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High power fiber lasers and amplifiers/Lasers et amplificateurs à fibre de puissance

Fibers for high-power lasers and amplifiers

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Abstract

A review is given on the recent developments of fibers for high-power cladding-pumped fiber lasers. The structures necessary for an efficient pump light absorption are described and the reasons for the use of silica as the main host material are explained. The advantages and problems of the new structures for high power stability like large-mode-area or microstructured fibers are discussed. The results from a successful kW-fiber-laser experiment are used to underline the importance of optimized structures and low background losses in the fiber core. ***To cite this article: H.-R. Müller et al., C. R. Physique 7 (2006).***

Résumé

Fibres pour lasers à fibre et amplificateurs de forte puissance. Cet article présente une revue sur les développements récents des fibres pour les lasers pompés par la gaine de forte puissance. Les structures nécessaires pour une absorption efficace de la lumière de pompe sont décrites, ainsi que les raisons du choix de la silice comme matériau hôte. Les avantages et les contraintes liées aux nouvelles structures, tel que les fibres à large surface de mode ou les fibres microstructurées, sont abordés. Les performances obtenues avec un laser de puissance supérieure à 1 kW soulignent l'importance des structures optimisées et des faibles pertes dans le cœur de la fibre. ***Pour citer cet article : H.-R. Müller et al., C. R. Physique 7 (2006).***

Keywords: Laser; Fiber; Ytterbium; High power; Double-clad fiber

Mots-clés : Laser ; Fibre ; Ytterbium ; Forte puissance ; Fibre à double gaine

1. Introduction

The field of high-power fiber lasers has developed in a dramatic manner during the last few years. From lab set-ups delivering some mW output power in the early 1990s, fiber lasers have evolved to multi-kilowatt-devices for use in material processing in industry. The motivation for the intensive development in the fiber laser field lies in the steadily growing laser market. The laser in general replaces progressively mechanical and electrical tools in different industrial branches. Therefore, laser devices have permanently to be improved and adapted to new requirements; naturally, also cost- and energy-efficiency are of highest priority. For instance, one essential disadvantage of the classical rod laser in the high-power regime is the instability of the operational parameters due to thermal effects, which must be compensated with big expenses.

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Two recent technical developments procured the prerequisites for the fiber laser: the optical communication industry delivered the preparation technologies for highly transmissive single-mode fibers (even for laser-active fibers in the form of Erbium-doped optical amplifier fibers), and the optoelectronics industry made available the high-power laser diodes necessary for the pumping of the fibers. So, the power increase of the fiber lasers reflects, to a certain extent, the availability of reliable and long-lived diode pump systems.

Considering the abundance of scientific and technical information published in this field, a short review must limit itself to some essential questions. This contribution will therefore concentrate on the fiber aspects of such high-power lasers; in our context, the notion 'high power' means cw and average output powers of about 100 W and more. The paper is organized as follows: after having discussed the advantages of fiber lasers and their differences to other laser types in Section 2, the following sections will be devoted to fiber geometry and design, to materials and preparation, and to the characterization of the most important fiber properties in this sequence. All discussions will be concentrated to the 'classical' fiber type and not to the new microstructured fibers, which are treated in parallelly published articles. Finally, in the sixth section, a summary and a short outlook will be given.

2. The special features of fiber lasers

The classical geometry of the solid-state laser is the rod. The last decade has seen the development of two new geometries competing with the rod and surpassing it partially in respect of the laser operational parameters. Besides the fiber laser geometry, the second new shape is the disk, pioneered by the work of Giesen et al. [1]. The most prominent difference to the rod shape—common to both fiber and disk laser—is the relatively small volume of the laseractive material. In Fig. 1, the geometric data for the different laser configurations are shown. Taking the typical data for diameter and length (or thickness), it can be seen that the active volume of disk and fiber is about the same and is three orders of magnitude smaller than in the rod.

Another parameter is different for disk and fiber: the surface-to-volume-ratio is much higher for the fiber and this leads to one of the big advantages of the fiber geometry. The heat, generated in the active volume by inevitable loss processes, can be carried away to the environment or to a cooling medium much faster in the fiber than in the disk or the rod and a thermal lens will not build up.

The active medium of most of the solid-state lasers consists of homogeneous material. In this point, the fiber laser differs from both rod and disk: it consists of at least two parts with different material properties, the waveguiding, laser-active core and the surrounding passive cladding. Therefore, the propagation characteristics of the fiber laser radiation are completely determined by the refractive index structure of the core and not by an external resonator as in the case of rod or disk. The guiding mechanism prevents any influence from heating phenomena even more efficiently than the high surface-to-volume-ratio. The index changes induced in conventional lasers by heating during high-power

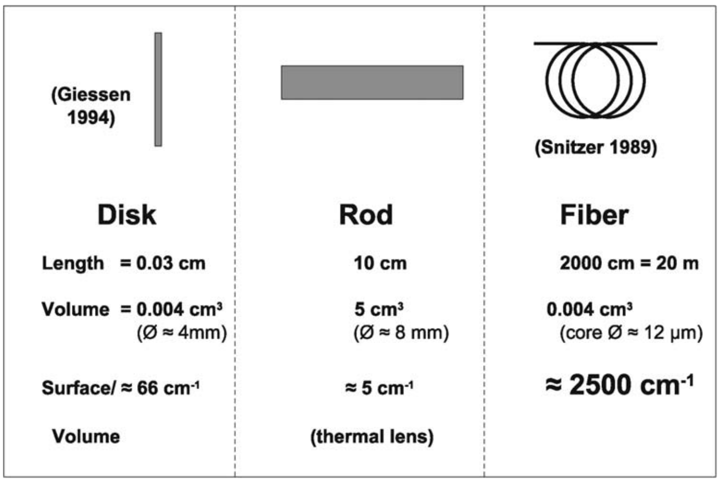

Fig. 1. Typical dimensional parameters of the different laser geometries.

Fig. 1. Valeurs typiques des dimensions pour différentes géométries de laser.

operation are between 0.0001 and 0.001 see, e.g., [2]—sufficient to generate the aforementioned thermal lens effects in an originally homogeneous medium, but even when the fiber would warm up to the same extent, the propagation would not be strongly disturbed because the index step between core and cladding is of the order of 0.01.

Generally, the power in lasers scales with the active material volume. This can be seen from laser modelling in its simplest form [2], where output power is usually expressed as proportional to saturation power P_s

$$P = \frac{P_s}{2} \cdot \left(\frac{R}{R_{thr}} - 1 \right) \tag{1}$$

with $P_s = A \cdot h \cdot \nu / (\sigma \cdot \tau)$, A being the mode area, σ the emission cross-section, τ the lifetime of the laser level, $h \cdot \nu$ the photon energy; R and R_{thr} are the pump rate and the pump rate at threshold, respectively.

This can be rewritten as

$$P = \frac{h \cdot \nu \cdot V \cdot N_0}{\alpha \cdot L - \ln(R_1 \cdot R_2)} \cdot R - \frac{P_s}{2} \tag{2}$$

if a simple expression for the threshold pump rate is derived. V is here the active volume, N_0 the laser ion doping density, R_1, R_2 are the resonator mirror reflectivities and α is the background loss in the resonator. It is evident, therefore, that in order to get high powers, one has either to choose a big volume and/or high doping density N_0 or—if this is not possible—one has to compensate this by a higher pump rate R.

From this point of view, the fiber geometry has no special advantages over rod or disk laser. If one uses silica as the host material, there is even a further drawback: due to quenching and precipitation processes connected with the laser ion doping, N_0 is limited to values in the order of 1000 mol-ppm (varying for the different used ions).

The fact that in spite of these drawbacks output powers of several kW and very high efficiencies are achievable is connected with the very good heat transfer already mentioned, and another material parameter of silica: α, the intrinsic loss of silica is lower than in most other laser materials and because the power—as seen from (2)—is inversely proportional to the loss term, silica was early identified as the most favourable material in this respect [3].

Naturally, the cited high fiber laser efficiency is not only connected with the low loss, but also with the choice of the lasing ion. Ytterbium which was used mostly during the last years can be pumped at $\lambda = 975$ nm for the lasing transition at $\sim$1080 nm and has therefore the advantage of a very low quantum defect of only $\sim$10%.

3. The cladding-pump principle

Practically all high-power fiber laser experiments are based on the cladding-pump principle. Such fibers—first described by Snitzer et al. in 1989 [4]—consist of a silica fiber core doped with the lasing ions and other, index-raising dopants like Ge- or Al-oxide, a cladding surrounding the core, usually pure silica, and a second cladding with a refractive index still lower than the silica index, mostly a polymer coating. Thus, pump light coupled into the silica cladding is guided by the total reflection at the silica-polymer interface and can interact with the ions in the core. The big advantage of this double-core geometry is the possibility to pump with sources having low beam quality like diode bars or stacks. The larger the pump cladding and its numerical aperture (i.e., the index difference between silica and the outer polymer coating), the higher the percentage of the incoupled pump light.

However, with increasing diameter and aperture of the pump guide, the number of rays (or modes in the wave optics description) which do not interact with the absorbing laser core also increases. In particular, the helical rays propagating in a meander-like path in the outer region of the cladding have negligible overlap with the core and may be lost at the output side. An improvement can be made by breaking the cylindrical symmetry forcing the rays to follow more irregular or even chaotic paths. Snitzer et al. [4] proposed originally an acentrically positioned core or a rectangular fiber shape, but this involves not only a more complicated preparation, but also leads to problems in connecting the laser fiber to normal round fibers. Zellmer et al. introduced and patented in 1995 the so-called 'D-fiber' [5]. Here, at the preform stage, a flat is polished parallel to the axis and this shape must be preserved during drawing with only small changes. With these results, it became clear that cladding-pumped fiber lasers have a considerable potential for power scaling, and therefore, a myriad of different principles was proposed and patented; some of these shapes are shown in Fig. 2.

Zellmer et al. has shown both experimentally and numerically [5] that the D-fiber has favourable properties compared to other structures. From ray tracing calculations, it can be seen in Fig. 3, that the asymmetric structures have

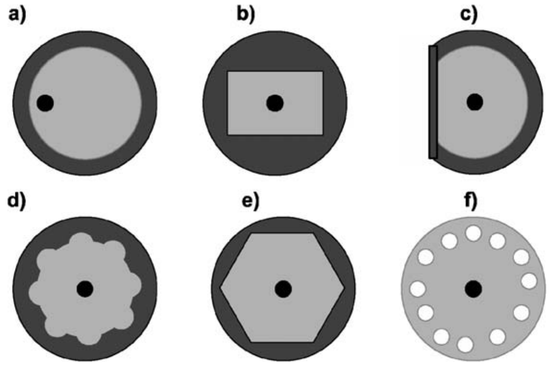

Fig. 2. Examples of patented cladding-pumped structures: (a) eccentric core, Snitzer, US 481 5079, (b) rectangle, Snitzer, US 4815079, (c) D-shape, Zellmer DE 19535526, (d) star, Digiovanni, US 5873923, (d) polygon, Muendel, US 5533163, (e) Digiovanni, US 59076522.

Fig. 2. Exemples des structures de pompage par la gaine brevetées : (a) cœur excentré, Snitzer, US 481 5079, (b) rectangle, Snitzer, US 4815079, (c) forme en D, Zellmer DE 19535526, (d) étoile, Digiovanni, US 5873923, (d) polygone, Muendel, US 5533163, (e) Digiovanni, US 59076522.

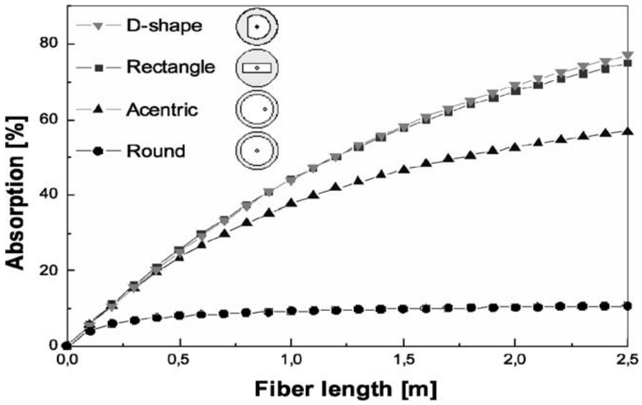

Fig. 3. Model calculations for the absorption of different cladding-pumped structures in dependence on fiber length (from Zellmer [5]).

Fig. 3. Calcul de l'absorption pour différentes structures de pompage par la gaine en fonction de la longueur de fibre (Zellmer [5]).

a far better absorption efficiency than the round fiber, and that the D-shape is even better than the rectangle. Because the preparation and coupling problems are also reduced in the D-fiber, many other labs have used this shape for their experiments.

An exact comparison between theory and experiment or even a general optimization of the fiber shape is actually not possible for different reasons. From the theoretical side, it is not only difficult due to the high number of modes for the used dimensions (e.g., for a 400 μm diameter fiber with an NA of 0.48, there exist more than 10^5 modes), but in certain structures the light propagates in a chaotic manner [6]. Experimentally, the difficulty lies in the separation of the absorption effects due to the cross section shape from other mechanisms. Minor index inhomogeneities, diameter fluctuations, microbending lead to mode coupling phenomena which mixes the modes not interacting with those overlapping with the core. This is favourable for the absorption efficiency, but because the dimensions of these defects are very small and experimentally not accessible, it is not possible to separate the different effects.

This uncertainty also means that the pump absorption dependence on fiber length can not be predicted precisely. An empirically supported rule of thumb for the estimation of a cladding absorption coefficient (valid for mode-mixing structures, like D-shape) is to multiply the core absorption coefficient with the ratio of core area/cladding area. However, this is a crude approximation and its validity is especially doubtful in the critical parts of the laser fiber, namely in the pump input and the laser output region.

Naturally, for the properties of a double-clad fiber, not only the geometry is decisive, but also the materials used. Core and pump-clad are usually based on silica and are therefore well suited for the high-power operation. So, often the used polymer coating was the limiting element, because these materials withstand temperatures between 200 and 300 °C at best. Two alternatives have appeared during the last years with higher temperature stability. Doping the outer zone of the pump clad with fluorine decreases the index, and because the pump intensity follows the index profile, the power at the interface F-doped silica/coating is reduced considerably, see Fig. 4, center (a polymer coating is always necessary for reasons of mechanical strength). The other possibility is the so-called 'air-clad', where the pump region is bounded by narrowly neighbouring air holes, Fig. 4, right. With such structures, the highest apertures up to 0.8 are possible. However, for this, the bridges between the holes must be very thin (some 100 nm) in order to avoid leaking out of the pump light. The preparation of such structures is demanding and the long-term stability is not investigated up to now.

If one asks what are the open questions or urgent problems concerning cladding pumping, one should surely list a better understanding and description of the absorption process. Further, the use of axially symmetric shapes with the

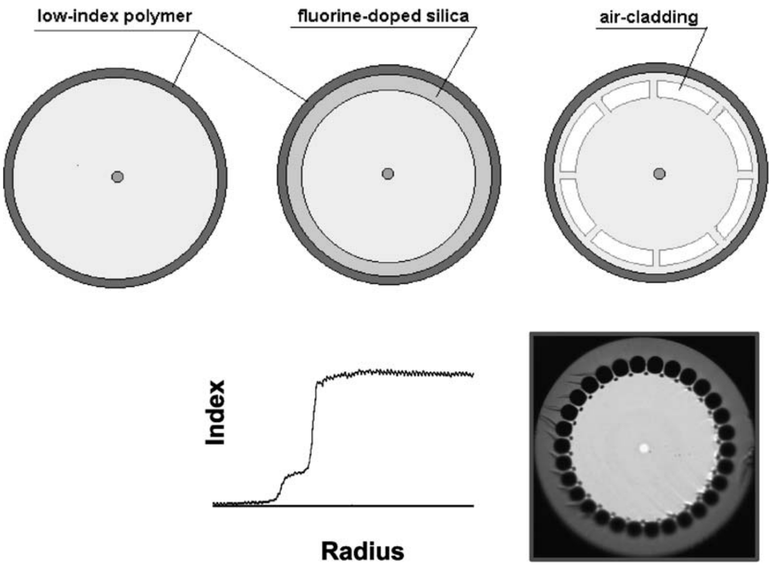

Fig. 4. Schemes of the actual possibilities for the outer coating. For the F-doped silica coated fiber, the measured index profile is shown below, for the air-clad fiber across-section photograph is shown.

Fig. 4. Géométries schématiques possibles de la gaine externe. Le profil d'indice est représenté dans le cas d'une gaine externe en silice dopée F. La photographie correspond à la section transverse d'une fibre air-silice.

same absorption efficiency as asymmetric ones would be highly desirable, because all asymmetric structures bring problems beyond the difficult coupling, e.g., for the coating process during fiber drawing or for the UV-imprinting of Bragg gratings. A possible solution to both problems could be the use of new types of cladding structures: up to now, all cladding-pump principles are based on an irregular cross section of the fiber and rely mostly on a random mode mixing. It should be possible to use also round fibers with suitable internal index structures effecting intentionally mode coupling. For instance, a parabolic index gradient in the cladding would allow one to induce strong mode coupling between all modes due to the special mode structure of such profiles [7].

4. Material and preparation

If we limit our discussions strictly to fiber lasers with output powers above 100 W, only silica comes into consideration as the host material, because to the best of the authors' knowledge, no other materials have shown to withstand powers of more than some ten watts in fiber shape. However, it was already said in Section 2. that silica also has certain disadvantages, and therefore, two alternative materials shall be at least mentioned: phosphate glass and fluoride glass (ZBLAN). Phosphate glass is interesting due to the very high quantities of rare-earth ions which can be incorporated. This makes it possible to get several W output from a 12-cm fiber [8], but for further power scaling this is of limited use because the high losses per unit length will lead to excessive heating and eventually destruction of the fiber. Rare-earth-doped fluoride fibers have been thoroughly investigated for their ability to emit laser radiation in the visible spectral range. This is due to the low phonon energy in fluoride glass which makes radiationless deexcitation of the laser levels by multiphonon processes less probable. But fluoride fibers have big problems with defect formation at higher power levels, are expensive in manufacturing, and difficult to handle.

Therefore silica actually seems to be without competitor as a fiber laser host material due to its better thermal and mechanical stability. This is due to the glass transition temperature T_g, which has a value in silica more than double its value in fluoride or phosphate glass. Clearly, operating at core temperatures of about 300 °C possible in silica would change drastically the guiding properties in fluoride or phosphate glass by component diffusion and stress relaxation processes.

The most used rare-earth (RE) ions for laser emission in silica fibers are Praseodymium, Neodymium, Holmium, Erbium, Thulium, and Ytterbium (Pr, Nd, Ho, Th, Er, Yb), the best candidate for the high powers being the Yb. The reason is the very simple structure of the Yb^{3+}-level scheme, which allows no branching of fluorescence transitions, no competing ESA- or upconversion transitions. Further, Yb has a high absorption cross section and it can be pumped at 975 nm for a laser emission at about 1080 nm, resulting in the already mentioned low quantum defect of about 10%. This is a decisive advantage because the heat generated by quantum defect and other losses limits actually the further cw power scaling. An additional point promoting the use of Yb is the availability of powerful diode pump sources for several Yb pump transitions at 915, 940, and 975 nm.

Interestingly, nearly all mentioned RE-ions have electronic levels energetically neighbouring the excited Yb level. This opens the possibility to use the high Yb-absorption cross section in fibers doped with different types of RE ions, to pump firstly the Yb ions, to transfer the excitation to the other ion types, and to get then lasing from these ions at new wavelengths. If one succeeds in finding suitable doping concentrations for a high transfer efficiency, this works rather well. The best example is the codoping of Er with Yb, whereby recently more than 180 W output power have been reached for the Er transition at 1.55 μm.

The preparation process mostly used is the modified chemical vapour deposition (MCVD) combined with a solution doping method for the incorporation of the RE ions, followed by the fiber drawing. The MCVD is a standard process in the fiber industry and consists of the porous layer deposition (from gaseous SiCl4, GeCl4, ... and O_2) inside the silica tube, the consolidation of the layers to a clear glass, followed by collapsing of the tube to the preform. Because there are no volatile RE compounds, this process must be interrupted for the doping of the laser ions at the stage of the porous layer, and this soaking of the layers with the aqueous solution, followed by purifying and drying, extends and complicates the preparation considerably. There are different attempts for alternative preparation methods, but up to now, MCVD gives still the best results concerning transmission quality and high-power stability.

The recent developments to power values of some 100 W and more have required more sophisticated fiber structures. An example is the so called 'large-mode-area' fiber (LMA). In order to reduce the huge power densities in the fiber core, one wants to use fibers with larger cores, but this can lead to multimode propagation. If it is necessary to preserve the beam quality, one has also to decrease the NA of the core, i.e., the index difference. This causes two problems explained schematically in Fig. 5. It is straightforward in conventional step index fibers to choose the doping levels of the different dopants (Fig. 5, left) to get the necessary index difference. However, in the LMA-fiber (Fig. 5, right), the required amount of Yb and codopant Al (necessary for sufficient gain) creates an index difference larger than the desired small value. The second problem is the general difficulty to adjust precisely such small index differences of the order of 0.001. Several methods and sophisticated index profiles have been proposed to overcome these problems, but we will mention here only the most modern and versatile solution, namely the use of microstructured or 'holey' fibers.

It is well known that the index difference between core and cladding can be adjusted by the size and distance of the air holes in the cladding of holey fibers. This can be done very sensitively and this solves one of the mentioned problems. Further, the problem of the too high index in the core region can be tackled by 'diluting' the index in the core through mixing of Yb-doped regions with undoped, or better still, with F-doped material. Fig. 6 shows as an example the microscopic image of such a prepared structure. Naturally, one must keep in mind that such 'photonic

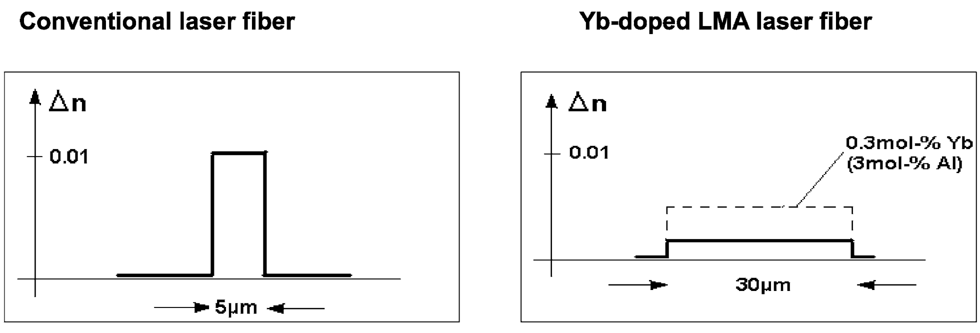

Fig. 5. Illustration of the problems encountered in preparing LMA fibers with low index steps and simultaneously maintaining the adequate doping levels.

Fig. 5. Illustration des problèmes rencontrés dans la réalisation des fibres LMA à faible saut d'indice, conservant simultanément les niveaux adéquats de dopage.

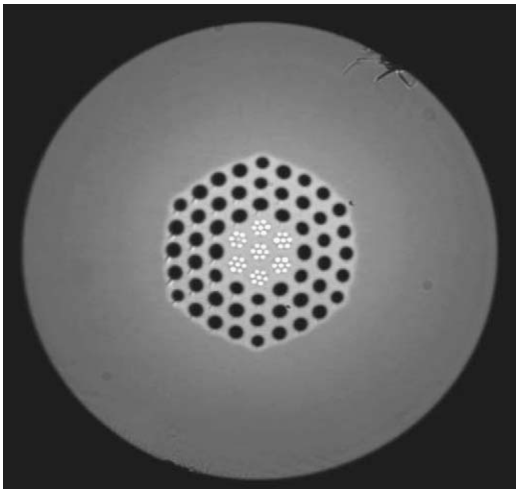

Fig. 6. Cross section microphotograph of a microstructured laser fiber with diluted Yb doping (the core is prepared by repeated stacking and elongating Yb-doped rods with pure silica cladding).

Fig. 6. Photographie de la section transverse d'une fibre microstructurée dopée Yb (le coeur est réalisé par empilements et tirages successifs de barreaux dopés Yb avec une gaine en silice pure).

crystal fiber lasers' have their prize: all this microstructuring must be done additionally to the MCVD-preparation of the RE-doped core.

Looking again for actual unsolved problems concerning materials and preparation, a faster and more productive preparation method—shortly a more cost-effective—would be highly desirable. Silica as the host material is not in question for high-power laser fibers, but a better insight in the doping-related phenomena like quenching, precipitations, or defect formation would be very helpful for the optimization of the laser fibers. A related question is the long-term stability of the doped silica at the extreme optical intensities of some 100 MW/cm^2 for kW output powers.

5. Properties and characterization

For the development of high-power stable laser fibers, many different characterization methods are necessary. The light propagation in the fiber is determined by the index profile of the fiber and the spectral attenuation behaviour, both have to be measured. The index profile is usually measured non-destructively at the preform stage and scaled down according to the fiber/preform diameter ratio. The attenuation is measured by the cut-back method with the help of suitable optical spectrum analyzers, these measurements give informations on the absorption cross sections at the pump wavelengths, on the background absorption, and also on potential undesired losses from impurities, defect states or scattering. The lasing behaviour is determined by the fluorescence properties of the RE ions. Here, both fluorescence lifetime and spectral dependence should be measured to recognize errors in composition or in the preparation process. For instance, quenching or segregation processes due to too high RE content or inadequate codoping often lead to changes in the fluorescence properties. All parameters enumerated up to now depend on the chemical composition of the fiber; therefore, for the fiber optimization it is essential to measure also the composition and to investigate the correlation of the different components with the optical properties. The mode field diameter and the numerical aperture of the laser fiber (or in other words, the beam quality) can be derived from the index profile of the fiber. Their experimental determination can be regarded as a control measurement, indicating how good the real fiber corresponds to the design.

It is not the place here to describe the measurement tasks for the different parameters and the involved problems in detail, so we will only discuss the significance of the fiber loss and its determination as an example. The core background loss of the laser fiber can be disastrous under two aspects: firstly, it reduces directly the useful gain and consequently the attainable output; secondly, because nearly all losses in the core transfer the energy finally to the fiber material, it contributes to the heat generation in the fiber. At least three other effects add contributions to this heating: the quantum defect (at least ~10% for every useful laser transition in the case of Yb), the pump background

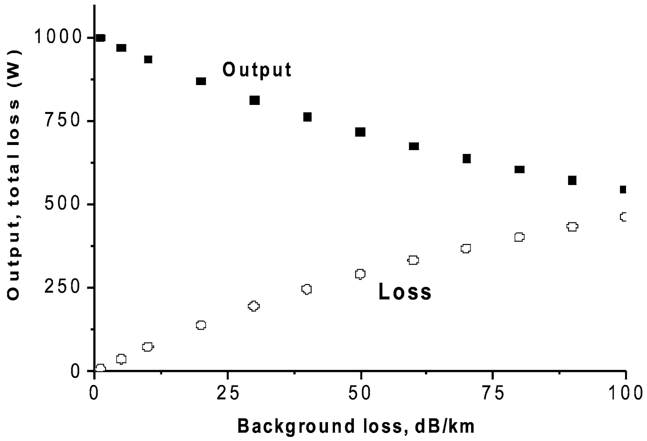

Fig. 7. Estimated fiber laser output power lost in dependence on core background absorption.

Fig. 7. Evolution des pertes estimées de la puissance de sortie d'un laser à fibre en fonction de l'absorption dans le cœur.

absorption in the cladding and the absorption and scattering losses at the silica-coating boundary. The quantum defect losses are inevitable; therefore, the causes for the other losses should be thoroughly investigated in order to minimize them. The consequence for the pump cladding is that one should use the best available silica quality as the tube material in the MCVD process. Concerning the losses at the silica-polymer interface, a position-dependent, or better mode-selective loss measurement would be the best method to clear up the questions of evanescent field absorption in the polymer, the role of defects or microdeformations at the boundary, but it seems that no one has tackled thoroughly such a task up to now.

Let us return to the core loss. In order to find a simple approximation for the loss effect on the laser operation, one can use the known spatial constancy of the product $I_+ \cdot I_-$, i.e., the intensity of the forward propagating times the intensity of the backward propagating wave in the resonator. The spatial derivatives give differential equations for I_+, I_-, which can easily be resolved numerically including the influence of background loss [3].

If we use material parameters for typical Yb-doped LMA-fibers (core radius = 25 μm, fiber length = 50 m), the diagram of Fig. 7 results. Assuming sufficient pump power for generating 1000 W output at negligible core loss, one has at 10 dB/km a decrease of the output to ∼930 W, at 50 dB/km already to 720 W. The loss power appearing as heat distributed in the fiber has grown at this loss value to about 280 W. For a temperature calculation, the contributions from the quantum defect (⩾70 W) and from the pump loss in the cladding have also to be considered.

To illustrate the importance of the loss effects also from the experimental side, we will discuss our recent kW-experiment with a Nd–Yb-doped fiber [9]. This LMA-fiber with a core diameter of about 40 μm and a numerical aperture of about 0.06 had a F-doped clad around the pure silica clad (courtesy to CeramOptec GmbH, Bonn Germany) in order to reduce the interface losses as discussed before. It was codoped with Nd in order to have the possibility to pump it also with high-power diode systems at 808 nm wavelength; wavelength-multiplexed diode systems with this wavelength and others for Yb-pumping are commercially available.

The diagram in Fig. 8 shows two curves. The upper one resulted from pumping only the Yb ions at the wavelength 940 and 978 nm, it ends at ∼1300 W output power because no more pump power at these wavelength was available. The other curve corresponds to pumping with all three wavelength delivered from the used system (Laserline GmbH, Mülheim-Kärlich/Germany), i.e., 808, 940, and 978 nm. Slightly above 1200 W output, the fiber end was destroyed because of overheating. This is clearly due to the higher quantum defect for Nd pumping. Because the different wavelength contributed equally to the total pump power, one can estimate that the loss power is about 60 W higher in the case of pumping additionally with 808 nm, and this suffices to overheat and destroy the fiber.

6. Summary and outlook

It is difficult to cite the actual 'records' in the fiber laser field, because one is never sure that the results are still the best ones, due to the rapid developments in the many involved laboratories worldwide. So we will give here as examples only two results reported at the CLEO Europe conference 2005 in Munich/Germany: The company IPG

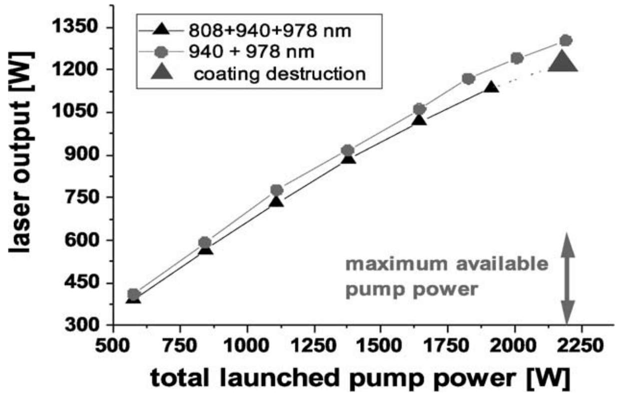

Fig. 8. Result of kW-output power experiment with optimized fiber (see text for detailed explanation).

Fig. 8. Performances d'une configuration de puissance de sortie supérieure au kW avec une fibre optimisée (se reporter au texte pour l'explication détaillée).

Photonics reported on an Yb-doped cw single-mode laser with 2 kW output power, and colleagues from the ORC in Southampton reached 188 W cw output power with an ErYb-laser at the 1.55 µm wavelength.

The race for still higher powers and better properties is clearly not at its end. Further optimization of the fiber structures and the material properties will shift the output powers for single fibers with diffraction limited beam quality into the 5 to 10 kW region, where—according to theoretical estimations—the limits due to thermal, nonlinear-optical, and/or high-field effects are to be expected.

Driven by commercial, but also military interests, new research fields have already been opened in order to exploit further the potential of the fiber lasers. The beam combining efforts are an example, where one tries to combine the outputs of several fibers or of multicore fibers into one beam (either coherently or incoherently). Another field is the 'fiber integration'; here, the aim is to integrate functions necessary for the laser operation directly into the fiber in order to reach higher reliability and compactness. The best example is the fiber Bragg grating already in use as a resonator element. All these developments will contribute not only to the scientific attractivity of the fiber lasers, but also to their progressing penetration into the different laser applications and markets.

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