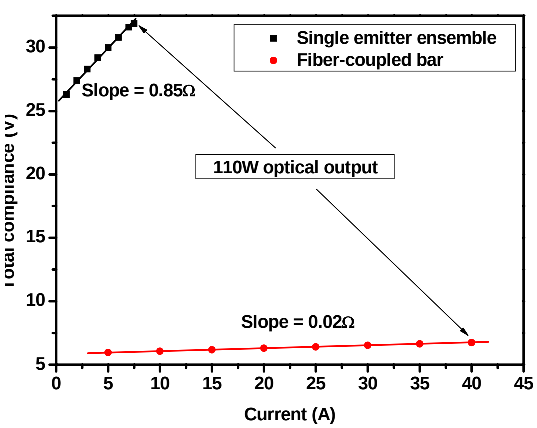

Fig. 8. Comparison of electrical drive requirements for two types of pump sources

By fitting straight lines to the plot we can see that the bar diode has approximately 40 times lower dynamic resistance than the single emitter source. This factor makes it very difficult to achieve fast modulation (microsecond regime) without sacrificing electrical efficiency. There are certainly commercially available high current bar diode drivers with modulation capabilities; for example the PCO-6130 from Directed Energy Inc. This device employs a hysteretic switch-mode DC-DC converter for high efficiency operation and a fast MOSFET load bypass-shunt to modulate the diodes. Unfortunately the unit is only able to hard switch the diodes on and off, not provide amplitude modulation as many applications may require.

Conversely, single emitter diodes may be driven via much more simple and compact Class-B amplifier circuitry. Fig. 9 shows the optical output from an ensemble of 18 diodes using a simple current feedback regulated Class-B circuit. This circuit provides rapid modulation with high stability and precise current control from threshold to full power.

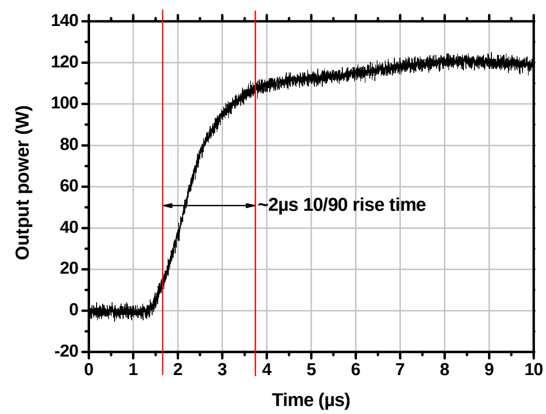

Fig. 9. Rise time from combined 18 single emitter ensemble

Diode protection

For laser diodes, catastrophic optical damage (COD) from excessive back-coupled light is a major concern. For fiber-coupled bars where bulk-optics are used, this problem is easily solved by inserting dichroic filters to block light other than the pump wavelength.

In the case of single emitter diodes, we understand that typical power levels for COD are ~250mW [13]. For CW systems this usually does not present a problem; however in pulsed systems care must be taken.

Let us consider the case presented in Fig. 10. Here we have an amplifier which is counter-pumped with 18 single emitter diodes via an (18+1)×1 TFB. For the system we assume that the splice from the active fiber to the combiner has 3% loss, that is 3% of the core light enters the cladding. Through the (18+1)×1 combiner, this light will be distributed approximately equally between each of the pump and signal fibers. Accounting for this cladding light and assuming a COD power of 250mW for the diodes we can conclude that the output of the amplifier can not exceed 158W. For CW applications this may be acceptable; however for a pulsed system producing kW+ pulses, the diodes are clearly going to fail.

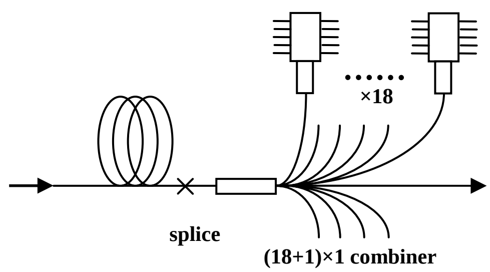

Fig 10. Monolithic amplifier counter-pumped using single emitters

One obvious design change to avoid this problem is to limit pumping to the co-propagating direction however this is often disadvantageous from the point of view of optical system performance. In-line optical filters may be inserted into the system however these devices add cost, complexity and construction time to the system. The absolute best place we see to protect the diodes is at the diodes themselves.

Price

Oftentimes the most pivotal factor in the choice between bars and single-emitters remains price. In dollars-per-watt, single emitters have consistently been cheaper than bars for many years. However this is not necessarily a fair comparison. Also taken into consideration must be the additional engineering and assembly time when incorporating single emitters into a system as well as the cost of components to combine multiple emitters into a single fiber.

To better illustrate this, let us examine a scenario where we are building a simple end-pumped laser with ~100W of pump, water-cooled. We will compare the two options outlined in the electrical drive requirements section of this report.

To fully utilize the brightness of the diode, we will often taper down the delivery fiber (usually 0.22NA) so it may be spliced to a smaller diameter 0.46NA double-clad fiber. Other than that, we simply connect the power supply and water lines. Furthermore, the use of connectorized delivery cables can offer advantages in many scenarios.

For the single emitters we must acquire a cold-plate then modify it to mount the diodes, wire all the diodes in series, acquire a combiner, splice the diodes, mount the combiner, manage the fibers and so forth. Neglecting engineering costs, taking into account the associated components, materials and labor, the user may need to factor in another 50% above the basic single emitters $/W figure for a realistic comparison.

Multi-emitter packages

One solution to realize the benefits of both bars and single emitters is to combine multiple single emitters within one package. In this case, the efficiency and electrical drive requirements of single emitters are retained. The higher brightness hence lower package count decreases coupling and assembly costs. The use of free-space optics provides an excellent opportunity to incorporate dichroic filtering for protection of the diodes.

Conclusions

The improvements in fiber laser performance over the last several years has largely been enabled by the increased power from high brightness, fiber coupled diode pumps. As this technology has matured, the $/watt cost of diode power for pumping fiber lasers has reduced which in turn has an impact on the cost of making fiber lasers. This trend is expected to continue to over the next years. In many applications when pumping fiber lasers with either single emitters or diode bars is possible, the choice often determined by a combination of the performance, reliability and cost requirements of the application. The extension of high brightness diode pump technology to efficient eyesafe fiber lasers is now starting to occur, with 790nm pumping of Tm- fiber lasers at 2µm making rapid progress.

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