High-Power and Tunable Operation of Erbium-Ytterbium Co-Doped Cladding-Pumped Fiber Lasers

Johan Nilsson, Shaif-Ul Alam, Jose A. Alvarez-Chavez, Paul W. Turner, W. Andrew Clarkson, and Anatoly B. Grudinin

***Abstract*—We describe erbium-ytterbium co-doped fiber lasers in different free-running and tunable configurations. The lasers were cladding-pumped by high-power multimode diode sources. We compare pumping at 915 and 980 nm. With a free-running laser, we obtained slope efficiencies of up to 50% with 915-nm pumping and 38% with 980-nm pumping, with respect to absorbed pump power. We reached a double-ended output power of 16.8 W from the free-running laser. Thanks to a high rare-earth concentration and a small inner cladding area (possible with the high-brightness pump sources we used), the operating pump absorption of the fiber reached 8 dB/m. With such high absorption, short fibers with high nonlinear thresholds are possible even with cladding pumping. The tunable fiber laser had a tuning range from 1533 to 1600 nm and emitted 6.7 W of output power at 1550 nm in a high-brightness, single-polarization, narrow linewidth beam.**

***Index Terms*—Double-clad fiber, erbium, fiber laser, laser tuning, ytterbium.**

I. Introduction

CLADDING-PUMPED fiber lasers offer a unique combination of high power, high efficiency, compactness, simple service-free operation, and high reliability. The shape of an optical fiber laser reduces the thermal loading density and is good for heat-sinking. Optical waveguiding further safeguards against thermal distortion of the lasing field even at high powers. For these reasons, fiber lasers can be power-scaled without the reduction of efficiency and brightness that are common problems for conventional "bulk" lasers. To date, output powers of well over 100 W in nearly diffraction-limited beams and 1 kW in multimode beams have been reported from ytterbium- and neodymium-doped fiber lasers at wavelengths of around 1.1 μm [1]–[4]. While ytterbium- and neodymium-doped fiber lasers are attractive because of their efficiency, emission in other wavelength regions requires other dopants. For the important wavelength range around 1.55 μm, there are erbium-ytterbium co-doped fiber lasers (EYDFLs) and amplifiers (EYDFAs). For cladding pumping, the absorption of erbium is impractically low. Therefore, ytterbium is added to absorb the pump. The pump energy is transferred nonradiatively from Yb^{3+}-ions to Er^{3+}-ions, which then emit around 1.55 μm [5]. Cladding-pumped EYDFLs and EYDFAs have both attracted considerable attention, though mostly at modest power levels, typically a few watts or less in line with the requirements of optical communications and other applications [6]–[18]. However, EYDFLs and EYDFAs can deliver more power than that, making them useful, e.g., for applications like LIDAR as well as applications in medicine that benefit from the relatively eye-safe nature of 1.55-μm light. The commercial appearance of EYDFAs with up to 20 W of output power underlines the significance of these devices [19]. The use of such amplifiers in pulse amplification and wavelength conversion schemes has recently been reported [20], [21]. Still, though high-power cladding-pumped EYDFL and EYDFAs have been with us for several years now, and despite their significance, experimental details remain scarce in the literature.

In this paper, we present experimental data on high-power cladding-pumped EYDFLs in different configurations. With a free-running laser, we reached 16.8 W of double-sided output power. With an external grating, the EYDFL was tunable from 1535 to 1600 nm, with a maximum output power of 6.7 W at 1550 nm and with a linewidth of 0.25 nm. We studied the influence of fiber length and found the EYDFL to be efficient for fibers as short as 1.4 m. We compared pumping at 915 and 980 nm, which are preferred pump wavelengths. The slope efficiency was up to 50% with 915-nm pumping and 38% with 980-nm pumping, both with respect to absorbed pump power.

II. Experimental Setup

Our erbium-ytterbium co-doped fiber (EYDF) was a conventional double-clad fiber, with a core for guiding the lasing light centered in a circular inner cladding that also served as a waveguide for the pump light. The fiber was made in-house with the standard MCVD and solution-doping technique. The core consisted of a phosphosilicate glass activated with Er^{3+} and Yb^{3+}. It had a diameter of 12 μm and a numerical aperture of 0.175, resulting in a calculated cutoff wavelength of 2.7 μm with five modes supported at 1550 nm. However, if the core NA is reduced to ~0.1, the core would become strictly single-moded at 1550 nm. The inner cladding was made of pure silica and had

Manuscript received December 2, 2002.

J. Nilsson, W. A. Clarkson, and A.B. Grudinin are with the Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, U.K. (e-mail: jn@orc.soton.ac.uk).

S.-U. Alam and P. W. Turner are with Southampton Photonics, Chilworth Science Park, Southampton SO16 7NS, U.K.

J. A. Alvarez-Chavez was with Xtera Communications, Inc., Allen, TX 75013 USA. He is now with Southampton Photonics, Chilworth Science Park, Southampton SO16 7NS, U.K.

Digital Object Identifier 10.1109/JQE.2003.814373

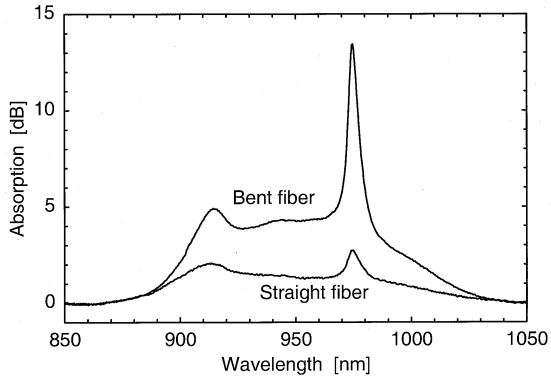

Fig. 1. Absorption spectra of a 1-m-long piece of our EYDF. The curve with the low absorption was measured without any sharp bends on the fiber. The curve with the high absorption was measured with the fiber bent to a figure-eight shape.

a diameter of 125 μm. It was coated by a low-index UV-curable polymer outer cladding that provided a nominal numerical aperture of 0.48 for light in the inner cladding. Our fabrication process for EYDFs is described in [22].

From a large number of EYDFs fabricated in house, we selected a fiber with large pump absorption for the experiments described here. The high pump absorption allowed for a good efficiency for fibers as short as 1.4–2 m, even in this cladding-pumped configuration. Short fibers are attractive for mitigating various nonlinear effects, such as stimulated Brillouin scattering. We measured the absorption in a 1-m-long piece of fiber and found it to be ~2.7 dB at the absorption peak at around 975 nm and ~2.0 dB at 915 nm. It was measured with a white light source that filled the NA and the aperture of the inner cladding. We further measured the erbium core absorption at the 1535-nm peak to 60 dB/m. The pump beam in an actual EYDFL is typically launched under different conditions, which modifies the absorption somewhat. Much more important, though, is that different pump modes (of the inner cladding) are absorbed at different rates. In a double-clad fiber with a rare-earth doped core centered in a circular inner cladding, a large number of pump modes have a poor overlap with the core. The absorption of such pump modes will be poor. For efficient absorption of all pump light, we need to scramble the pump modes somehow, especially when working with short fibers for which mode-scrambling would otherwise be negligible. See [23]. In our laser experiments, we did scramble the modes by bending the fiber into a figure-eight. However, in each end approximately 0.2 m of the fiber remained essentially straight. This reduced the overall mode-scrambling, and thus the total pump absorption, especially with short fibers. Fig. 1 illustrates the absorption spectra, measured with and without bending the fiber to a figure-eight. By bending the fiber, we increased the small-signal absorption of the 1-m-long fiber to 4.9 dB at 915 nm and to 13.4 dB/m at the 975-nm peak. Still, for Yb^{3+} in phosphosilicate, the peak absorption at ~975 nm is typically more than five times larger than the absorption at 915 nm, which would be even more than in Fig. 1. In a fiber with a core centered in a circular inner cladding, some modes overlap significantly with the core, and are almost completely absorbed over 1 m, at both 975 and 915 nm. However, most of the transmitted power propagates in the modes with poor overlap with the core. These modes are only weakly absorbed in 1 m of fiber, at 975 nm as well as at 915 nm. The overall effect of having strong absorption of some modes and weak absorption of other modes is to reduce the difference in absorption at different wavelengths. If this effect could be eliminated, the 975-nm absorption could be still higher. Noncircular fiber cross-sectional geometries reduce the number of modes with poor overlap with the core [23], [24]. In a noncircular fiber, we believe that the 975-nm pump absorption may exceed 20 dB/m with the same core and a similarly sized inner cladding as in the fiber we used.

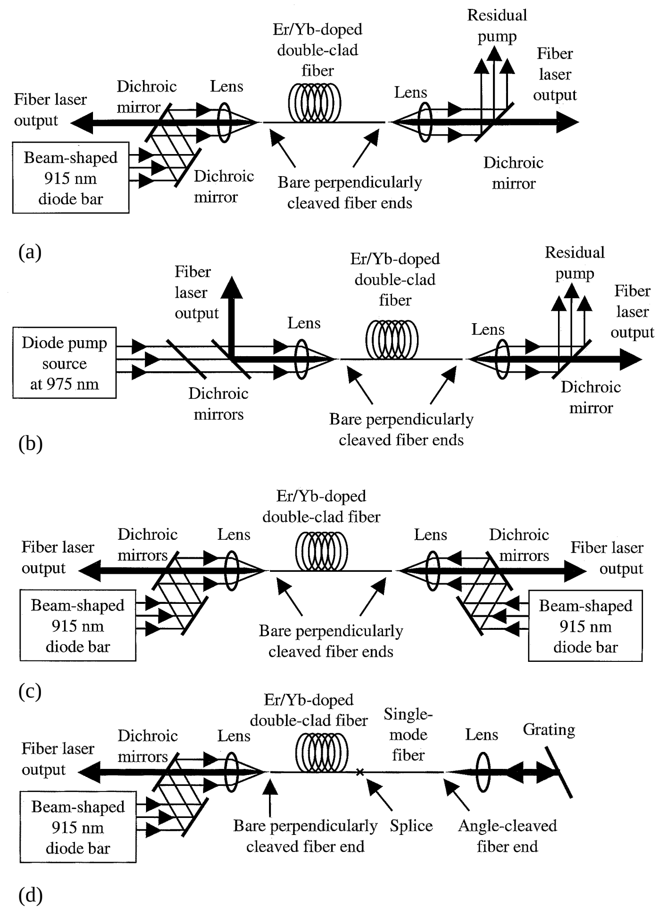

Fig. 2. Experimental setup. (a) Free-running laser pumped by single beam-shaped 915-nm diode bar. (b) Free-running laser pumped by 980-nm diode source. (c) Free-running laser pumped in opposite ends by two beam-shaped 915-nm diode bars. (d) Tunable laser pumped by single beam-shaped 915-nm diode bar.

From the absorption measurements, we estimate the Yb-concentration to 2% by weight and the Er-concentration to 0.2% by weight.

The experimental setup we used for the free-running laser is shown in Fig. 2. Slightly different configurations were used, with either single-ended pumping at 980 nm or with single- or double-ended pumping at 915 nm. For single-ended 915-nm pumping, we used a diode bar from Optopower and a two-mirror beam-shaper to equalize the beam propagation parameters in orthogonal directions [25]. The pump beam was launched via two dichroic mirrors and a gradient-index lens with a 25-mm focal length into the EYDF. The lens was broadband AR-coated.

The fiber was perpendicularly cleaved in both ends. The 4% reflecting bare fiber facets provided feedback for the laser. The output from the fiber laser was thus double-sided. This configuration is suitable for characterization of the efficiency of rare-earth doped fibers. For a more practical laser with a single-sided output, we frequently use a high-reflecting element in one end (e.g., a butted dichroic mirror or a fiber grating). With a high-reflection mirror in one end of the cavity, the total (single-ended) output power typically remains similar to the double-ended one with two 4% reflecting ends. Alternatively, a 4% reflecting end can be used together with a low-reflecting (e.g., angle-cleaved) fiber end to generate predominantly uni-directional output [26]. The dichroic mirrors at the input end separated the laser output from the path of the pump beam. An identical mirror and lens arrangement was used in the other end of the fiber to split the pump and laser output beams. We separately measured the power of the three beams exiting the fiber. In order to determine the power conversion properties of the fiber as accurately as possible, we compensated for losses in the dichroics and lenses. Thus, the powers and results quoted refer to the fiber's exit facets. We measured the pump outcoupling loss to 12%, coming mostly from the lens while the mirror reflectivity was nearly 100%. The signal outcoupling loss was 9%, of which 1%–2% was due to the lens. For double-ended pumping we used two beam-shaped diode bars, as illustrated in Fig. 2, with no provisions for measuring the transmitted pump power.

For 980-nm pumping, we used a Polychrome laser system (Polaroid), combining eight broad-stripe diodes with a total linewidth of ~5 nm (full-width at half-maximum). The center wavelength changed with pump current, from 973 nm at threshold to 981 nm at maximum current. Nevertheless, we refer to this as 980-nm pumping. The output from the pump laser was collimated by a gradient-index lens with a 15-mm focal length and launched through two dichroic mirrors and an 8-mm focal-length aspheric lens into the fiber. The second dichroic mirror provided extra protection for the pump diodes from spurious spiking from the fiber laser. In the far end of the fiber, an identical lens collimated the transmitted pump and fiber laser output beams, with a dichroic mirror separating the two beams. Again, reflections from perpendicularly cleaved bare fiber ends closed the fiber laser cavity. Also with this set-up, we compensated for outcoupling losses (between 5% and 8%) in order to determine the powers exiting the fiber facets.

For the tunable laser, we only used single-ended pumping at 915 nm. The far end of the fiber was spliced to a standard single-mode fiber with a core diameter of 8 μm. The splice loss from the EYDF to the single-mode fiber was less than 1 dB. The single-mode fiber was then angle-polished to suppress reflections. An external diffraction grating blazed for 1.55 μm with 600 lines/mm mounted on a rotation stage provided a wavelength selective tunable feedback via an aspheric lens with a 14 mm focal length. See Fig. 2. We estimate the fiber-to-fiber reflectivity to 20%. The standard single-mode fiber in the cavity prevented signal light from being fed back into cladding-modes. Furthermore, with a good splice to the EYDF, the single-mode beam from the single-mode fiber can be preserved through the multimoded EYDF, thus significantly improving output beam quality [27], [28]. In addition, the linewidth of the feedback from the diffraction grating can be smaller with single-mode beams. The single-mode fiber protected the grating from excessive transmitted pump power, too. The single-sided output was taken from the pump launch end through a dichroic mirror.

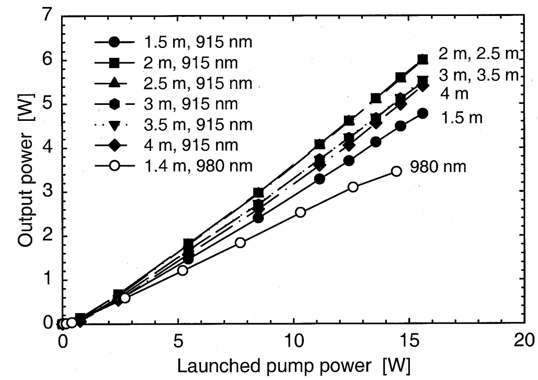

Fig. 3. Output power (double-ended) versus launched pump power for different fiber lengths with single-ended pumping at 915 and 980 nm.

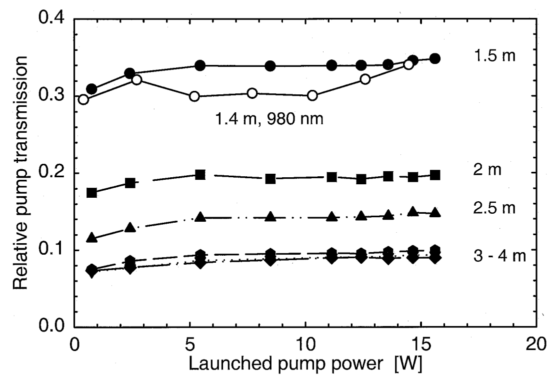

Fig. 4. Transmitted pump power versus launched pump power for different fiber lengths with single-ended pumping at 915 and 980 nm.

III. Free-Running Laser

Fig. 3 shows the total (double-ended) free-running laser output power versus launched single-ended pump power for different fiber lengths between 1.5 and 4 m with 915-nm pumping, as well as for a fiber length of 1.4 m with 980-nm pumping. For the 915-nm pumping, the slope efficiency with a 1.5-m-long fiber was lower than with longer fibers because of incomplete pump absorption. It then increased before it gradually decreased again for longer fibers. The highest output power was 6.0 W, which was reached both with 2- and 2.5-m-long fibers. We attribute the decrease to excess propagation losses: As the fiber gets longer, excess losses start to surpass the benefits of increased pump absorption. Fig. 4 shows how the pump transmission depends on the pump power for the same set of parameters as used in Fig. 3.

The 1.5-m-long fiber emitted at 1536 and 1542 nm simultaneously. The wavelength then shifted to longer wavelengths with longer fiber, to ~1550–1560 nm for the 4-m-long fiber, as a result of increased Er^{3+} reabsorption. The performance with 980-nm pumping was worse than that with 915-nm pumping,

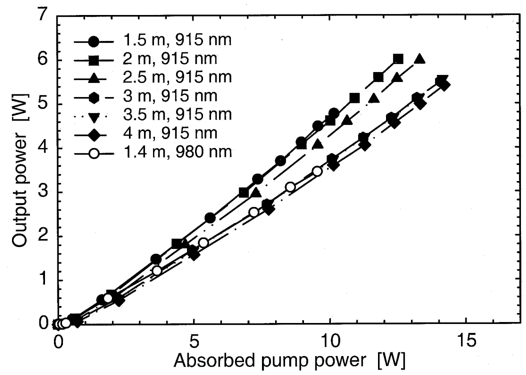

Fig. 5. Output power (double-ended) versus absorbed pump power for different fiber lengths with single-ended pumping at 915 and 980 nm.

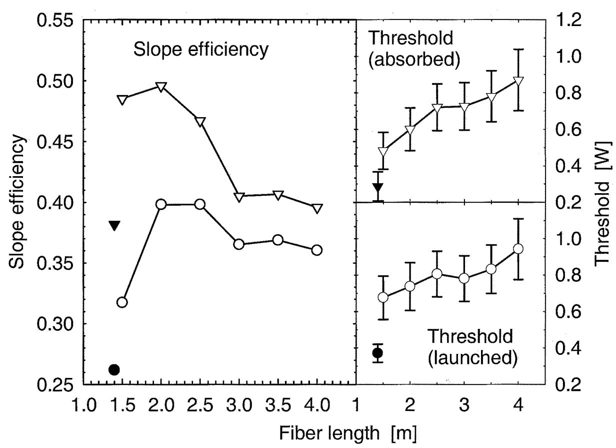

Fig. 6. Slope efficiency and pump threshold power versus fiber length, with respect to launched pump power (circles) and absorbed pump power (triangles). Empty symbols: single-ended pumping at 915 nm (fiber lengths 1.5 – 4 m). Filled symbols: single-ended pumping at 980 nm (single fiber length of 1.4 m).

with a maximum output power of 3.5 W. Again, the laser emitted simultaneously at 1536 and 1542 nm.

In order to differentiate the influence of incomplete pump absorption on slope efficiency from genuine loss mechanisms, Fig. 5 plots the double-ended laser output power versus absorbed pump power for the configurations used for Fig. 3. As we expect, the shortest fibers now have the highest slope efficiency with 915-nm pumping, since the excess propagation losses would be smaller in a shorter fiber. Fig. 6 further illustrates how the slope efficiency depends on fiber length for 915-nm pumping. The laser threshold is shown, too, as are data obtained with 980-nm pumping for a single fiber length of 1.4 m. We determined the slope efficiencies by fitting straight lines to the measured data of Figs. 3 and 5. Also the thresholds were determined from these lines, instead of being directly measured. This was a rather imprecise way of determining threshold, as illustrated by the large error bars. The slope efficiency with respect to launched power peaked for fiber lengths of 2 and 2.5 m, with a maximum value of 40%. The slope efficiency with respect to absorbed power reached 49%–50% for 1.5–2-m-long fibers. It then decreased for longer fibers, to 41% for a 4-m-long fiber. With 980-nm pumping of the 1.4-m-long fiber, the slope efficiency was 38% with respect to absorbed pump power.

We were unable to directly measure the launched pump power by cutting back the fiber, since the absorption of our EYDF was too high to be neglected except for impractically short fibers. Instead, we measured the launched pump power on an undoped but otherwise identical fiber with a length of $\sim$1 m, and compensated for the reflection loss at the output facet of the fiber. A difficulty arises in that pump modes near cut-off have a large loss over 1 m, e.g., several decibels. Consequently, the power decreases significantly over 1 m even in the undoped fiber, and to measure the launch after 1 m is somewhat arbitrary. A more precise quantification of the EYDFL would need to take into account the different loss of different pump modes.

For further investigations of loss mechanisms, we simulated the EYDFL with a spectrally and longitudinally resolved amplifier model (similar to [29]) with feedback from the end-facets. We assumed the pump to be evenly distributed throughout the core and cladding, in each transverse cross-section of the fiber. This is an approximation: While the figure-eight layout of the fiber scrambles the modes, the mode-scrambling is not sufficient to fully negate the effect of different modal absorptions, given that a part of the fiber was not mode-scrambled and the high rate at which the pump was absorbed. We used rate equations detailed in [30] to calculate the Er^{3+}-inversion in the fiber. Several other models have been developed for the simulation of Er/Yb co-doped systems [18], [31]–[41]. However, in general, EYDFs are quite complicated and any model has drawbacks, including difficulties with determining critical model parameters. In high-power EYDFLs, the temperature rise in the core may be large enough to modify the spectroscopic parameters of an EYDF, which further significantly complicates the system [42]. Using a model for heating in rare-earth doped fibers [43], we calculated temperature rises of over 100 K in our EYDFLs. A high-power cladding-pumped EYDFL has yet to be accurately simulated. Nevertheless, we believe that the model we use is adequate for qualitative as well as reasonably accurate quantitative calculations, and we did indeed obtain fair quantitative agreement with experiments.

The model showed that a propagation loss of 0.5–1 dB/m would account for the dependence of the slope efficiency on fiber length with 915-nm pumping. We did not measure the propagation loss, but background losses can be several tenths of decibels per meter in fibers with high rare-earth concentrations. In addition, quenching via energy-transfer upconversion is a known problem in erbium-doped fibers, leading to a certain fraction of the Er-ions being impossible to excite and unsaturable absorption [44]. Though Er-quenching is low in highly Yb-doped phosphosilicate fibers [22], it may still occur in our EYDF, especially since the Er-concentration is quite high. A loss of 0.5–1 dB/m would correspond to a quenched erbium fraction of 1%–2%. Levels as low as 1%–2% are difficult to measure, and we did not try to measure the quenching level. We nevertheless tentatively attribute the reduction of slope efficiency with fiber length to Er-quenching and background loss. Erbium quenching could also account for the nonperfect quantum slope efficiency. Our highest slope efficiency of 50% corresponds to a quantum slope efficiency of 84%. However, the details of how energy quanta are trapped by the quenched centers are unknown, preventing us from quantifying this

TABLE I
OPERATING PUMP ABSORPTION AT LOW AND MAXIMUM PUMP POWER AT 915 AND 980 NM, FOR DIFFERENT FIBER LENGTHS

Pump wavelength	Fiber length	Low-power pump absorption		Pump absorption, maximum power	
915 nm	1.5 m	5.1 dB	3.4 dB/m	4.6 dB	3.1 dB/m
	2 m	7.6 dB	3.8 dB/m	7.1 dB	3.5 dB/m
	2.5 m	9.4 dB	3.8 dB/m	8.3 dB	3.3 dB/m
	3 m	11.2 dB	3.7 dB/m	10.0 dB	3.3 dB/m
	3.5 m	11.4 dB	3.3 dB/m	10.3 dB	2.9 dB/m
	4 m	11.4 dB	2.8 dB/m	10.5 dB	2.6 dB/m
980 nm	1.4 m	5.3 dB	3.8 dB/m	4.7 dB	3.4 dB/m

process. We note that several other parasitic processes are possible in EYDFLs, e.g., cumulative energy transfer from ytterbium to high-lying erbium states [22], [31], [38]. We do not know why 980-nm pumping is less efficient than 915-nm pumping in our fiber. However, the 980-nm pump interacts more strongly with the gain medium than a 915-nm pump does. Certain loss mechanisms, and especially nonlinear loss mechanisms like cumulative transfer, may then be expected to have a greater impact with 980-nm pumping.

The energy transfer efficiency from ytterbium to erbium impacts on the overall slope efficiency, too. Since the pump excites the Er^{3+}-ions indirectly via energy transfer from Yb^{3+}-ions, more Yb^{3+}-ions are excited at higher pump levels. This reduces the pump absorption and thus the laser output power. (The direct excitation of Er^{3+}-ions when pumping at 980 nm is negligible, because of the weak erbium absorption.) If the energy transfer is poor, a large number of Yb^{3+}-ions needs to be excited in order to generate a certain rate of energy transfer. Returning to Fig. 4, we see that there is some bleaching at low pump powers with 915-nm pumping, as the pump transmission increases with pump power. Higher pump powers lead to even more bleaching (at least for a fiber length of 1.5 m), but the change is not so large. Table I lists the low- and high-power operating pump absorption with 915- and 980-nm pumping. The absorption should be better with 980-nm pumping but actually, it is similar to that with 915-nm pumping. We believe that the reason for the unexpectedly poor absorption with 980-nm pumping is that the mode scrambling was not as efficient as it was with 915-nm pumping (the fiber had been moved and rearranged). The decrease in transmission at intermediate pump levels can be understood as a change of pump wavelength with pump power: at intermediate powers, the pump wavelength is better matched to the Yb^{3+} absorption peak. However, especially with 980-nm pumping, the heating of the EYDF with stronger pump power may also affect the absorption, making the bleaching difficult to interpret.

In order to better realize the potential of our EYDFL with 980-nm pumping, we bent the fiber more tightly to increase the mode scrambling and thus the pump absorption. The absorption then increased to $\sim$11 dB (8 dB/m) at a low pump power and to 9 dB at maximum pump power, with a simultaneous increase in laser output power. The absorption was still less than the peak absorption in Fig. 1, because the absorption at 980 nm is significantly lower than that at the peak. At lower pump powers, the pump wavelength is closer to the absorption peak, on its short wavelength side. To fully utilize the high absorption in this fiber requires a better matched pump source than ours, with a narrower spectrum.

The reduced absorption at higher pump powers leads to lower slope efficiency with respect to launched pump power. However, the bleaching also reduces the slope efficiency with respect to absorbed pump power via spontaneous emission from the Yb^{3+}-ions. In addition, excited Yb^{3+}-ions generate gain around 1060 nm. We have seen some EYDFLs with poor energy transfer efficiency oscillate around 1060 nm (also reported in [17]). This is the long-wavelength tail of the Yb^{3+}-emission, where reabsorption is small. The threshold for 1060-nm lasing was typically $\sim$3–5 W. Though one can argue that all EYDFLs eventually lase at Yb^{3+} wavelengths with strong enough pumping, Yb-lasing did not occur in the EYDFL described in this paper. Still, the losses from Yb^{3+} spontaneous emission can be significant. We did not directly

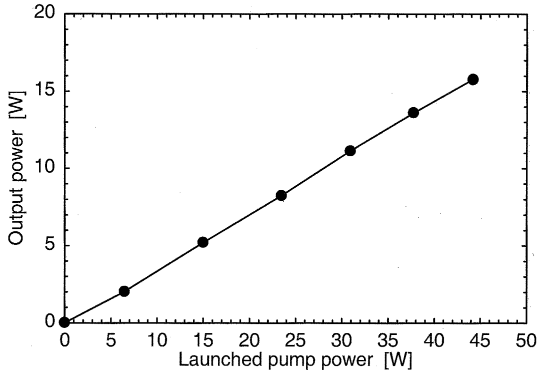

Fig. 7. Output power (double-ended) versus launched pump power, double-ended pumping at 915 nm.

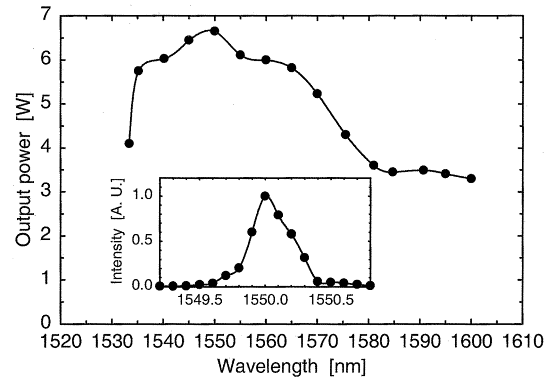

Fig. 8. Output power versus wavelength, tunable laser. Inset: line shape of laser.

measure the integrated spontaneous emission, but it is possible to estimate it from the pump bleaching. At a fluorescence power equal to the pump saturation power (compensating for the difference in pump and fluorescence photon energy, and in the absence of energy transfer to erbium), the pump absorption decreases by 4.34 dB. The pump saturation power is approximately 7 W at 915 nm. At 975 nm, it should be around one tenth of that, though it decreases rapidly at other wavelengths because of the narrow linewidth of the absorption peak. Furthermore, the multimode nature of the inner cladding complicates the saturation characteristics and reduces the difference between 915- and 980-nm pumping. At 915 nm, Fig. 4 reveals a bleaching of between 0.5 and 1.2 dB, which would correspond to a spontaneous emission of between 1 and 2 W. This suggests that an even more efficient energy transfer with a reduced Yb-bleaching could significantly improve the overall efficiency of the EYDFL.

Bleaching of the pump absorption (and 1060-nm lasing as an ultimate consequence of a higher Yb-excitation) can limit how much power an EYDFL can generate. Fig. 3 does indicate a tendency for the power to roll over with 980-nm pumping, perhaps because of the drifting pump wavelength though the data is uncertain. However, with 915-nm pumping, the curves show no sign of the output power rolling over as the pump power increases. Furthermore, the bleaching in Fig. 4 is small even at high powers. This suggests that the output power could be even higher with stronger pumping. To investigate this, we pumped an EYDFL with two 915-nm beam-shaped diode bars in opposite ends of a 4-m-long fiber, as illustrated in Fig. 2. Fig. 7 shows the laser output power versus total launched pump power. The maximum output power is 15.8 W, still reached without any signs of rollover. We then changed the fiber configuration in order to improve the pump absorption and attained an output power of 16.8 W.

IV. Tunable Laser

We investigated tuning characteristics of an EYDFL, using the same fiber as before. Fig. 2 depicts the setup. We pumped the 3.3-m-long EYDF with a launched pump power of approximately 25 W from a single beam-shaped 915-nm diode bar. The laser could be tuned over a wide range of the erbium gain band thanks to the high cavity gain. Fig. 8 plots the output power of the laser as a function of wavelength. The variation in output power was less than 3 dB from 1533 to 1600 nm. Thus, the tuning range was 67 nm (full-width at half-maximum). A maximum output power of about 6.7 W was obtained at 1550-nm with a pump to signal conversion efficiency of 27%. We believe that losses at the diffraction grating, including the fiber back-coupling losses, caused the reduction in conversion efficiency of the tunable laser compared to that of the free-running laser. The shift in the emission peak toward 1550 nm from the intrinsic peak at $\sim$1535 nm is caused by reabsorption in the relatively long EYDF: a long fiber is required to absorb the pump power, but as a side effect, the emission shifts to longer wavelength. A shorter cavity length shifts the tuning range to shorter wavelengths, however at the expense of lower pump-to-signal conversion efficiency as the pump absorption drops [26].

Typical tuning curves for fiber lasers tend to be relatively flat and drop sharply at the edges of the tuning range. The tuning curve in Fig. 8 differs from this, with the power dropping beyond 1560 nm. This is peculiar; it suggests some excess loss at long wavelengths, but we have not identified any loss mechanism. The drop in gain at long wavelengths could also reduce the output power, but simulations showed that the gain should be high enough to maintain a high output power even at 1600 nm.

The linewidth of the output beam was much narrower than that of the free-running laser. It remained approximately constant over the whole tuning range and was less than 0.25 nm everywhere. The inset in Fig. 8 shows one example. The linewidth decreased somewhat at lower output powers. The temporal behavior of the laser output was monitored using a fast InGaAs photodiode. Good temporal stability was observed throughout the whole tuning range of the laser with power fluctuations of less than 10%. The single-mode fiber spliced in one end of the EYDF improved the beam quality. We did not measure the beam quality directly. However, we did investigate the polarization of the output beam. We found that more than 95% of the total output power was preferentially linearly polarized in a single direction. This is a result of the polarization dependence of the diffraction grating and the fact that a mode that is linearly polarized in one end of the cavity is also linearly polarized in the other end of the cavity. However, different modes would be polarized at different orientations. The high degree of polarization suggests that the output was (nearly) single-moded. High-power, high-brightness, linear polarization, and narrow linewidth output are attractive features in a pump source for various nonlinear conversion processes. Since our EYDF was not polarization-maintaining, and since there was no control of net birefringence (varying with temperature changes and with changes in the position of the fiber), the polarization angle of a linearly polarized output beam is expected to drift over timescales of a few minutes. For practical applications, a fixed-polarization angle can be obtained simply with a rotatable halfwave-plate, automatically controlled with feedback.

V. CONCLUSIONS

We have described cladding-pumped EYDFLs in free-running and tunable configurations. In a free-running laser configuration, we obtained slope efficiencies of up to 50% with 915-nm pumping and 38% with 980-nm pumping, with respect to absorbed pump power. We reached an output power of 16.8 W from the free-running laser, pumped by two 915-nm beam-shaped diode bars. The operating pump absorption of our fiber laser reached 8 dB/m at 980 nm, and the small-signal absorption reached over 13 dB/m at 975 nm. Our fiber had a circular inner cladding with a centered core. We predict even higher absorption with a noncircular inner cladding and with an off-centered core, at least if the pump source is accurately matched to the narrow Yb absorption peak. The high pump absorption allows for short fibers with high nonlinear thresholds, even with cladding pumping. This can be useful, for instance, for amplification of single-frequency signals. The tunable fiber laser emitted up to 6.7 W of output power in a tuning range from 1533 to 1600 nm, in a high-brightness, narrow linewidth, temporally stable beam with a single-polarization, though with a varying polarization angle.

REFERENCES

[1] V. Dominic, S. MacCormack, R. Waarts, S. Sanders, S. Bicknese, R. Dohle, E. Wolak, P. S. Yeh, and E. Zucker, "110 W fiber laser," *Electron. Lett*, vol. 35, pp. 1158–1160, 1999.

[2] J. Limpert, A. Liem, S. Höfer, H. Zellmer, and A. Tünnermann, "150 W Nd/Yb codoped fiber laser at 1.1 μm," in *OSA Trends in Optics and Photonics (TOPS)—Conf. Lasers and Electro-Optics, OSA Tech. Dig.*, vol. 73, Washington, DC, 2002, pp. 590–591.

[3] N. S. Platonov, D. V. Gapontsev, V. P. Gapontsev, and V. Shumilin, "135 W cw fiber laser with perfect single mode output," in *Proc. Conf. Lasers Electro-Optics*, Long Beach, CA, 2002, post-deadline paper CPDC3.

[4] K.-I. Ueda, H. Sekiguchi, and H. Kan, "1 kW cw output from fiber embedded lasers," in *Proc. Conf. Lasers Electro-Optics*, Long Beach, CA, 2002, post-deadline paper CPDC4.

[5] J. E. Townsend, W. L. Barnes, K. P. Jedrzejewski, and S. G. Grubb, "Yb^{3+} sensitised Er^{3+} doped silica optical fiber with ultrahigh transfer efficiency and gain," *Electron. Lett.*, vol. 27, pp. 1958–1959, 1991.

[6] J. D. Minelly, W. L. Barnes, R. I. Laming, P. R. Morkel, J. E. Townsend, S. G. Grubb, and D. N. Payne, "Diode-array pumping of Er^{3+}/Yb^{3+} co-doped fiber lasers and amplifiers," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 301–303, 1993.

[7] V. P. Gapontsev, V. V. Fomin, I. E. Samartsev, and A. Unt, "25 kW peak power, wide-tuneable-repetition-rate and pulse duration eye-safe MOPFA laser," in *Conf. Lasers Electro-Optics—OSA Tech. Dig. Series*, vol. 9, 1996 , Washington, DC, 1996, pp. 209–210.

[8] L. Goldberg, B. Cole, and E. Snitzer, "V-groove side-pumped 1.5-μm fiber amplifier," *Electron. Lett.*, vol. 33, pp. 2127–2129, 1997.

[9] M. Hofer, M. E. Fermann, and L. Goldberg, "High-power side-pumped passively mode-locked Er-Yb fiber laser," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1247–1249, 1998.

[10] L. Goldberg and J. Koplow, "Compact, side-pumped 25 dBm Er/Yb co-doped double cladding fiber amplifier," *Electron. Lett.*, vol. 34, pp. 2027–2028, 1998.

[11] F. Di Pasquale, G. Grasso, F. Meli, G. Sacchi, and S. Turolla, "23 dBm output power Er/Yb co-doped fiber amplifier for WDM signals in the 1575 – 1605 nm wavelength region," *Opt. Fiber Commun. (OFC 1999) Tech. Dig.*, 1999.

[12] D. M. Dagenais, L. Goldberg, R. P. Moeller, and W. K. Burns, "Wavelength stability characteristics of a high-power, amplified superfluorescent source," *J. Lightwave Technol.*, vol. 17, pp. 1415–1421, 1999.

[13] J. Koplow, L. Goldberg, D. A. V. Kliner, and R. P. Moeller, "High power PM fiber amplifier and broadband source," *Opt. Fiber Commun. (OFC 2000) Tech. Dig.*, 2000.

[14] G. Wilson, J.-M. P. Delavaux, A. Stentz, I. Ryazansky, R. Windeler, M. Fishteyn, and C. McIntosh, "Low-noise 1-watt Er/Yb fiber amplifier for CATV distribution in HFC and FTTH/C systems," *Opt. Fiber Commun. (OFC 2000) Tech. Dig.*, 2000.

[15] S. U. Alam, J. Nilsson, P. W. Turner, M. Ibsen, A. B. Grudinin, and A. Chin, "Low cost multi-port reconfigurable erbium doped cladding pumped fiber amplifier," in Eur. Conf. Optical Communication 2000, München, Germany, 2000, 5.4.3.

[16] A. B. Grudinin, J. Nilsson, and P. W. Turner, "New generation of cladding pumped fiber lasers and amplifiers," in Conf. Lasers and Electro-Optics Europe (CLEO-E'00), Nice, France, 2000, CWA3.

[17] P. K. Cheo and G. G. King, "Clad-pumped Yb:Er codoped fiber lasers," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 188–190, 2001.

[18] M. Achtenhagen, R. J. Beeson, F. Pan, B. Nyman, and A. Hardy, "Gain and noise in ytterbium-sensitized erbium-doped amplifiers: Measurement and simulations," *J. Lightwave Technol.*, vol. 19, pp. 1521–1526, 2001.

[19] Product Catalog of IPG Photonics (2002). [Online]. Available: www.ipgphotonics.com

[20] S. A. E. Lewis, M. J. Guy, S. V. Popov, and J. R. Taylor, "Fiber MOPFA source of femtosecond pulses with wavelength tunability from 790 to 830 nm," *Opt. Quantum Electron.*, vol. 32, pp. 193–196, 2000.

[21] P. A. Champert, S. V. Popov, and J. R. Taylor, "Power scalability to 6 W of 770 nm source based on seeded fiber amplifier and PPKTP," *Electron Lett.*, vol. 37, pp. 1127–1129, 2001.

[22] G. G. Vienne, J. E. Caplen, L. Dong, J. D. Minelly, J. Nilsson, and D. N. Payne, "Fabrication and characterization of Yb^{3+}:Er^{3+} phosphosilicate fibers for lasers," *J. Lightwave Technol.*, vol. 16, pp. 1990–2001, 1998.

[23] H. Zellmer, A. Tünnermann, H. Welling, and V. Reichel, "Double-clad fiber laser with 30 W output power," *Opt. Amplifiers and their Applic., Tech. Dig.*, pp. 251–252, 1997.

[24] M. Muendel, "Optimal inner cladding shapes for double-clad fiber lasers," in *Conf. Lasers and Electro-Optics—OSA Tech. Dig. Series*, vol. 9, 1996 , Washington, DC, 1996, p. 209.

[25] W. A. Clarkson and D. C. Hanna, "Two-mirror beam-shaping technique for high-power diode bars," *Opt. Lett.*, vol. 21, pp. 375–377, 1996.

[26] J. Nilsson, J. A. Alvarez-Chavez, P. W. Turner, W. A. Clarkson, C. C. Renaud, and A. B. Grudinin, "Widely tunable high-power diode-pumped double-clad Yb^{3+}-doped fiber laser," *Advanced Solid-State Lasers, OSA Tech. Dig.*, pp. 285–287, 1999.

[27] M. E. Fermann, "Single-mode excitation of multimode fibers with ultrashort fibers," *Opt. Lett.*, vol. 23, pp. 52–54, 1998.

[28] J. A. Alvarez-Chavez, A. B. Grudinin, J. Nilsson, P. W. Turner, and W. A. Clarkson, "Mode selection in high power cladding pumped fiber lasers with tapered section," *Conf. Lasers and Electro-Optics, OSA Tech. Dig.*, pp. 247–248, 1999.

[29] C. R. Giles and E. Desurvire, "Modeling erbium-doped fiber amplifiers," *J. Lightwave Technol.*, vol. 9, pp. 271–283, 1991.

[30] J. Nilsson, P. Scheer, and B. Jaskorzynska, "Modeling and optimization of short Yb^{3+}-sensitized Er^{3+}-doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 383–385, 1994.

[31] V. P. Gapontsev, S. M. Matitsin, A. A. Isineev, and V. B. Kravchenko, "Erbium glass lasers and their applications," *Opt. Laser Technol.*, pp. 189–196, Aug. 1982.

[32] P. R. Morkel, "Modeling erbium/ytterbium- doped fiber amplifiers," *Opt. Amplifiers and their Applic., Tech. Dig.*, vol. 17, pp. 206–209, 1992.

[33] P. Laporta, S. Longhi, S. Taccheo, and O. Svelto, "Analysis and modeling of the erbium-ytterbium glass laser," *Opt. Commun.*, vol. 100, pp. 311–321, 1993.

[34] F. Di Pasquale and M. Federighi, "Improved gain characteristics in high-concentration Er^{3+}/Yb^{3+} codoped glass waveguide amplifiers," *IEEE J. Quantum Electron.*, vol. 30, pp. 2127–2131, 1994.

[35] C. Lester, A. Bjarklev, T. Rasmussen, and P. G. Dinesen, "Modeling of Yb^{3+}-sensitized Er^{3+}-doped silica waveguide amplifiers," *J. Lightwave Technol.*, vol. 13, pp. 740–743, 1995.

[36] M. Federighi and F. Di Pasquale, "The effect of pair-induced energy transfer in the performance of silica waveguide amplifiers with high Er^{3+}/Yb^{3+} concentrations," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 303–305, 1995.

[37] F. Di Pasquale, "Modeling of highly-efficient grating-feedback and Fabry-Perot Er^{3+}-Yb^{3+} codoped fiber lasers," *IEEE J. Quantum Electron.*, vol. 32, pp. 326–332, 1996.

[38] E. Maurice, G. Monnom, B. Dussardier, and D. B. Ostrowsky, "Clustering effects on double energy transfer in heavily ytterbium-erbium-codoped silica fibers," *J. Opt. Soc. Amer. B*, vol. 13, pp. 693–701, 1996.

[39] P. Wysocki, "Accurate modeling of next generation rare-earth doped fiber devices," in *Optical Society of America TOPS*, M. N. Zervas, A. E. Willner, and S. Sasaki, Eds., 1997, vol. 16, Optical Amplifiers and Their Applications, pp. 46–71.

[40] M. Karasek, "Optimum design of Er^{3+}-Yb^{3+} codoped fibers for large-signal high-pump-power applications," *IEEE J. Quantum Electron.*, vol. 33, pp. 1699–1705, 1997.

[41] G. C. Valley, "Modeling cladding-pumped Er/Yb fiber amplifiers," *Opt. Fiber Technol.*, vol. 7, pp. 21–44, 2001.

[42] C. J. da Silva, M. T. de Araujo, E. A. Gouveia, and A. S. Gouveia-Neto, "Fourfold output power enhancement and threshold reduction through thermal effects in an Er^{3+}/Yb^{3+}-codoped optical fiber laser excited at 1.064 μm," *Opt. Lett.*, vol. 24, pp. 1287–1289, 1999.

[43] D. C. Hanna, M. J. McCarthy, and P. J. Suni, "Thermal considerations in longitudinally pumped fiber and miniature bulk lasers," in *Fiber Laser Sources and Amplifiers—Proc. Soc. Photo-Opt. Instrum. Eng.*, M. J. F. Digonnet, Ed., 1989, vol. 1171, pp. 161–166.

[44] T. Georges, E. Delevaque, M. Monerie, P. Lamouler, and J.-F. Bayon, "Pair induced quenching in erbium doped silicate fibers," *Opt. Amplifiers and their Applic. Tech. Dig.*, vol. 17, pp. 71–74, 1992.

Johan Nilsson received the Ph.D. degree in engineering sciences from the Royal Institute of Technology, Stockholm, Sweden, in 1994, for research on optical amplification.

Since then, he has worked on optical amplifiers and amplified lightwave systems, optical communications, and guided-wave lasers, first at Samsung Electronics and now at the Optoelectronics Research Centre, University of Southampton, Southampton, U.K. His research has primarily focused on devices but has also covered system, fabrication, and materials aspects. He is currently leading a group in the field of high-power active fiber devices and applications. His work has resulted in over 100 scientific publications, with many invited and post-deadline papers. He is a co-founder of Southampton Photonics, Inc., Southampton, U.K.

Dr. Nilsson is a member of the technical program committees of the Advanced Solid State Photonics and Optical Amplifiers and Applications topical meetings, as well as of Photonics West's Fiber Laser Systems Technology and Applications conference.

Shaif-Ul Alam received the B.Sc. and M.Sc. degrees in physics from the University of Dhaka, Dhaka, Bangladesh, in 1989 and 1990, respectively, and the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., in 2000.

From 1994 to 2001, he was a Lecturer (on study leave from August 1996 to December 2000) with the Department of Physics, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh. Currently, he is with Southampton Photonics, Inc., Southampton, U.K. His research interests are short-pulse fiber lasers, nonlinear fiber optics, and high-power fiber lasers and amplifiers.

Jose A. Alvarez-Chavez received the B.Eng. degree in electronics in 1992 and the M.Sc. degree in telecommunications in 1997, and the Ph.D. degree in 2003 from the University of Southampton, Southampton, U.K., for work on high-power, cladding-pumped Yb and Er/Yb-doped fiber lasers and amplifiers.

He is currently with Southampton Photonics, Inc., Southampton, U.K. He was previously with Iusacell-Bell Atlantic, the Optoelectronics Research Centre, University of Southampton, and Xtera Communications Inc., Allen, TX, an optical systems company.

Paul W. Turner joined Pirelli Optical Systems Group in 1980, where he was involved in the early fabrication of optical preforms using the MCVD process. He was also closely involved in the design and development of fabrication processes to manufacture polymeric fibers for both communication and high-temperature applications and in the design and development of assemblies and procedures for the polarization control and alignment of fibers for pig tailing to lithium–niobate optical modulators, as well as the industrialization of the manufacturing process for erbium-doped optical fibers for use in optical amplifiers and all associated components. In 1995, he moved to the Pirelli VAD fiber fabrication unit as a Process Engineer. In 1997, he joined the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., with involvement in the fabrication of rare-earth-doped fibers for experimental and advanced research activities. Since 2000, he has been a Manager of fiber fabrication at Southampton Photonics, Inc., Southampton, U.K., with responsibility for the development and productization of special fiber designs for core business. He has coauthored more than 20 technical papers, including three patents and a book chapters.

W. Andrew Clarkson received the B.Sc. degree (with first-class honors) in physics from the University of Manchester, Manchester, U.K., in 1984 and the Ph.D. degree from the University of Southampton, Southampton, U.K., in 1991.

He joined the Optoelectronics Research Centre, University of Southampton, in 1990, where he currently holds the position of Reader and is the Group Leader of the Advanced Solid-State Sources group. His current research interests include high-power fiber lasers and amplifiers, diode-pumped solid-state lasers, and nonlinear frequency conversion schemes for these devices, with particular emphasis on schemes for scaling output power and brightness. He has published over 160 conference and journal papers in the fields of solid-state lasers and nonlinear frequency conversion.

Dr. Clarkson is a Topical Editor for *Optics Letters* and a member of the Optical Society of America. He has served on the technical program committees of numerous international conferences including CLEO, CLEO/Europe, and Advanced Solid-State Lasers.

Anatoly Grudinin graduated from Moscow State University, Moscow, Russia, and received the Ph.D. degree on nonlinear and polarization effects in optical fibers from the General Physics Institute, Russian Academy of Science.

In 1992, he joined the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., where he conducted research on short-pulse fiber lasers, soliton transmission systems, and cladding-pumped fiber lasers. He has over 200 publications, holds four patents, and is a frequent invited speaker at major international conferences.

Dr. Grudinin is a member of the Optical Society of America.