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The all-fiber cladding-pumped Yb-doped gain-switched laser

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Abstract: Gain-switching is an alternative pulsing technique of fiber lasers, which is power scalable and has a low complexity. From a linear stability analysis of rate equations the relaxation oscillation period is derived and from it, the pulse duration is defined. Good agreement between the measured pulse duration and the theoretical prediction is found over a wide range of parameters. In particular we investigate the influence of an often present length of passive fiber in the cavity and show that it introduces a finite minimum in the achievable pulse duration. This minimum pulse duration is shown to occur at longer active fibers length with increased passive length of fiber in the cavity. The peak power is observed to depend linearly on the absorbed pump power and be independent of the passive fiber length. Given these conclusions, the pulse energy, duration, and peak power can be estimated with good precision.

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1. Introduction

Gain-switching of fiber lasers has been established as an alternative pulsing method due to the simplicity and all-fiber integration [1–4]. The output pulse energies are often in the microjoule range and with repetition rates spanning from a few kilohertz up to the megahertz range [2, 5]. These properties make the gain-switched fiber lasers interesting for many applications; directly or after single-stage amplification in high-power fiber amplifiers [1, 2, 6, 7].

A gain-switched laser is constructed exactly as a continuous-wave laser, which makes it cost-effective and reliable. The all-fiber laser cavity is typically build from two fiber Bragg gratings (FBGs) written in a length of passive Ge-doped fiber, which are spliced to active fiber with a low pump and signal loss. The pump of the laser is pulsed, which forces the laser to emit powerful relaxation oscillations [8]. Stable Gaussian-like nanosecond pulses can be produced by choosing the pump power and duration appropriately [9].

Gain-switching is related to Q-switching in the way that the pulses grow from spontaneous emission within the nanosecond time scale. The major difference is the time available for pumping [8]. In gain-switching the gain medium can only be pumped for a short time interval, typically a few microseconds, before the pulse builds up. This is in contrast to Q-switching, where the pump time can be as long as the lifetime of the upper state, which for rare earth doped glasses is hundreds of microseconds. This means that the pump power requirement for applying gain-switching is more than an order of magnitude higher. However, gain-switching is increasingly interesting due to the decreasing cost of pump diodes and the all-fiber construction [10].

Convenient pumps for gain-switching of fiber lasers are fiber-coupled diode lasers or another fiber laser depending on the pumping wavelength and the pumping geometry. The nominal pump absorption in the core of a doped fiber is typically more than 100 dB/m. This means that in core-pumping the fiber can be short (centimeters), but when the pump power exceeds tens of Watts problems with heat dissipation occurs [11]. To get around the problem of power scaling the cladding-pumping geometry can be used. The cladding pump absorption is typically less than 10 dB/m, which means that the cavity length should be a few meters to maintain a sufficient absorption of the pump. Furthermore, the brightness of the pump can be reduced so that low cost and high power diode pumps are applicable [10].

In this paper we will focus on gain-switching of cladding-pumped Yb-doped silica fiber lasers due to their power scalability and the vast amount of applications [1,2,7]. The underlying physics and correlations of gain-switching are thoroughly investigated. The derived analytic relations are confirmed with experimental data over a wide range of parameters. We point out that the length of passive fiber, in which the FBGs are written, is crucial in the analysis and introduces a global minimum achievable pulse duration occurring at an active fiber length that increases with the passive fiber length. Furthermore, we show that the peak power can not be increased by minimizing the pulse duration, if this is done by shortening of the active fiber. We therefore present a comprehensive picture of the design variables, which enables optimization

of the pulse duration, the peak power, and the pulse energy.

2. Model of gain-switching

The quantitative description of the process of gain-switching is quite involved due to the linear growth of the population inversion at the same time as the exponential amplification of spontaneously emitted photons (ASE), which reduces the population inversion. This dynamics are sensitive to the exact fiber geometry and doping concentration, and therefore fitting parameters are required [12]. Solving the involved gain-switching dynamics numerically is out of the scope of this paper. Instead we derive an analytic solution to a simplified model, which has the advantage of not requiring any fitting parameters in contrast to more general numerical models [12].

We assume that the population inversion and the photon density are homogeneously distributed along the length of the cavity. This is a fair approximation when the cavity round trip time is much faster than the pulse generation process. Therefore, we can consider the simple rate-equations for a point model of a quasi four level laser medium, for which the population inversion density (n) and the photon density in the cavity (ϕ) are given by [8]:

$$\frac{dn}{dt} = -\Gamma c \sigma_e n(t) \phi(t) - \frac{n(t)}{\tau_2} + p \tag{1}$$

$$\frac{d\phi}{dt} = \Gamma c \sigma_e n(t) \phi(t) - \frac{\phi(t)}{\tau_c} + S - c\phi(t)\delta, \tag{2}$$

where Γ is the effective overlap of the optical mode and the doped area, c the speed of light in the medium, σ_e the emission cross section at the signal wavelength λ_{sig}, τ_2 the upper state lifetime, p the photon pump rate density (m^{-3}s^{-1}), τ_c the cavity decay time, S the source of photons due to spontaneous emission, and δ the loss. In the following the fiber loss is small and therefore neglected.

We define $n_1(t) = n(t) - n_s$ and $\phi_1(t) = \phi(t) - \phi_s$, where the steady state solution is given by $n_s = p_s \tau_2$, $\phi_s = \tau_c(p - p_s)$, and the threshold power is defined as $p_s = (\Gamma c \sigma_e \tau_c \tau_2)^{-1}$. We then linearize Eqs. (1) and (2) around the steady-state solution by assuming that $n_1 \phi_1 = 0$. This gives the equation [8]

$$\frac{d^2 \phi_1}{dt^2} + (\Gamma c \sigma_e \phi_s + \tau_2^{-1})\frac{d\phi_1}{dt} + (\Gamma c \sigma_e)^2 n_s \phi_s \phi_1 = 0. \tag{3}$$

It can be shown that the equation is dominated by the last term because τ_2 is much longer (hundreds of microseconds) than τ_c (nanoseconds) for rare earth doped glasses [8]. From the solution to Eq. (3) we find the period of the relaxation oscillations, which is given by

$$T_R = 2\pi\sqrt{\tau_2 \tau_c}(p/p_s - 1)^{-1/2} \approx 2\pi\left(\frac{n_{SiO_2} AL}{c_0 \Gamma \sigma_e} \frac{h\nu_p}{P_{abs}}\right)^{1/2}, \tag{4}$$

when we assume that the laser is driven well above threshold ($p/p_s \gg 1$). We used that $c = c_0/n_{SiO_2}$, and that the photon density is related to the absorbed pump power by $p = P_{abs}/(ALh\nu_p)$, where A is the core area, and $h\nu_p$ the pump photon energy. The total cavity length is the sum of the passive and the active fiber length $L = L_{pas} + L_{Yb}$. The absorbed pump power is related to the active fiber length by $P_{abs} = P_{pump}(1 - exp\{-0.23\alpha_{dB}L_{Yb}\})$, where α_{dB} is the pump absorption coefficient and P_{pump} is the incident pump power. In [9] the same expression as Eq. (4) is derived, except that the overlap Γ is not taken into account as we do here.

At first glance it might seem unreasonable to use the linear stability analysis of the rate equations to describe the gain-switching process, which is not a small perturbation to a steady state. However, in the gain-switching process the population inversion oscillates out of phase with the photon density, which means that the assumed product $n_1 \phi_1 = 0$ is a fair approximation. We have also confirmed numerically that the approximation is applicable.

The relaxation oscillation period is central for gain-switching because it dictates the time scale of the dynamics. In [9] the pulse duration t_0 of pulses produced by gain-switching of an Nd-doped, core-pumped fiber laser was found theoretically and experimentally to be related to T_R by

$$t_0 = T_R/\pi^2. \tag{5}$$

The pulse duration, therefore, has a square root dependence on the cavity length and the core area and an inverse square root dependence on the pump power. This is in contrast to Q-switching where the pulse duration depends on the mirror reflectivities and has a linear dependence on the cavity length [8].

In the following we demonstrate experimentally the validity of the relation for the pulse duration, and show that the length of passive fiber has a strong influence on the cavity design and the minimum achievable pulse duration.

3. Experimental setup and method

The experimental setup is illustrated in Fig. 1. The fiber laser consists of a 12 μm core Yb-doped double clad fiber with a cladding pump absorption (α_{dB}) of about 2 dB/m at 915 nm and 6 dB/m at 976 nm. The cladding diameter is 125 μm. The active fiber is spliced in-between the high reflectance (HR) and the low reflectance (LR) fiber Bragg gratings (FBGs). Fiber coupled pump diodes are spliced through a 7:1 combiner to the cavity. The HR FBG has a reflectivity of >99%, a center wavelength and bandwidth of 1064 nm and 1.9 nm, respectively. The LR FBG has a 3 dB bandwidth of 0.9 nm and a peak reflectivity of 15%. The total length of passive fiber in the cavity was chosen to 1.1 m in order to clearly identify the influence. The active fiber has a core NA of 0.08 and is coiled to a diameter of 0.1 m to force single-mode operation without compromising the efficiency. The fiber laser is tested in CW mode. When pumping with 915 nm diodes the achieved slope efficiency with respect to absorbed pump power is 83% (the quantum defect is 86%) at the longest active fiber length of 7 m and it decreased to 67% at 0.5 m. For 976 nm pumping the maximum slope efficiency reaches 90% (the quantum defect is 91.7%).

Fig. 1. Yb-doped fiber laser pumped by the diode pumps that are spliced to a high reflector fiber Bragg grating (HR FBG). A varying length of Yb-doped fiber is spliced to the HR and the low reflector grating (LR FBG). By modulating the pumps the laser produces stable pulses.

In gain-switching the pumps are modulated and the pump pulse duration is adjusted to co-incide with the build-up time, i.e. the time before emission of the peak in the relaxation oscillations. The maximum rise and fall time of the pump pulses are 0.4 μs and the typical pump pulse duration is 1.6–3.5 μs depending on the pump power. A pump power of 75 W at 915 nm or 100 W at 976 nm is used. The narrow absorption peak of Yb doped silica at 976 nm requires

careful control of the pump central wavelength, which is tuned by the heat sink temperature, pump current, and duty cycle.

The pulse duration (FWHM) of the output pulses are found by a Gaussian fit to data measured with a fast photodiode and a digital oscilloscope. Typical pulses are shown in Fig. 2, from which it is seen that the envelope is well-defined, which means that the stability is high. In the following the fiber laser is only operated in the stable regime. Longitudinal mode beating results in random fringes on top of the envelope.
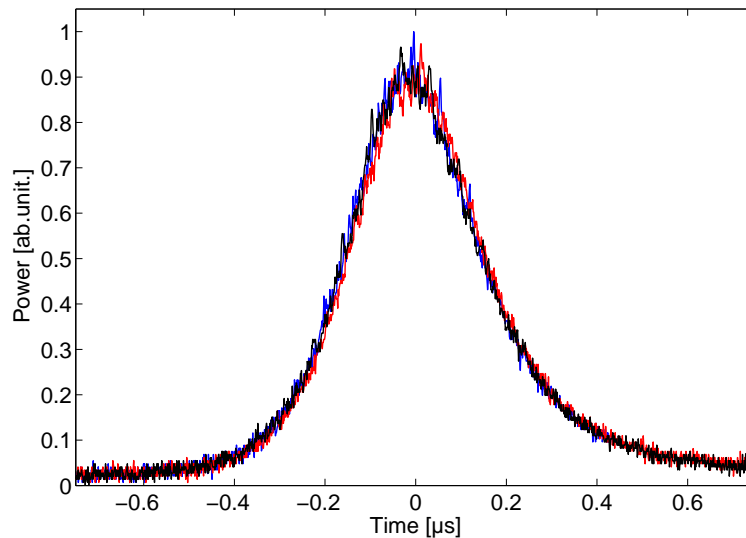

Fig. 2. Three superimposed pulses from a typical pulse train (red, blue, and black lines). The timing jitter and the peak power fluctuations are low, hence the stability is high. Longitudinal mode beating results in random fringes on top of the envelope.

4. Gain-switching results

The cladding-pumped fiber laser is gain-switched for a range of pump power levels, pump wavelengths, and doped fiber lengths. In Fig. 3 the resulting pulse durations are shown for 915 nm diodes with a pump power level of 25–75 W and for 976 nm diodes with a pump power level of 100 W. The cavity length is varied between 1.6 m and 8 m (corresponding to 20%–95% absorption efficiency). The pulse duration varies from 80 ns at the highest pump power level to 260 ns at the lowest. Results from [2,12] are also included. The dotted lines in the plot are found using Eq. (5) and a good agreement with the experimental results can be seen. Considering the large parameter space spanned (cavity length, pump wavelengths, pump power, core diameter, and doping level), the validity of Eq. (5) can be confirmed.

At small cavity lengths of 2–3 m, a minimum of the pulse duration for a fixed pump power level can be seen in the experimental data as well as in the analytical results. We have not seen such a minimum reported in the literature before. Note also that the cavity length at the minimum is independent of the pump power level. This minimum can be explained by the presence of a certain length of passive fiber in the cavity of $L_{pas} =1.1$ m. To illustrate the influence of the passive fiber on the pulse duration, we have plotted the duration for various passive lengths in Fig. 4. They have been calculated by using Eq. (5). In the figure it is seen that decreasing the passive fiber length reduces the pulse duration, which is expected. It is also seen that the minimum pulse duration occurs at a shorter active fiber length, the shorter the passive
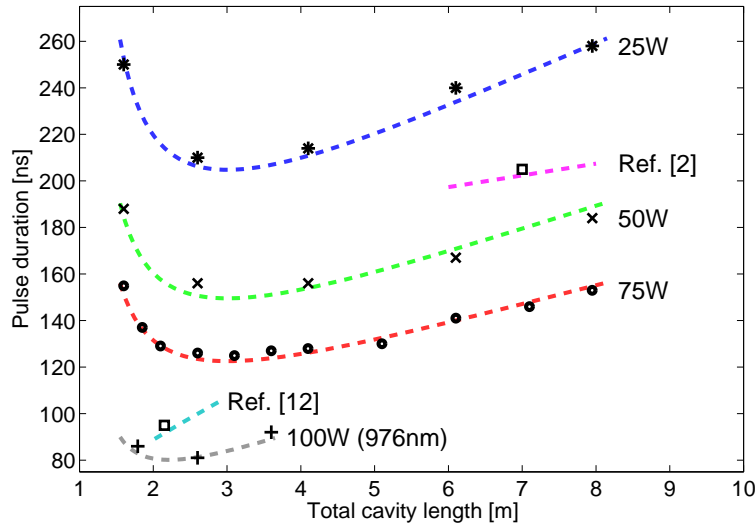
Fig. 3. Pulse duration versus cavity length. The pump power at 915 nm is varied from 25 W–75 W and the pump power at 976 nm is fixed at 100 W. The points mark experimental results. The dotted lines are the results predicted by Eq. (5) with n_{SiO_2}=1.45. The emission cross section is provided by the manufacture and is $\sigma_e = 2.5 \times 10^{-25} \text{m}^2$. The overlap Γ=0.93 is evaluated by use of a mode-solver. Note that the active fibers used in [2, 12] are different from the fiber used in this study.

fiber length is. Gain-switched all-fiber lasers are commonly constructed with FBGs that add a certain length of passive fiber to the cavity, and thus this minimum in the pulse duration is important to take into account. In [12] the active fiber length was also reduced but a minimum in the pulse duration was not identified and the influence of a passive fiber length was not discussed.

Above we have analyzed the pulse duration and seen that a short active fiber and as short as possible passive fiber result in the most narrow pulses. We now consider optimization of the peak power, which is critically important in for example long-pulse supercontinuum generation initiated by modulation instability (where the gain is proportional to the peak power) [7, 13]. In recent publications [12, 14, 15] the peak power was shown to vary linearly with the pump power for a fixed active and passive fiber length. However, the effect of varying the cavity length on the peak power was not explained in detail.

The peak power of the pulses is shown in Fig. 5 for the data with 915 nm pumping. It is seen that the peak power increases with the pump power, and that for a fixed pump power the peak power saturates as the active fiber length is increased. In [12] this saturation with active fiber length was shown numerically but three measurements showed a significant discrepancy. Here our more comprehensive experiments for several pump power levels confirm the saturation. This saturation is related to the fact that for lengths longer than 6 m the pump absorption is >12dB and increasing the length will only increase the gain marginally.

Considering that the absorbed pump power saturated with the active fiber length as $P_{abs} = P_{pump}(1 - exp\{-0.23\alpha_{dB}L_{Yb}\})$, we show with dashed lines in Fig. 5 a fit of the peak power to this dependence by

$$P_{peak} = \beta P_{abs}, \qquad (6)$$

where the slope β is found to be 9.1 W/W for all pump power levels. The good agreement means that the peak power depends linearly on the *absorbed* pump power both when only the
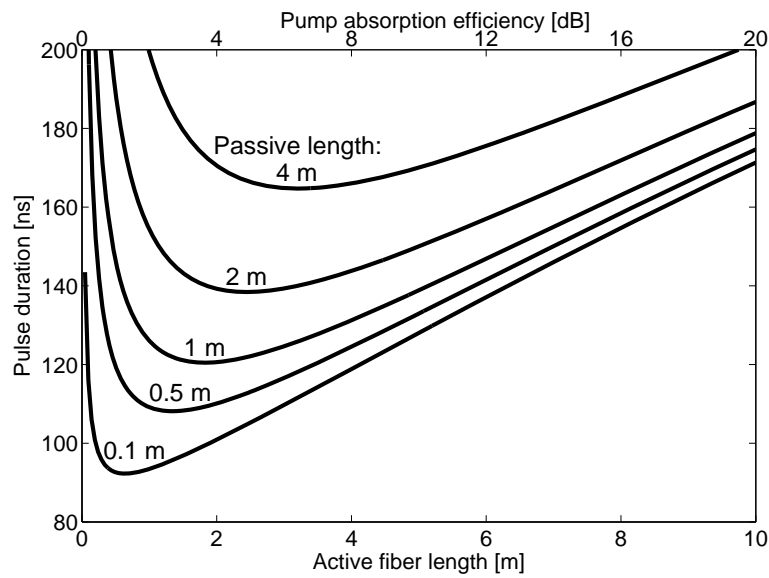
Fig. 4. Calculated pulse duration vs. length of the active fiber (pump absorption efficiency) for passive fiber lengths between 0.1 m and 4 m. It is calculated by Eq. (5) using 75 W pump, an $\alpha_{dB}(915\ nm) = 2$ dB/m, and the same fiber parameters as in Fig. 3.
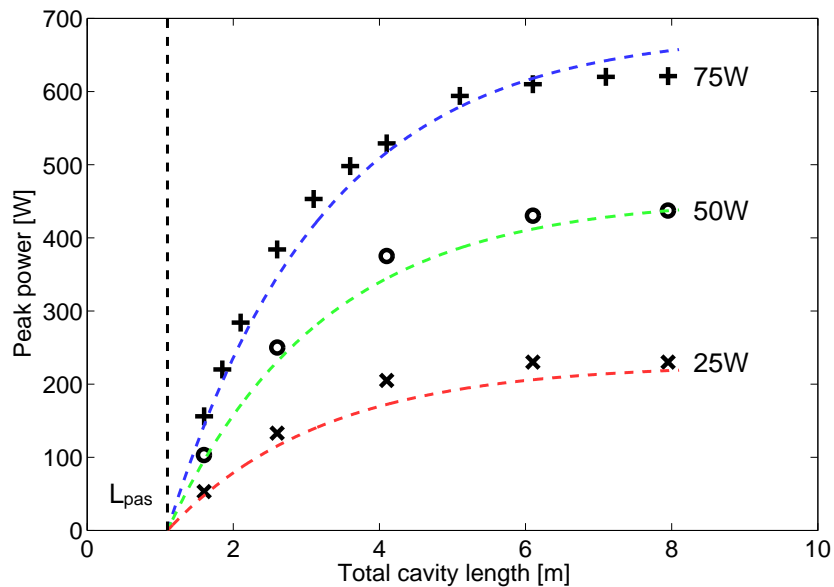

Fig. 5. Peak power versus total cavity length for the result with 915 nm pumping. The dashed lines are fits given by $P_{peak} = 9.1P_{pump}(1 - exp\{-0.23\alpha_{dB}L_{Yb}\})$. The passive length of 1.1 m is indicated by the vertical dashed line.

pump is varied and also when only the active fiber length is varied.

To further test this generalization, we have plotted the peak power against the absorbed pump power in Fig. 6, for several pump powers, pump wavelengths, and active fiber lengths. A clear linear dependence can again be seen. Given the span of tested pump power levels, pump wavelengths, and cavity lengths we find it reasonable to believe that the slope only differs slightly for other Yb-doped fiber lasers. This is further supported by the fact that a slope of ∼9.4 W/W can be extracted from [12], where the cavity length was fixed to 2.12 m and pump wavelength was fixed at 976 nm.

The results from our investigation therefore show that the length of passive fiber in the cavity has a negligible influence on the peak power. To control this finding we have reduced the passive length to 0.5 m, and found an unchanged peak power, which confirms this result.
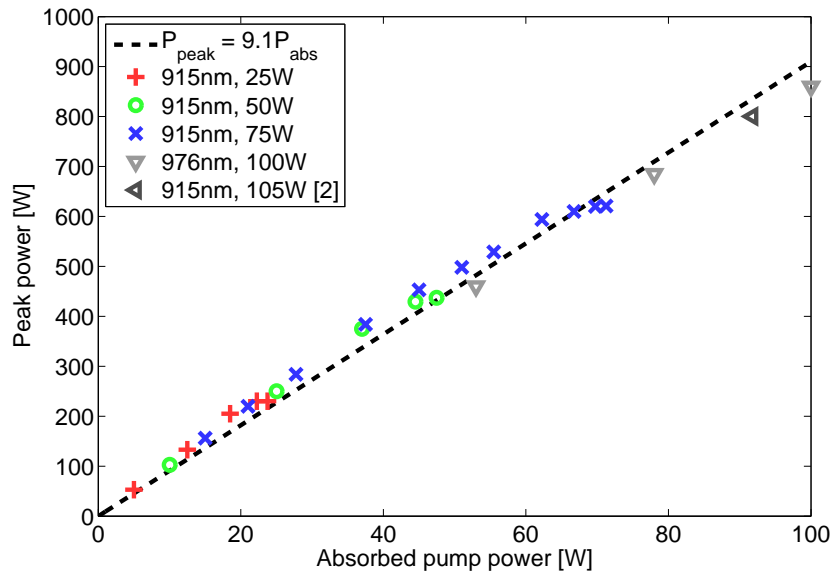

Fig. 6. Peak power versus absorbed pump power. The linear fit shows a slope of 9.1 W/W. The result at 915 nm and 105 W is from [2]

5. Discussion

Above we have derived analytic formulas for the characteristics of gain-switching, which enable us to discuss the important output pulse parameters: pulse duration, peak power, and pulse energy. Such an analytical theory is highly desirable [1], and provides a better intuitive understanding and is a stronger design tool than numerical simulations [12].

Cladding pumping is advantageous in regards to power scaling because the generated heat is distributed over a long fiber length. A long cavity length, however, leads to a long duration of the pulses, and minimizing the pulse duration turns out to be rather challenging. The pulse duration scales as $P_{pump}^{-1/2}$ and the scaling possibilities are typically limited by the available pump power. Controlling the pulse duration by the fiber design involves tuning the core area, dopant concentration (N), and cladding area (A_{clad}). In this regard the pulse duration scales as $t_0^2 \propto A(L_{Yb}+L_{pas})\left[1-exp\{-N\sigma_a\Gamma AL_{Yb}/A_{clad}\}\right]^{-1}$. Increasing N, σ_a and decreasing A_{clad} will increase the pump absorption and hence reduce the pulse duration. The influence of the core area and the active fiber length is not trivial, and therefore in Fig. 7 the pulse duration is

calculated for fibers with core diameters between 5 μm and 20 μm. It is seen that the smallest fiber core results in the shortest pulse duration. However, if one wants a fixed high peak power then the required active fiber length increases rapidly when the core diameter decreases, in order to maintain the same pump absorption. This is illustrated in Fig. 6 with the dashed line, which corresponds to a pump absorption of 10 dB and a peak power of 615 W.
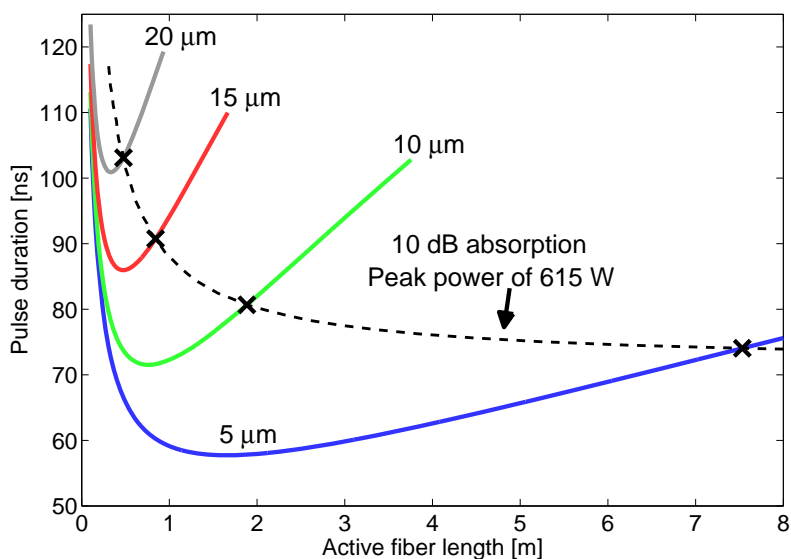

Fig. 7. Calculated pulse duration vs. length of the active fiber for fiber core diameters between 5 μm and 20 μm. The 'x's corresponds to 10 dB absorption and the peak power will at these points be 615 W for all core diameters. It is calculated by Eq. (5) using 75 W pump and $N = 9 \times 10^{25}$m^{-3}, $\sigma_a(976\ nm) = 2.5 \times 10^{-24}$m^2, $\Gamma = 0.85$, $A_{clad} = 0.25\pi125^2\mu$m^2, and $L_{pas} = 0.5$m.

The peak power is shown to depend linearly on the absorbed pump power, and hence the passive fiber play no role for the obtainable peak power. Given our results, a typical diode pump module with a power of 25 W can produce a pulse with a peak power of more than 200 W and an average power of more than 10 W, when driven with a realistic duty cycle of 50%. Some applications require a higher peak power, e.g. in the tens of kilowatt regime, and in this case the pump power needs to be in the kilowatt range. This increases the complexity and the cost of the laser significant. A more cost-effective solution would be to generate gain-switched pulses with a moderate pump power and then amplify them in a large mode area fiber amplifier [7, 16, 17].

The product of the peak power (P_{peak}) and pulse duration (t_0) gives the output pulse energy (E), hence $E = P_{peak}t_0 = \beta P_{abs}T_R/\pi^2$. The measured pulse energies are up to 100 μJ, which fit excellent to the relation. The pulse energy therefore scales as $E \propto (ALP_{abs})^{1/2}$. This is in contrast to Q-switching, where it has been shown that the maximum energy that can be extracted from a fiber is about 10 times the saturation energy, $E_{sat} = Ah\nu_{sig}/\Gamma\{\sigma_e + \sigma_a(\lambda_{sig})\}$ [10]. The significant difference is that the pulse energy in gain-switching has a dependence on the cavity length. The upper limit of the pulse energy will be given by the nonlinearities and the damage threshold of the fiber. We can estimate that a pulse energy of 2 mJ can be reached using a state of the art pump ($\sim$600 W) and 30 m large mode area fiber (30 μm core diameter). For such pulses the estimated peak power exceeds 5 kW, the pulse duration is less than 350 ns, and the

average power is more than 250 W when the pump is driven with a realistic duty cycle of 50%.

6. Conclusion

Gain-switching is a cost-effective method for constructing pulsed fiber lasers and is interesting for many applications. This study on cladding-pumped gain-switched fiber lasers is motivated by the power scalability and simplicity of such lasers. We focused on an all-fiber configuration in which the presence of a section of passive fiber is taken into account.

We have used a linear stability analysis of the well-known rate equations to find the period of the relaxation oscillations and thereby an analytical expression for the pulse duration. We have measured the pulse length for a range of doped fiber lengths and pump powers for several pump configurations including pumping at both 915 nm and 976 nm. The experimental results confirm the theoretical expressions, in particular the predicted doped fiber length for which the minimum pulse duration is achieved for a given pump power.

In particular we have investigated the influence of an often present length of passive fiber in the cavity and shown that it introduces a finite minimum in the achievable pulse duration. This minimum pulse duration was shown to occur at longer active fibers length with increased passive length of fiber in the cavity. The peak power was observed to depend linearly of the absorbed pump power and be independent on the passive fiber length. Given these conclusions, the pulse energy, duration, and peak power of cladding pumped gain-switched fiber lasers can be estimated with good precision.

Acknowledgments