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High Power Fiber Lasers: New Developments

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ABSTRACT

We assess different power limits of cladding-pumped fiber lasers. Despite recent advances in pump sources, these are still primarily limited by available pump power. We find that it should be possible to reach output powers beyond 1 kW in single-mode ytterbium doped fiber lasers. Experimentally, we have realized an ytterbium-doped fiber laser with 272 W of output power at 1080 nm, with an M^2-value of 3.2, as well as an erbium-ytterbium co-doped fiber laser with 103 W of output power at 1565 nm, with an M^2-value of 2.0. We believe these are the highest-power ytterbium and erbium-ytterbium fiber lasers ever reported.

Keywords: Fiber laser, power-scaling, diode-pumping, wavelength-tuning

1. INTRODUCTION

Cladding-pumped fiber technology has revolutionized fiber lasers over the last decade, increasing output power from less than 1 W with traditional core-pumping to well over 100 W [1], [2], [3]. Even 1 kW of power has been reached in multi-mode designs [4], when several devices have been arranged in series or in parallel. For output powers below 100 W, a few diode bars or multi-emitter laser diode assemblies are adequate pump sources. However, for powers beyond the 100 W level, diode stacks seem to be a better choice. The increasing availability of suitable diode stacks and the possibility of efficient fiber launch make them very attractive for pumping of high-power fiber lasers. At the same time, while fibers proved very reliable at powers up to ~100 W, it is clear that further power-scaling to the kW level with diode stack pumping requires significant fiber optimization in terms of fiber composition, pump coupling, and/or overall device layout. This is especially true when a single-mode output is required.

We will present recent work on high-power fiber lasers and amplifiers at University of Southampton and Southampton Photonics. We will cover work in the 1 and 1.5 μm spectral regimes with ytterbium-doped and erbium-ytterbium co-doped fibers, as well as power scaling via stack-pumping to several hundred watts of output power. We will also discuss relative advantages of fiber lasers compared to traditional bulk lasers, and highlight strengths of cladding-pumped fiber devices in areas such as broadband amplification, wavelength tuning, and operation at wavelengths where fiber lasers perform particularly well. We will also discuss narrow-linewidth devices, since nonlinear degradation arising from nonlinear effects such as stimulated Brillouin scattering is seen as a weakness of high-power, cladding-pumped, fiber sources.

2. THE CASE FOR HIGH-POWER CLADDING-PUMPED FIBERS AND STACK-PUMPING

Rare-earth (RE) doped fiber lasers were demonstrated as early as the 1960s [5], [6], [7]. Nevertheless, for many years they remained relatively obscure with performance far inferior to that offered by their "bulk" (i.e., non-waveguiding) counterparts like Nd:YAG lasers and gas lasers such as argon ion lasers. While bulk lasers can be lamp pumped or pumped by electrical discharges, it is essential to use laser sources for pumping of rare-earth doped fibers. However, at the time, laser pump sources were generally large, costly, and inefficient, and rare earth doped fiber devices offered no compelling benefits that outweighed the disadvantages of laser pumping. This changed in the mid 1980s, with the realization of rare-earth doped single-mode high silica fibers with low loss [8], [9], [10]. A single-mode core ensures robust single-mode operation, which is necessary for many applications. Furthermore, the tight beam confinement of a single-mode fiber leads to low laser thresholds, even though glass hosts (normally used for fibers) intrinsically have higher laser thresholds than crystal hosts (normally used for bulk lasers). RE-doped single-mode fibers constitute a glass gain medium with which low-threshold lasers, and high gain amplifiers (with a high gain efficiency) can be realized relatively easily. The transitions in glass are spectrally much broader than they are in crystals, which is important for broadband amplification, tunable lasers, and for short pulses. Crucially, high gain can be reached even in three-level systems with pump powers as low as a few milliwatts. A low propagation loss is important since it allows for devices many meters long, and thus for fibers doped sufficiently lightly for concentration quenching to be avoided.

These advantages of rare-earth doped fibers enabled the erbium-doped fiber amplifier (EDFA) [11], which can be used in optical communication systems. The EDFA has been a most compelling reason for the further development of rare earth doped fiber technology as well as of single-mode laser diodes at 980 and 1480 nm, for use as compact, low cost, and efficient laser pump sources.

While it is easy to reach, say, 40 dB of gain in an EDFA, bulk devices are not appropriate for high-gain broad-band amplifiers. Especially in case of a rare-earth doped glass amplifier, their large beam size leads to a low gain efficiency, and the short length essentially rules out a high gain. For example, in an erbium-doped glass it is difficult to reach more than 1 dB gain per centimeter. A crystalline amplifier is more efficient and allows for higher gain, but with a narrow bandwidth. In addition, in a bulk amplifier a large number of modes would see the high gain, leading to large amounts of undesired amplified spontaneous emission and making it difficult to ensure single-mode operation.

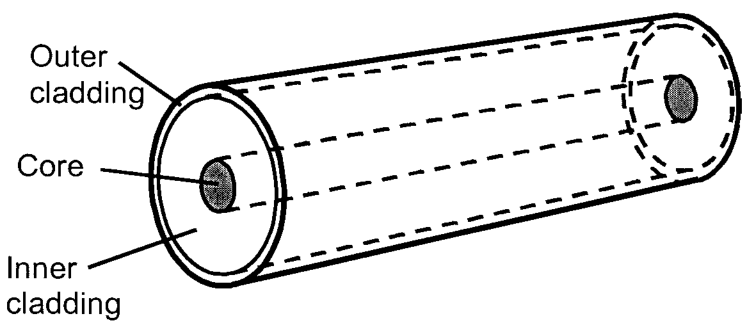

Figure 1. Schematic drawing of double-clad fiber.

The considerations for high-power devices are partly quite different from those for high gain and low power devices such as the EDFA. The very low threshold and high gain efficiency possible with a single-mode core are important features for low-power devices, but less important at higher powers. On the contrary, a small single-mode core is a serious obstacle to power-scaling of fiber lasers. Initially, fiber lasers as well as EDFAs were simple structures with a single core for guiding both the signal and the pump light, implying that single-mode pump diodes must be used. The limited power of single-mode diode pump sources has then limited the output powers to ~1 W. Consequently, cladding-pumping has been developed as a method to overcome this limitation [12]. Cladding-pumped fiber lasers do not require single-mode pump sources, but can still produce a single-moded laser output. In this case, a fiber that guides light in the inner cladding, typically a so-called double-clad fiber (DCF), must be used. See Fig. 1. A DCF has a primary waveguide (the core) for guiding the signal, surrounded by a lower-index inner cladding. Both of these are made from glass. The inner cladding also forms the core for a secondary waveguide that guides the pump light. The inner cladding is surrounded by an outer cladding of lower refractive index polymer or glass to facilitate waveguiding. In either case, the fiber may have a further layer of polymer for protection. Typically, the fiber is rare-earth doped throughout the core, while the inner cladding is undoped. The core is located within the inner cladding and forms a part of the pump waveguide, so pump light propagating in the pump waveguide reaches the core and excites the laser-active rare-earth ions. Since the gain medium is still a rare-earth doped glass, the gain remains spectrally broad, allowing for broadband amplification and wavelength tuning.

With a sufficiently thick inner cladding, it is at least in principle possible to launch arbitrarily large amounts of pump power into a double-clad fiber. This would mean that the usable pump power is only limited by the power delivered by the pump sources at hand. However there are many disadvantages with a thick inner cladding, and in practice a limited inner cladding diameter will restrict the amount of pump power that can be launched. The launched pump power obviously limits the output power from the fiber laser, and is therefore of principal importance for high-power operation. Power handling and power conversion efficiency are other important factors. By contrast, the threshold is quite low for high-power fiber lasers, and therefore normally insignificant. We will next discuss these limitations, in order to estimate the power limit of a cladding-pumped fiber laser.

We start with the pump power that can be launched into a fiber. We assume here a simple end-pumped configuration. Various alternatives for side-pumping exist, with the pump light propagating either along the core or perpendicular to it. These may allow for more pump power to be launched, but only insofar as thicker or longer fiber arrangements can be used.

To reach the power limit of doped fibers will require kilowatt class pump sources. Diode stacks seem most suitable at such power level. At Southampton we have state-of-the art diode stack sources capable of delivering approximately 0.4 kW of pump power into a 0.4 mm diameter inner cladding at an NA of ~0.3. With a thicker inner cladding and a higher NA, we will be able to launch more pump power (with a higher-power pump source). Inner cladding diameters of up to 1 mm may be feasible, but fibers thicker than that rapidly become difficult to manage. With a 2.5 times thicker inner cladding, we would be able to launch roughly 2.5 kW of pump power with an appropriate pump source of similar brightness. It may be possible to increase the NA somewhat, but on the other hand, higher-power pump sources are normally less bright than lower-power ones, offsetting the benefits of a higher NA. Thus, we take 2.5 kW as the maximum pump power that currently can be launched through the end of a double-clad fiber. Note though that this power will increase as brighter pump diodes become available in the future.

Once the pump power has been launched, the fiber has to efficiently convert it into usable laser output. Neodymium and ytterbium are the most efficient fiber dopants for which high-power diode stack pump sources are available, for Nd at ~808 nm and for Yb at 910 – 980 nm. High-power Nd-doped and Yb-doped fiber lasers both emit at around 1060 nm, with relatively large variations in wavelengths depending on device configuration and host composition. Neodymium's 1060 nm transition is a four-level system, which means that the threshold can be insignificant and that low-brightness pumping can be used. This is utilized in fiber embedded lasers, in which a large pump cavity allows for simple, high-power, but relatively low-brightness pumping. Three Nd-doped fiber embedded lasers were recently combined for a total output power of over 1 kW [4]. However, because the pump cavity is quite large, the doped volume must also be large in order to absorb the pump, especially since self-quenching limits the maximum allowable concentration of neodymium. Unfortunately it is difficult to achieve single-mode operation in a long, large-diameter, core. By contrast, ytterbium is a quasi-four level system at 1060 nm, with significant reabsorption. Therefore, a high pump intensity must be used to excite a sufficient fraction of the Yb-ions. This also means that it becomes easier to absorb the pump, allowing for a smaller core, especially since Yb can be used at higher concentrations than Nd. In addition, an ytterbium-doped fiber laser (YDFL) can be more efficient than a neodymium-doped fiber laser (NDFL). Thus, YDFLs look more attractive than NDFLs, at least when a high-brightness output is needed. Diffraction-limited or nearly diffraction-limited YDFLs with well over 100 W output power have been reported [1], [3]. We regularly attain 80% power conversion efficiencies in our Yb-doped fiber lasers, suggesting that 2 kW and 4 kW of output power would be possible with 2.5 kW of pump power launched in one or both ends of the fiber.

It is far from obvious that a fiber can handle such high power without failing. While powers of over a kilowatt have been reported, this was in heavily multimode designs with large cores. A single-mode realization is much more challenging, because of the higher power densities involved and the risk for optical damage. Certainly, one should not strive for a small core, but for a large core that can still operate on a single mode. We have demonstrated previously a Q-switched YDFL with 2.3 mJ pulses with 10 kW of peak power, corresponding to a power density of 6.5 W/μm^2 (650 MW/cm^2) [13], as well as a holey fiber Raman laser with a cw power density (of the pump) of 2 W/μm^2 [14] without reaching the damage threshold. These values can be compared to the damage threshold of bulk silica of ~20 W/μm^2. Though a cw YDFL is likely to have a damage threshold lower than the pure silica and pulsed peak power values, we estimate a cw damage threshold of ~1 W/μm^2 for our rare-earth doped fibers, or possibly a few times more. Special fiber terminations such as end-caps may have to be used to reach such damage threshold [15]. Still, a drawback of the end-pumping scheme is that the optical power densities and heat generation peak at the pump launch end. Schemes that use distributed injection of the pump power into the doped fiber, and leave the ends of the doped fiber free to be terminated in a damage resistant manner, are preferable from this point of view. The GTWave fiber is an example of such a scheme [16]. We also note that recently demonstrated cladding-pumped Raman fiber lasers [17] can be fabricated with a pure silica core, likely to have a higher damage threshold than an ytterbium-doped one.

With a cw damage threshold of ~1 W/μm^2, a kW class fiber laser will require a core area of ~1000 μm^2 or more. Such a core will not be intrinsically single-moded at ytterbium wavelengths. However, there are several ways of achieving single-mode operation of a multi-mode core, e.g., with a mode-selecting taper [18] or with selective excitation of the fundamental mode. For example, stable spatial fundamental mode operation has been demonstrated in a 50 μm core fiber amplifier [19], i.e., with a core area of 2000 μm^2. Thus, though these estimates are relatively uncertain, they do suggest that a multi-kW single-mode fiber laser is viable.

Besides optical damage, heat generation can also destroy an optical fiber, via thermal damage of the coating, fracture, or even melting of the core. However YDFLs are exceptionally good in terms of thermal management for two reasons: The high efficiency means that the fraction of absorbed pump power that is converted into heat can be less than 15%. Thus, the heat generation in the fiber will be approximately 150 W per kilowatt of output power. Furthermore, the fiber geometry means that heating can be distributed over a long length, and because of the proximity of the heat-generating core to the fiber surface, heat-sinking can be quite efficient. Brown and Hoffmann have evaluated fracture limits in optical fibers to over 0.1 kW/cm of generated heat [20], which is orders of magnitude larger than the heat that will be generated in kW-class fiber lasers. Thermal damage of the coating as well as melting of the core can occur at lower power levels, but can be mitigated by a suitable heat-sinking arrangement, as well as by using long fibers with low levels of power conversion per unit length. In practice, we have operated erbium-ytterbium co-doped fiber lasers that generated approximately 100 W of heat per meter [21].

The fiber geometry is then quite good from a thermal point of view. Furthermore, the ability to maintain a tight pump confinement, given by the spot size that the pump beam can be focused to at the relatively high inner-cladding NA, means that the threshold is relatively low, typically a few watts. Thus, the elongated geometry, as well as the benefits of pump and signal waveguiding, are key advantages of cladding-pumped fiber lasers for high power operation. The high pump intensity also enables operation of systems with high ground-state absorption, such as ytterbium's two-level transition at ~980 nm [22], albeit with significantly lower output power than at the quasi-four level transition at ~1060 nm. Besides, a glass host brings advantages in terms of wide wavelength tunability and access to different wavelengths in general. For example, for high-power operation in the "eyesafe" 1550 nm wavelength regime, erbium-ytterbium co-doping is often used, but this only work well in glasses.

There is a large variety of different high-power bulk lasers, with different gain media, cavity configurations, and pumping schemes. Ytterbium-doped crystal lasers [23] (e.g., Yb:YAG) are emerging as the preferred choice for high-power bulk solid state lasers. Thermal issues are critical for these lasers, and therefore, crystals, with superior thermal properties, are favored over glass hosts. Though Yb:YAG lasers with many kilowatts of output powers have been demonstrated, the non-waveguiding nature and large thermal gradients lead to aberrated thermal lensing and, therefore, a poor beam quality at high powers. Single-mode lasers operate at significantly lower powers. Compared to fiber lasers, the efficiency of Yb:YAG lasers is lower (but still quite good). Furthermore, the absence of tight waveguiding of the pump leads to a pump beam size that is significantly larger than in a fiber laser, and the larger signal beam implies that a larger number of ions need to be excited to reach sufficient gain than with a fiber laser. This leads to high thresholds that may well exceed 100 W even in quasi-four level systems such as Yb:YAG at ~1040 nm.

Because of the high efficiency and the beneficial effects of a waveguiding core on beam quality, high-power cladding-pumped fiber lasers seem likely to surpass bulk lasers in many areas, not least those for which a glass host brings particular advantages. However, the fiber geometry does have drawbacks: The tight signal confinement restricts energy storage to, say, values of the order of 10 mJ, while some pulsed laser applications require higher pulse energy than that. Furthermore, the tight signal beam confinement, together with the long length and high powers, means that well-known fiber nonlinearities such as stimulated Raman scattering, stimulated Brillouin scattering (for narrow-linewidth beams), and self-phase modulation (for pulsed light) occur quite readily in cladding-pumped fibers. For example, at a wavelength of 1 μm with an effective spot area of 100 μm^2, we get a Raman gain of 4×10^{-3} dB/m/W, a Brillouin gain of 2 dB/m/W, and a nonlinear phase shift of 2×10^{-3} rad/m/W. Nonlinear effects in fibers are further discussed in ref. [24]. Still, exciting results on the amplification of single-frequency beams in Yb-doped fiber amplifiers have recently been published [25]. An output power of 20 W has been achieved experimentally in a nearly diffraction-limited beam, from a 9 m fiber with a 30 μm diameter core [25]. This power was limited by available pump power, while the SBS limit was estimated to ~100 W. With shorter fibers, as should be possible with higher pump absorption (e.g., with 975 nm pumping instead of the 915 nm pumping used in ref. 25), the SBS limit would be several hundred watts, ultimately limited by attainable pump absorption, thermal limits, and the core size. In the past, we fabricated fibers with similar area ratios with peak absorption at ~975 nm of 12 dB/m, resulting in device lengths of 1.5 m [21]. This was an erbium-ytterbium co-doped fiber, but can equally well be realized without erbium, for operation at ~1060 nm. Thus, we believe that with appropriate fiber design, with a large, highly doped, core for a high pump absorption, SBS thresholds will be well above 100 W.

3. RESULTS

The case for cladding-pumped high-power fiber lasers is quite strong, made even stronger by recent results, enabled by developments in fiber and diode pump technology. We will next review some of our recent high-power results with ytterbium doped fibers operating at ~1060 nm [26] and erbium-ytterbium doped fibers operating at ~1550 nm [21], [27], as well as results on tunable fiber lasers [28].

Ytterbium-doped fiber laser

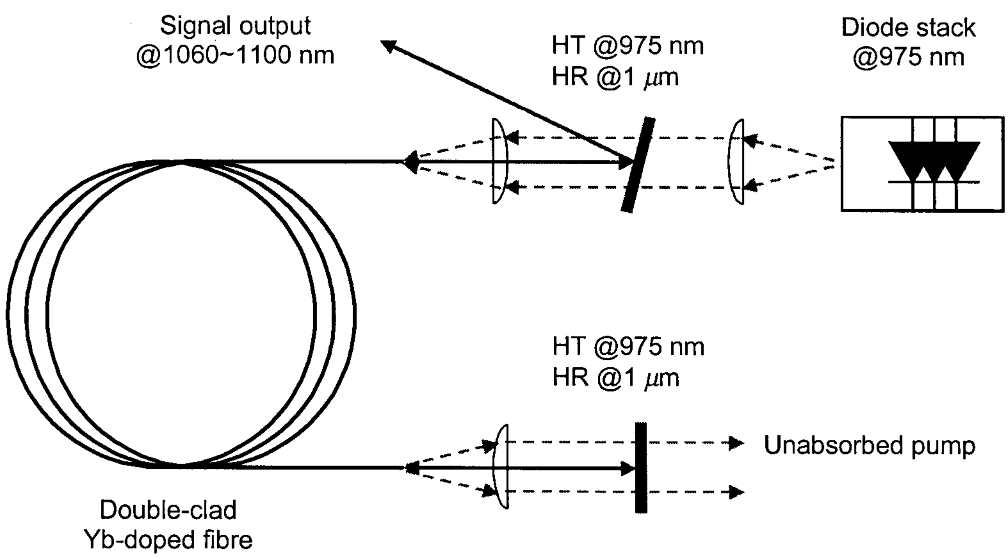

Figure 2. Yb-doped fiber laser arrangement comprising a diode-stack pump source. HR: high reflectivity, HT: high transmission.

Ytterbium-doping is attractive for high-power cladding-pumped fiber lasers because of the high efficiency and high pump absorption that are possible. Figure 2 shows our setup for high-power YDFLs. Our pump source is a beam-shaped diode-laser stack at 975 nm, coupled into the double-clad Yb-doped fiber through a combination of lenses. We set up an YDFL made with a fiber fabricated at the University of Southampton. The fiber was 5 m long and had 30 μm diameter Yb-doped core. The D-shaped inner cladding had a 375 μm diameter, and was coated with a low-refractive-index polymer outer cladding for a nominal inner-cladding NA of 0.48. The small-signal absorption at the pump wavelength was 3 – 4 dB in a 1 m long piece of fiber. The pump launch efficiency was more than 85%. A laser cavity was formed between a perpendicularly cleaved, 4% reflecting, facet in the pump launch end of the fiber and an external, high-reflecting mirror in the other end. The laser output was taken through the pump launch end. A dichroic mirror separated the output beam from the pump beam (Fig. 2).

The laser output power characteristics is shown in Fig. 3, together with an output spectrum [26]. The maximum laser output power was 272 W and the slope efficiency with respect to absorbed pump power was 85%. The laser spectrum was centered at ~1080 nm, and extended from 1070 nm to 1100 nm. The output power increased linearly with output power. There was no evidence of a power limit from nonlinear scattering or any other undesired effect. The fiber is multi-moded and no attempts were made to operate the laser on a single mode. We measured the beam quality factor (M^2) to 3.2.

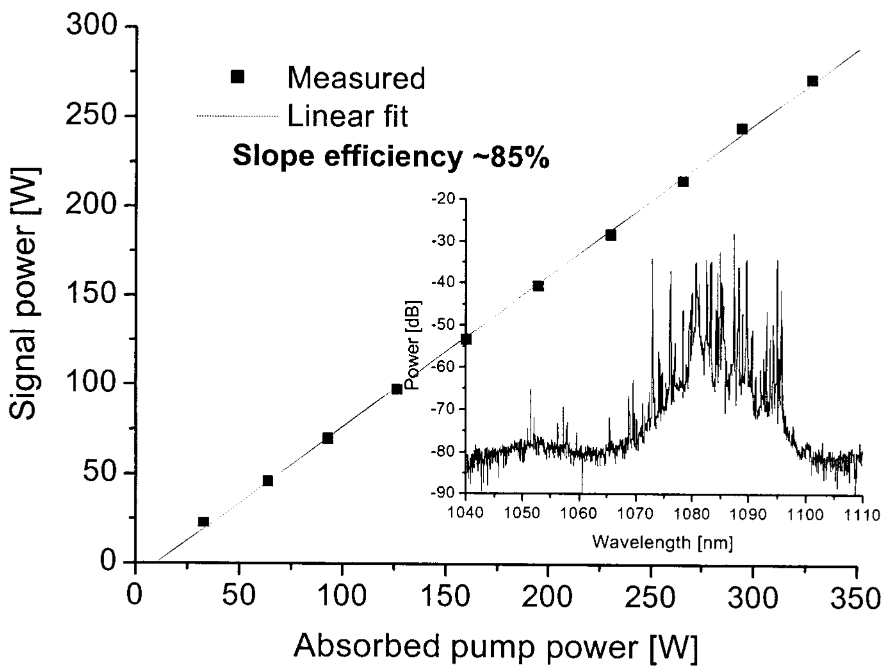

Figure 3. Output power characteristics of ytterbium-doped fiber laser. Inset: laser output spectrum.

Erbium-ytterbium co-doped fiber laser

The attraction of erbium-ytterbium co-doped fibers is their unsurpassed performance in the important, "eye-safe", 1550 nm wavelength region. In an erbium-ytterbium co-doped fiber, pump photons are initially absorbed by Yb-ions. Then, the energy is transferred nonradiatively from excited Yb-ions to Er-ions, resulting in de-excitation of the Yb-ions and excitation of the Er-ions. Ytterbium has a larger absorption cross-section than erbium, as well as a much broader absorption band, from 910 to 980 nm. Furthermore, Yb can be incorporated in much higher concentrations than Er, thanks to its relative immunity to self-quenching. In total, this means that a fully adequate pump absorption of several dB/m can be reached, even in fibers with a large inner cladding-to-core area ratio.

We set up an erbium-ytterbium co-doped fiber laser (EYDFL), very similar to the YDFL in Fig. 2, based on a fiber fabricated in house. The fiber was 5 m long and had 25 μm diameter erbium-ytterbium co-doped core. The D-shaped inner cladding had a 400 μm diameter, and was coated with a low-refractive-index polymer outer cladding for a nominal inner-cladding NA of 0.48. We were able to launch up to 340 W of pump power into the fiber, of which 295 W was absorbed. Thus, the operating pump absorption was ~87% or 9 dB. Also for the EYDFL, a laser cavity was formed between a perpendicularly cleaved, 4% reflecting, facet in the pump launch end of the fiber and an external, high-reflecting mirror in the other end. The laser output was taken through the pump launch end, and a dichroic mirror separated the output beam from the pump beam.

The laser output power characteristics is shown in Fig. 4, together with an output spectrum [27]. The maximum laser output power was 103 W at 1565 nm, with an M^2-value of 2.0. The slope efficiency was ~40% for low powers, with respect to launched pump power, and close to 50% with respect to absorbed pump power. There is a roll-off at higher powers, caused by ytterbium-lasing at ~1060 nm, as the ytterbium-excitation increases at high pump levels. We estimate the heat generation to over 100 W/m near the pump launch end at maximum pump power.

We believe that the parasitic ytterbium-lasing can be suppressed, for an increased slope efficiency at ~1560 nm. In Fig. 4, the threshold for ytterbium lasing is approximately 70 W, at which point the 1565 nm power is ~25 W. However, we have operated EYDFLs that are similar except for having thinner core and inner cladding, at higher power densities without seeing parasitic Yb-lasing. A 4 m long fiber with a 12 μm diameter core and a 125 μm diameter inner cladding generated 17 W of output power at 1560 nm with a pump power of 44 W at 915 nm, without any Yb co-lasing, and without any roll-off of the 1560 nm power [21]. If these values are scaled to a larger core size, they suggest that 1560 nm output powers of 70 W should be possible with a 25 μm core without any Yb co-lasing or roll-off.

Our results underline the impressive power capacity of erbium-ytterbium co-doped fibers, and of doped fibers in general. Though the efficiency and output power are much lower than with an YDFL, there are few, if any, high-power lasers that can compete with an EYDFL in this spectral regime.

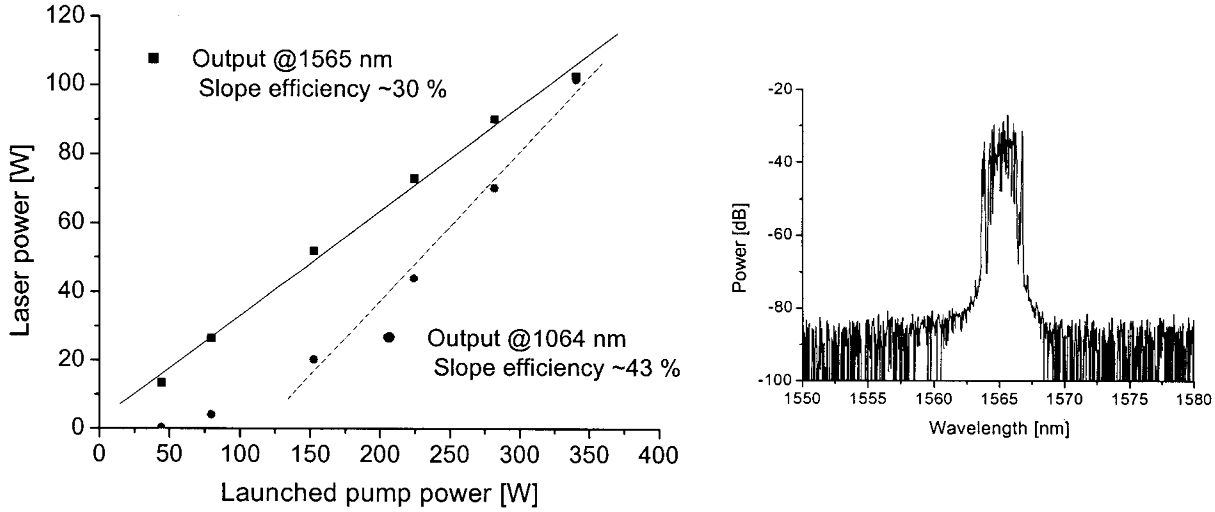

Figure 4. Output power characteristics of erbium-ytterbium co-doped fiber laser at ~1565 as well as ~1064 nm. Right: laser output spectrum at ~1565 nm.

Tunable fiber lasers

Wavelength-tunable rare-earth doped fiber lasers are attractive because of the high efficiency of rare-earth doped gain media and the broad emission linewidths in glass hosts. We have studied wavelength-tunable fiber lasers for several years. Figure 5 summarizes our results [28]. Though these investigations were performed with lower-power pumping, we expect that the benefits of new higher-power pump sources and improved fibers will have full impact on the performance of tunable fiber lasers, resulting in higher pump powers and also extended tuning ranges.

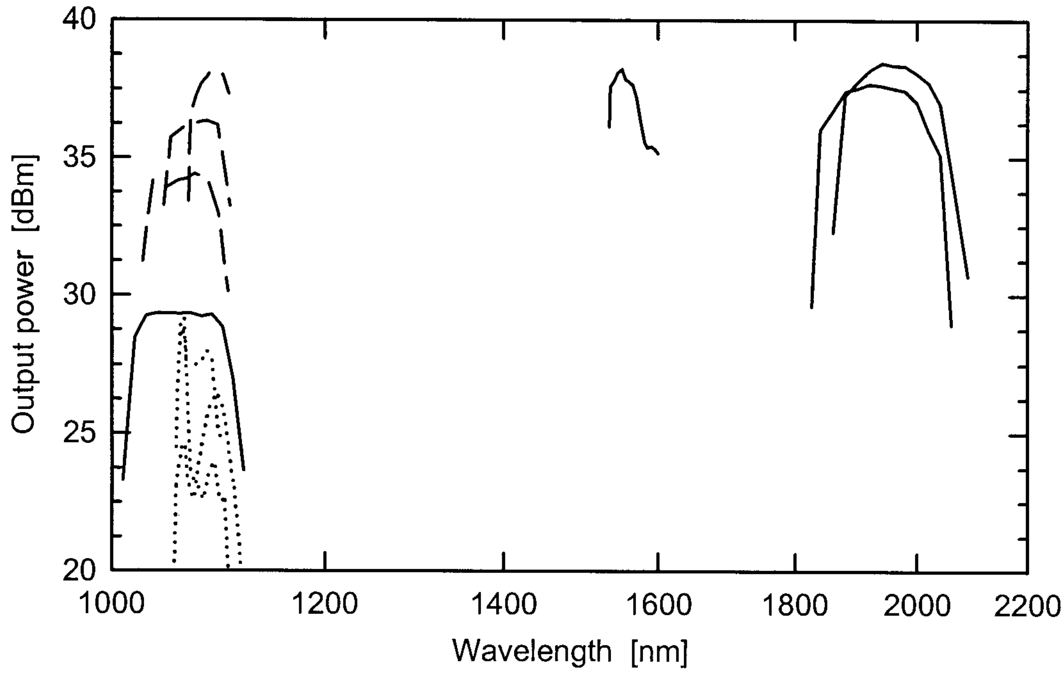

Figure 5. Tuning ranges of different cladding-pumped fiber lasers (logarithmic wavelength scale). The curves at ~2 μm are for a Tm-doped fiber of two different lengths, and the curve at ~1550 nm is for a Er-Yb co-doped fiber. At ~1 μm, the three dashed curves on top are for three different lengths of a Yb-doped fiber, the solid curve is for a Yb-doped fiber with a small inner cladding area, and the three dotted curves are for three different Nd-doped fibers.

4. CONCLUSIONS

We have analyzed the power-limit of end-pumped fiber lasers and estimate that it should be possible to reach output powers beyond 1 kW in single-mode ytterbium doped fiber lasers. Though nonlinear degradation may be a problem for some applications, the thermal properties of fibers and short fiber lengths possible with high concentration, large core, and high-brightness pumping suggest that the limits are quite high and have not been reached yet in general.

Experimentally, we have realized an ytterbium-doped fiber laser with 272 W of output power at 1080 nm, with an M^2-value of 3.2, as well as an erbium-ytterbium co-doped fiber laser with 103 W of output power at 1565 nm, with an M^2-value of 2.0. We believe these are the highest-power ytterbium and erbium-ytterbium fiber lasers ever reported. Ytterbium-doped fiber lasers are most efficient of all rare-earth doped fiber lasers, and erbium-ytterbium co-doped fiber lasers are the most efficient type of high-power laser of any kind operating in the in the "eye-safe" wavelength region at around 1550 nm.

Despite the rapid improvements of the output power of high-power fiber lasers, evidenced by these and other results, it is still limited by the available pump power. Single-mode fiber lasers with 1 kW of output power are not fundamentally beyond the fiber technology of today, and with appropriate fiber designs such lasers will be realized as soon as appropriate pump sources become available. We expect the rapid improvements to continue, and spread to more refined fiber lasers such as single-polarization, narrow-linewidth, wavelength-tunable, and pulsed sources. We believe that fiber lasers are leading candidates for various high-power applications, and will be chosen over bulk lasers, not least when the broad linewidths of glass hosts are advantageous.

5. ACKNOWLEDGEMENTS

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