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Stability of Er/Yb-doped fiber DFB laser with external reflections

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Abstract

The maximum tolerable amplitude back-reflection coefficient $r_{ext,c}$ into a fiber distributed feedback (DFB) laser before onset of instabilities has been investigated. $r_{ext,c}$ was found to decrease with increasing external cavity lengths up to about 320 m, and to be proportional to the relative linewidth of the relaxation oscillation resonance. The tolerable length of Rayleigh back-scattering standard telecom fiber was found to be between 135 and 200 m. An observed degradation in the laser stability and slope efficiency at low pump powers is believed to be due to UV-induced saturable absorbers.

Fiber DFB lasers are attractive used as sensor elements with optical frequency interrogation due to their low frequency noise and stable longitudinal mode operation. Remote pumping and interrogation of such sensor lasers through a long lead fiber may be required. For operational reasons, the use of optical isolators near the sensing point may be undesirable. Consequently, the laser will experience Rayleigh back-scattering from the lead fiber.

If in addition several sensor lasers at different wavelengths are serially multiplexed along the same fiber,[1] each laser may also experience reflections from the grating side-bands of the other lasers. It is known that external back reflections can cause excess frequency noise or even self-pulsing in narrow linewidth semiconductor lasers.[2] This problem increases with decreasing laser mirror reflectivity and with increasing distance to the external reflector. However, important parameters such as the optical coherence lengths and the relaxation oscillation resonance Q-factors and center frequencies differ largely between semiconductor lasers and fiber DFB lasers. Therefore, few quantitative conclusions can be made about fiber DFB laser stability from existing work on semiconductor lasers.

In this Letter we report on the tolerance of an Er/Yb-doped fiber DFB laser to external back-reflections. The investigated laser operated at 1549 nm in two polarization modes and was pumped by a 1480 nm diode laser. It was produced by writing a symmetric π phase-shifted grating of length L =40 mm into a UV-sensitized B/Ge doped ring enclosing the Er/Yb doped core of the fiber[3]. D_2-loading was used to enhance the UV-sensitivity. The grating coupling coefficient of the laser was measured by a heat-perturbation method[4] to be κ =230 m^{-1}±10%. Before UV exposure but after D_2-loading of the fiber, the fiber transmission spectrum was measured for various pump powers. From these measurements, the absorption (a_x) and gain (g_x) at zero and full inversion, respectively, at the laser signal ($x = s$) and pump ($x = p$) wavelengths were found to be $[a_s,\ a_p, g_s,\ g_p] = [11.7,\ 8.9,\ 15.9,\ 3.0]$ dB/m. The spontaneous emission power at full inversion was $P_{sp} = 4.1$ mW/m.

Figure 1 shows the measured left+right output power (crosses) emitted from the laser versus pump power. Curve A shows the theoretical output power, obtained from the measured gain parameters of the unexposed fiber and a DFB laser model described elsewhere.[5] The measured slope efficiency increases at low pump power and approaches a constant value of 0.7% above 40 mW. This indicates that bleachable absorbers are present which saturate for pump powers >40 mW. A good theoretical fit (curve B) was obtained by assuming a lifetime reduction ("quenching") by a factor of ζ = 26 for a fraction ξ = 37.7% of the Er-ions, and unbleachable losses of a_0 =0.243 dB/m. Here, ξ is essentially determined by the laser threshold, ζ by the position of the "knee" in the output power curve near 30 mW and a_0 by the slope efficiency at high pump powers.

It may be noted that higher slope efficiencies (>10%) could be obtained by pumping at 980 nm. However, the high pump absorption per laser in this case makes serial sensor multiplexing impossible. Moreover, the increased heat dissipation from the laser may disturb the sensor performance. For accurate interrogation of the laser as a sensor, the output power obtained with 1480 nm pumping is more than sufficient.

Before UV exposure the loss saturation versus bleaching power was measured for the laser fiber at 1535 nm. Parameter fitting to these measurements shows that less than $\xi_{\max} = 5\%$ of the Er-ions were quenched by the factor $\zeta = 26$. The unbleachable losses were limited to $a_0 < 0.3$ dB/m. Moreover, the transmission spectrum versus pump power measurements show that the effective value of ξ does not vary significantly between 1535 nm and 1549 nm. Consequently, the majority of the bleachable absorbers seem to have been introduced during the UV exposure.

The relaxation oscillation resonance Q-factor $Q_r = f_r/\Delta f_r$ of the solitary laser was also measured, and is shown as circles in Figure 1. Here, f_r is the peak frequency and Δf_r the 3 dB peak-width of the intensity noise spectrum. Below a pump level of 40 mW the laser was self pulsing. Above 40mW a steep reduction in Q_r was observed, parallel with the bleaching of the UV-induced absorbers. It is known that bleachable absorbers can cause laser instabilities,[6] and it is believed that the bleachable absorbers play an important role in reducing the stability of the investigated laser at low pump powers. f_r followed a nearly linear dependence (±1.5 kHz) on the pump power between f_r=109 kHz at 42 mW and f_r=207 kHz at 83 mW.

Figure 2 shows the setup used to study the effects of back-reflections. The laser was pumped from the left, and the left output power was guided through a wavelength division multiplexer (WDM), a polarization controller (PC2), an isolator (ISO) and a polarization beam splitter (PBS) to the detectors D1 and D2. PC2 was adjusted so that each detector received light from only one laser polarization mode. Back-reflection into the right end of the laser with variable attenuation, phase-shift, polarization-shift and delay was generated by use of a variable attenuator (VA), a piezo-electric fiber stretcher (PZT), a polarization controller (PC1) and a selection of delay coils with -14.5 dB cleaved end reflectors.

With an external cavity length of L_{ext} =22.3 m and a pump power of 83 mW, the effective external reflection coefficient r_{ext} seen by the laser was first adjusted to its critical value, $r_{ext,c} = -28.3\pm 1$ dB, where relaxation oscillation noise bursts started to occur for worst case settings of PC1 and the PZT voltage. By "worst case" we mean that the noise amplitude was at its maximum. Figure 3 shows the evolution of the left output power P_{left} from the laser (recorded by D1+D2) when the PZT was driven by a triangular waveform. The round-trip phase modulation ϕ_{ext} induced by the PZT is also shown in the figure. The periodic relaxation oscillation noise bursts are believed to be related to mode-hopping or to unstable regimes at the transitions between external cavity modes.[2] For higher back-reflection levels the laser was continuously self-pulsing. The deterministic dependence of P_{left} on ϕ_{ext} is believed to be due to a modulation of the effective right mirror reflectivity of the laser.

When PC1 was in its worst case position, the power fluctuations of the two laser polarization modes were practically equal and in phase. This indicates equal back-reflection phase shifts for the two polarizations. For other settings of PC1, the fast relaxation oscillations of the two polarizations would still be in phase, but the sign of the deterministic power oscillations could be made opposite for the two modes. For moderate phase modulation speeds ($d\phi_{ext}/dt < 5$ rad/ms), $r_{ext,c}$ could be increased by at least 10 dB by adjusting PC1. However, control of the reflected polarization to ensure stability is believed to be unrealistic in most real applications.

Figure 4 shows $r_{ext,c}$ measured for nine different combinations of L_{ext} and pump power, using worst case settings of PC1. Simulation results reported for semiconductor lasers[7] show that $r_{ext,c}$ versus L_{ext} decreases steeper than -20 dB per decade for $L_{ext} < L_r = c/2nf_r$, and flattens out for longer lengths. Here, L_r corresponds to a feedback delay of one relaxation oscillation period, c being the speed of light in vacuum and n the refractive index of the fiber. The results in Figure 4 are in qualitative agreement with the simulations.

For L_{ext} =22.3 and 318 m the measurements satisfy $r_{ext,c} \propto Q_r^{-1}$ to within ±0.6 dB. This is expected, as it can be shown that the phase stability margin of the intensity feedback loop that causes the relaxation oscillation resonance of the solitary laser equals Q_r^{-1} (rad). For L_{ext} =1518 m the deviations from $r_{ext,c} \propto Q_r^{-1}$ are larger. This may be related to variations in the relaxation oscillation phase $\Phi = 2\pi L_{ext}/L_r$ of the external feedback when L_r changes (c.f. table in Figure 4).

The feedback parameter[2,7] C can be written for a DFB-laser as

$$\begin{aligned} C &= \sqrt{1+\alpha^2}\frac{2L_{ext}}{L_L}T_2 r_{ext} \\ &= \sqrt{1+\alpha^2}4\kappa\exp(-\kappa L)L_{ext}r_{ext} \end{aligned} \tag{1}$$

with $L_L = 2/\kappa$ being the effective round-trip path length of the laser, L the DFB-grating length, $T_2 = 4\exp(-\kappa L)$ the power transmission coefficient of the right half of the grating, $\alpha = d\chi'/d\chi''$ the linewidth broadening factor and $\chi = \chi' + i\chi''$ the complex susceptibility of the gain medium. The limit $C = 1$ when assuming $\alpha = 3$ is shown in Figure 4. Below this line, only one external cavity mode solution will exist for any value of ϕ_{ext}, and mode-hopping cannot occur. Still, unlike the findings for semiconductor lasers,[2,7] self oscillations were observed for our investigated laser in this regime. This may partly be due to errors in the estimates for α and κ, which may cause significant errors in C. Moreover, it is believed that high-Q_r lasers like the one investigated can become unstable even for $C < 1$. This is because the laser stability margin Q_r^{-1} will be somewhat modified by the back-reflection.

Simulation results reported for an Er-doped amplifier[8] indicate that α is proportional to the signal to saturation power ratio P_s/P_{sat}, approaching $\alpha \sim 3$ for $P_s/P_{sat} = 20$. For our laser an effective ratio $4 < P_s/P_{sat} < 20$ is estimated, depending heavily on the ±10% error margin of κ. Thermal effects may also contribute to the effective value of α, as the refractive index depends on the laser power through self-heating of the cavity.

The tolerance to Rayleigh back-scattering was tested by disconnecting the VA and splicing a coil with standard telecom fiber to the right laser output. The coil end was terminated with bending losses. For 83 mW pump the laser was found to be stable with Rayleigh scattering from $\leq$135 m of fiber. At 135 m noise bursts could be observed in response to severe acoustical noise, such as clapping hands in the laboratory. Bursting or continuous self oscillations were observed for lengths $\geq$200 m. The dashed line in Figure 4 corresponds to a typical Rayleigh back-scattering level of -72 dB/m. The cross-over point between this line and the straight line interconnecting the discrete reflection measurements is at 175 m, which is in good agreement with the Rayleigh measurements.

In conclusion, we have found that $r_{ext,c}$ has a proportional dependence on the stability margin Q_r^{-1} of the solitary laser, and decreases with increasing external cavity length for $L_{ext} < L_r$. Both the stability margin and the slope efficiency of the laser were found to decrease dramatically at pump powers below 60 mW. This is believed to be related to saturable absorbers introduced during the UV-exposure. The laser frequency noise has not been measured in the present experiment. However, recent back reflection studies of similar fiber DFB lasers[9] have shown that the occurrences of excess frequency and intensity noise are highly correlated. One way of improving the tolerance to back-reflections may be by increasing κL, as indicated by Eq. (1). There is, however, a limit to how high κL can be made before the laser tends to operate in higher order longitudinal modes.[4] Moreover, the effective value of α may increase as the intensity inside the cavity increases with κL, contributing to a reduced back-reflection tolerance.

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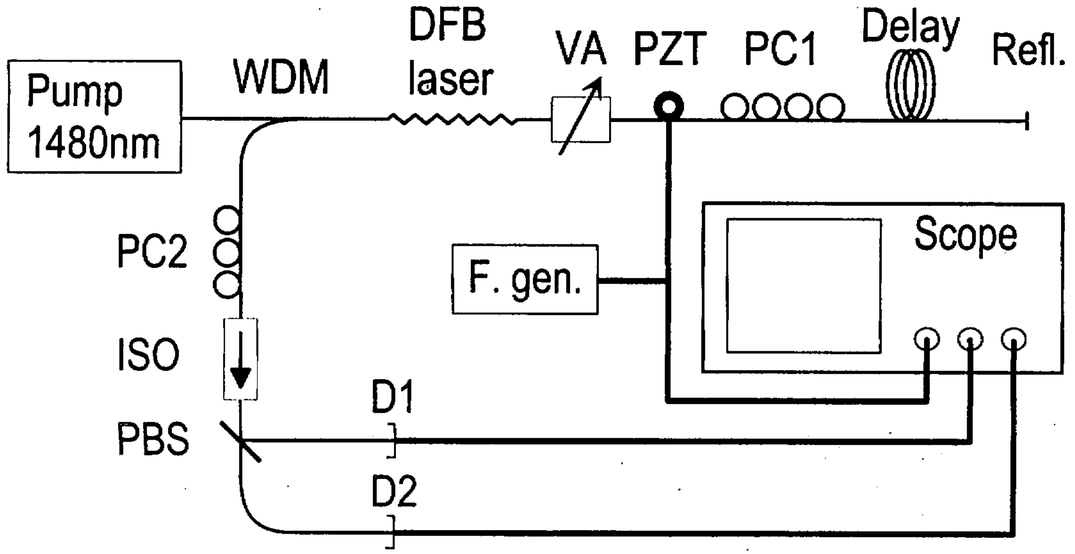
Figure captions

Fig. 1: Measured laser output power (crosses) and relaxation oscillation Q-factor Q_r (circles) versus pump power. Solid lines show theoretical output power assuming A: $\xi = 0$, $a_0 = 0$ and B: $\xi = 37.7\%$, $\zeta = 26$, $a_0 = 0.243$ dB/m.

Fig. 2: Setup for study of back-reflection induced self-oscillations.

Fig. 3: Scope traces of the left output laser power P_{left} and of the phase modulation signal ϕ_{ext} applied to the PZT. $L_{ext} = 22.3$ m and $r_{ext} = r_{ext,c}$.

Fig. 4: Measured critical external reflection coefficient $r_{ext,c}$ for different external cavity lengths L_{ext} and pump powers.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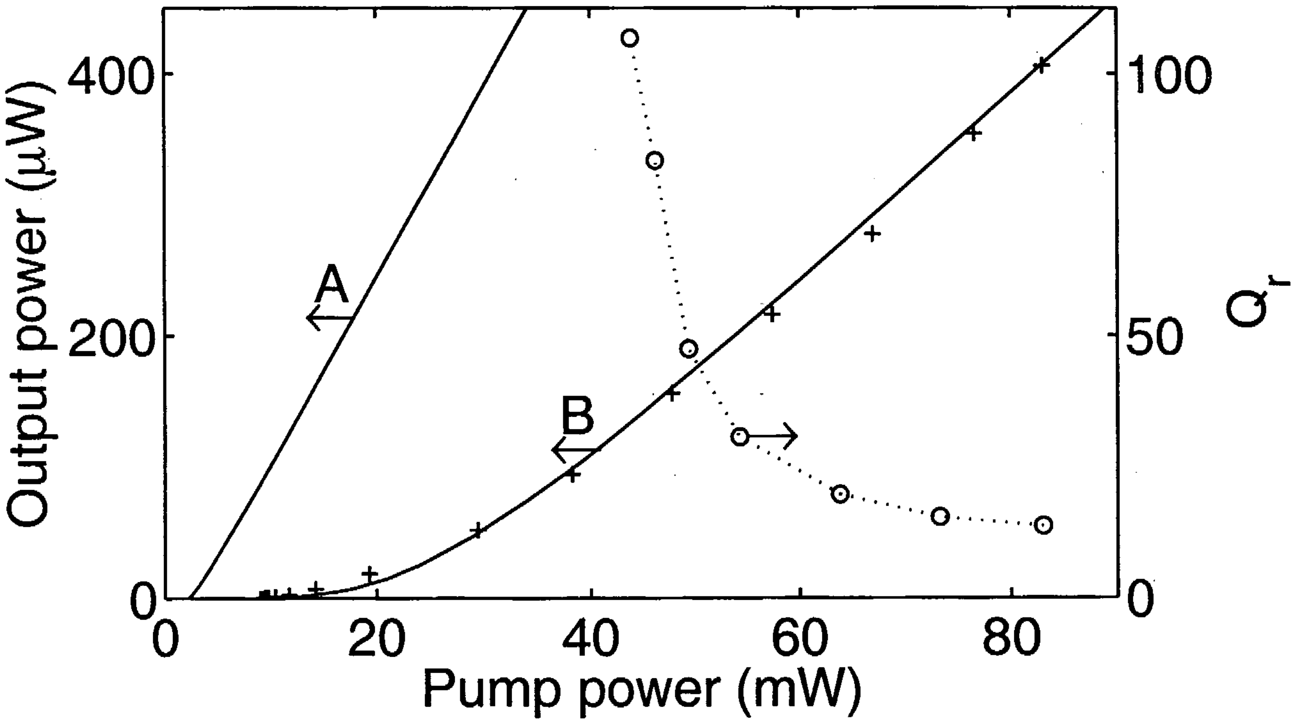
Output power (µW)
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200
0
0
20
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Pump power (mW)
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50
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Q_r
A
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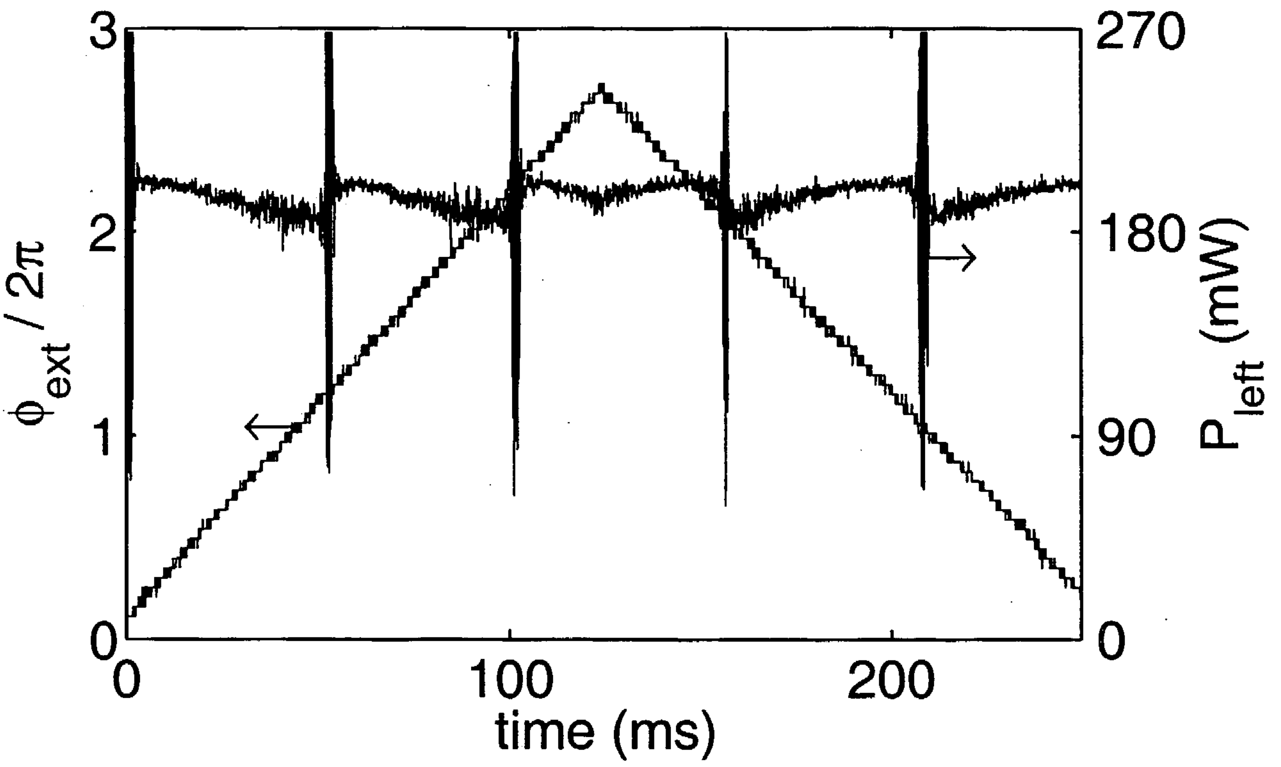
3
2
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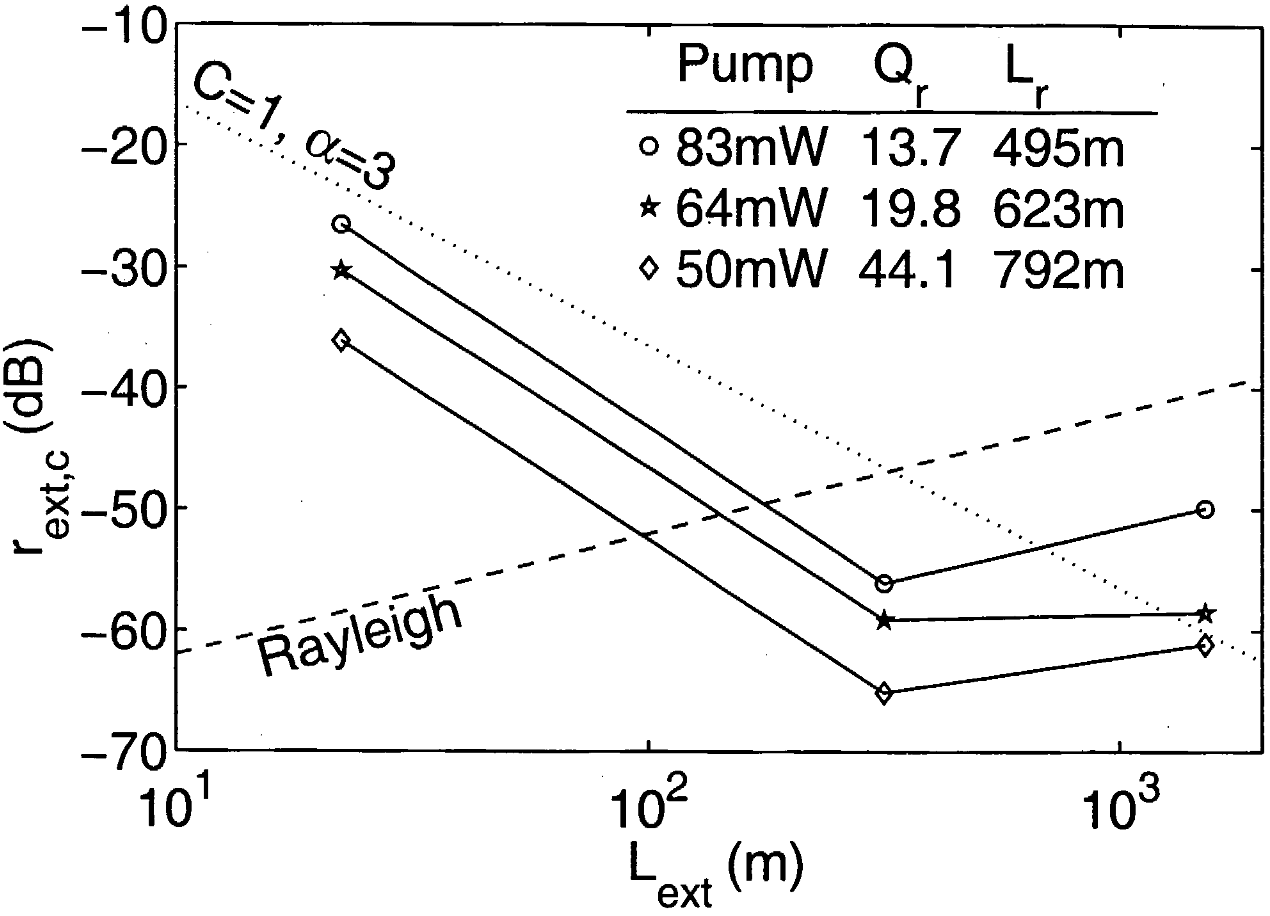
0
$\phi_{ext} / 2\pi$
270
180
90
0
P_{left} (mW)
0
100
200
time (ms)


−10
−20
−30
−40
−50
−60
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$r_{ext,c}$ (dB)
10^1
10^2
10^3
L_{ext} (m)
C=1, α=3
Rayleigh
Pump Q_r L_r
○ 83mW 13.7 495m
★ 64mW 19.8 623m
◇ 50mW 44.1 792m