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# Effect of thermal management on the properties of saturable absorber mirrors in high-power mode-locked semiconductor disk lasers

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***Abstract*.** **The thermal management of saturable absorbers is shown to have a critical impact on a high-power mode-locked disk laser. The absorber with efficient heat removal makes it possible to generate ultrashort pulses with high repetition rates and high power density.**

***Keywords***: *saturable absorber, semiconductor disk laser, ultrashort pulses, mode locking.*

## 1. Introduction

Semiconductor disk lasers (SDLs) are shown to be a promising candidate for multi-GHz short pulse generation which could be used in optical clocking, telecommunications and photonic switches [1]. The key to high power operation of SDLs is thermal management, which is usually accomplished with the so-called flip-chip thinned-structure design or by using an intracavity heat spreader. Normally, it is assumed that the extensive thermal management is applied to the gain medium only. However, the need for appropriate temperature control of the SESAM has been discussed elsewhere [2, 3].

Because the ratio of the average power to the pulse peak power increases with the repetition rate, the lasers producing GHz-range pulse trains exhibit a higher average power which is needed for the SESAM saturation and could further enhance the thermal load [4, 5]. The heating influences the SESAM characteristics through various versatile effects, particularly, due to temperature-dependent quantum-well bandgap energy, density of states, absorption, saturation fluence and modulation depth [6, 7]. Furthermore, without efficient heat removal, the thermal lensing effect could essentially deteriorate laser performance especially in cavities operating close to the stability limit, which is usually the case in high repetition rate mode-locked SDLs [8 – 10].

An improved thermal management of the SESAM could be obtained utilising the flip-chip scheme [3]. The flip-chip technology for the SESAM fabrication would assume a reverse growth order with subsequent substrate removal. As compared to intracavity heat spreader approach, this technique requires refined bonding and accurate etching to preserve high surface quality and prevent its contamination. The intracavity heat spreader is attached directly to absorbing section resulting in a short heat route, whereas in a flip-chip processed SESAM the heat generated in the absorbing layers is extracted through the distributed Bragg reflector (DBR) into the submount. This form of heat removal is especially harmful with DBRs having a low thermal conductivity. Thermal lensing is also expected to be stronger with the flip-chip design as compared to the intracavity diamond spreader approach [11]. Another limitation induced by the flip-chip SESAM design is that it prevents ion-irradiation on the wafer level and using surface-state assistance needed to achieve fast saturable absorption recovery.

Using quantum dot (QD) materials instead of widespread quantum well (QW) structures offers absorbers with a low saturation fluence, which allows a larger mode size and, consequently, reduces the thermal load on the SESAM [12, 13]. However, tailoring the operation of the QD material beyond 1.3 μm is problematic, making quantum well based SESAMs a primary candidate for long-wavelength mode-locked lasers [14, 15].

This study shows that thermal management of semiconductor saturable absorber mirrors should be considered for high-power mode-locked lasers. We demonstrate that the SESAM can significantly impair the output power and pulse quality when thermal management is not properly addressed.

## 2. Gain and SESAM structures

The epitaxial structures were grown in a single stage using the solid source molecular beam epitaxy (MBE) technique. The periodic-resonant gain structure with ten GaInAs quantum-wells and a GaAs/AlAs DBR forms a folding mirror of the cavity. The SESAM consisting of two GaInAs quantum wells was designed to operate at antiresonance at the laser wavelength. The saturation fluence of the SESAM was 10 J $cm^{-2}$, the modulation depth – 2 % and the nonsaturable losses – 0.5 %. The thermal management of both the gain element and the SESAM was achieved by capillary bonding them to 300 μm-thick type-III diamonds using de-ionised water. The assembly was then placed between two copper plates using a thin indium foil as a

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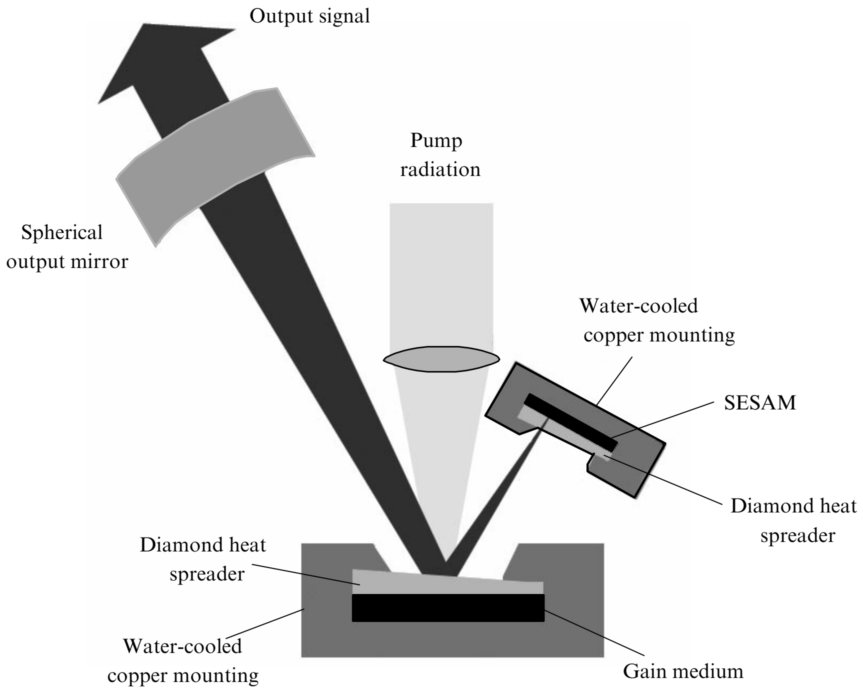


**Figure 1.** Schematic of a mode-locked disk laser. The gain chip is pumped at an angle of 25° with respect to the SDL cavity plane.

contact substance to ensure good thermal and mechanical contact. Finally, the 2° wedge diamonds were AR coated in order to prevent surface reflection. The temperature of the gain element and the SESAM was kept at 15 °C.

## 3. Experimental

The V-cavity of the disk laser consists of the mounted gain chip, SESAM and a spherical output mirror with radius of curvature of 50 mm and reflectivity 97.5%, as shown in Fig. 1.

The gain element was pumped through the diamond heat spreader with an 808-nm fibre coupled diode laser at an incident angle of 25°. The pump spot diameter on the gain element was 290 μm and the mode diameter on the SESAM was 94 μm. The geometry of laser cavity ensures a proper overlap of the pumped spot and the fundamental Gaussian mode at the signal wavelength.

## 4. Results

Figure 2 shows the dependence of the average output power and pulse duration on the pump power. One can see that the pulse duration of the disk laser using the SESAM equipped with an intracavity diamond heat spreader increases with increasing pump power [16]. With an efficient heat removal from the SESAM, the dominant factors in pulse formation are most likely the nonlinear phase shifts and dispersion.

The estimated single-pass contribution of the intracavity diamond heat spreader to the total cavity dispersion is 40 $fs^2$ and it could be neglected as compared with the dispersion induced by the periodic resonant gain structure [10]. The autocorrelation trace and the optical spectrum of the pulse train at an average power of 1 W are shown in Fig. 3. The repetition rate of the laser was 3.05 GHz.

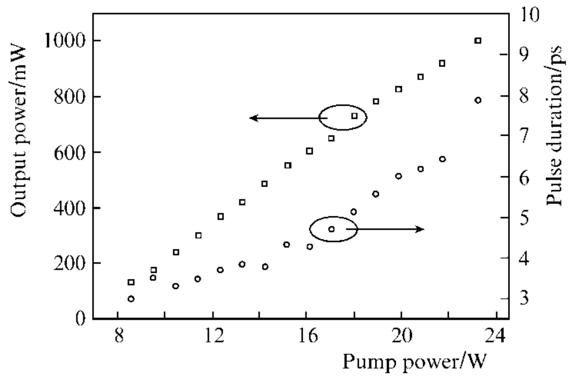


**Figure 2.** Average output power and pulse duration ($sech^2 x$ fit) as a function of pump power for a laser with an intracavity diamond heat spreader on the SESAM.

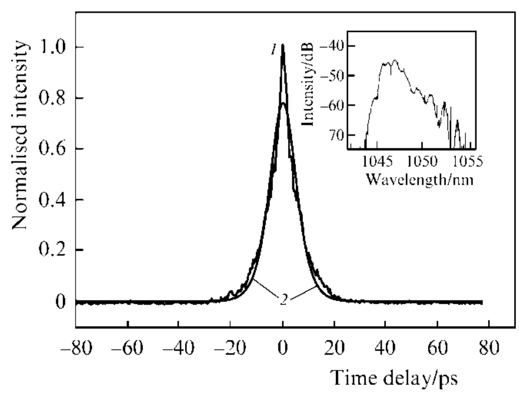


**Figure 3.** Pulse autocorrelation trace for the pulses with the average output power of 1 W (*1*) and with the $sech^2 x$ fit (*2*). The laser is equipped with an intracavity diamond heat spreader on the SESAM. The inset shows the corresponding optical spectrum of the pulses.

The microwave spectrum measured with a 3-kHz resolution comprises the fundamental frequency component and its harmonics with extinction over 60 dB, which indicates a steady-state highly periodic mode-locked pulse train. It was observed, that a non-ideal AR coating of the wedged diamond bonded to the SESAM induces some losses into the cavity and provides certain penalty to overall efficiency of the laser.

The SESAM was then replaced by an identical sample cut from the same wafer, but assembled without a heat spreader. It was confirmed that in this case the thermal effects in the SESAM dominate due to efficient heat removal from the gain medium. The experimental results shown in Figs 4 and 5 were obtained for a cavity with a pulse repetition rate of 3.084 GHz.

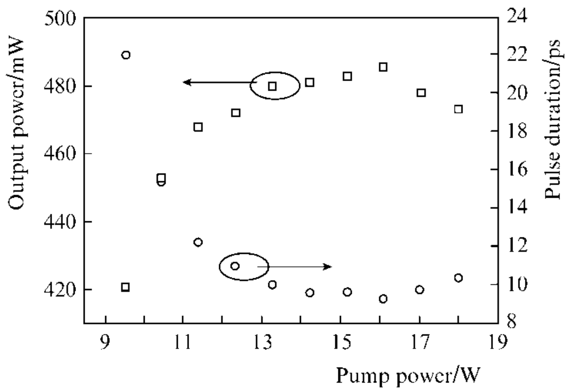


**Figure 4.** Average output power and pulse duration ($\mathrm{sech}^2 x$ fit) as a function of pump power without thermal management of the SESAM.

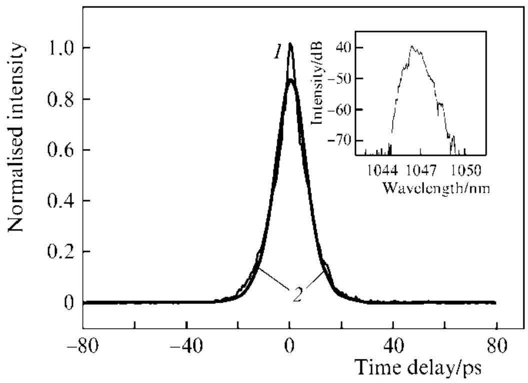


**Figure 5.** Pulse autocorrelation trace for the pulses with the average output power of 485 mW (*1*) and with the $\mathrm{sech}^2 x$ fit (*2*). The laser is equipped with the SESAM without an intracavity diamond heat spreader. The inset shows the corresponding optical spectrum of the pulses.

The principal mechanism of SESAM heating originates from both saturable and nonsaturable losses [17]. Numerical simulation shows that local heating of the SESAM could introduce another thermal lens into the cavity in addition to the lens developed in the gain element, which increases the mode size on the SESAM and decreases the mode size on the gain element. This feature decreases the ratio of the mode size at the gain to mode size at the SESAM and degrades the performance of the mode-locking process, which critically depends on this parameter [17]. The output power reduction and the increase in the pulse duration for a laser without SESAM heat removal can be clearly seen by comparing Figs 2 and 4. Another effect which deteriorates the pulse quality is an increase in the SESAM saturation fluence with temperature due to a gradual red shift of its bandgap wavelength with temperature [18]. Consequently, the reduced absorption saturation elevates the losses and further enhances the SESAM heating [3]. The SESAM without heat removal could then work in a weakly saturated regime and steady-state mode-locking starts at a higher output power of 420 mW as compared with the SESAM assembled with diamond heat spreader, as seen from Figs 2 and 4. It should also be noted that a SESAM with a low level of absorption saturation exhibits higher unbleached losses which further rises the local temperature in the SESAM. With the development of mode-locking and with a gradual increase in the output power, the absorption saturation becomes stronger resulting in an increase in the effective modulation depth. This phenomenon accounts for the inverse dependence of output power and pulse duration shown in Fig. 4.

## 5. Conclusions

We have demonstrated that the thermal management of a saturable absorber has a considerable effect on the efficiency and pulse quality of mode-locked lasers. The experimental results show that the degradation of mode-locked laser performance with an increased power is strongly affected by the local heating of the SESAM, resulting in a loss increase and incomplete saturation of absorption. These effects become progressively more important at high repetition rates when the increased average power results in a larger power density and severe thermal load of the absorber.

## References

1. Okhotnikov O.G. (Ed.) *Semiconductor disk lasers, physics and technology* (Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2010) pp. 51 – 52, 216 – 218.
2. Burns D., Hetterich M., Ferguson A., Bente E., Dawson M., Davies J., Bland S. *J. Opt. Soc. Am. B*, **17** (6), 919 (2000).
3. Lorenser D., Unold H., Maas D., Aschwanden A., Grange R., Paschotta R., Ebling D., Gini E., Keller U. *Appl. Phys. B*, **79** (8), 927 (2004).
4. Massoubre D., Oudar J., O'Hare A., Gay M., Bramerie L., Simon J., Shen A., Decobert J. *J. Lightwave Technol.*, **24** (9), 3400 (2006).
5. Krainer L., Paschotta R., Lecomte S., Moser M., Weingarten K., Keller U. *IEEE J. Quantum Electron.*, **38** (10), 1331 (2002).
6. Savitski V., Burns D., Calvez S. *Opt. Express*, **17** (7), 5373 (2009).
7. Savitski V., Kemp A., Calvez S., Burns D. *IEEE J. Quantum Electron.*, **46** (11), 1650 (2010).
8. Aschwanden A., Lorenser D., Unold H., Paschotta R., Gini E., Keller U. *Opt. Lett.*, **30** (3), 272 (2005).
9. Aschwanden A., Lorenser D., Unold H., Paschotta R., Gini E., Keller U. *Appl. Phys. Lett.*, **86**, 131102 (2005).
10. Hoogland S., Garnache A., Sagnes I., Roberts J., Tropper A. *IEEE Photon Technol. Lett.*, **17** (2), 267 (2005).
11. Lindberg H., Strassner M., Gerster E., Bengtsson J., Larsson A. *IEEE J. Sel. Top. Quantum Electron.*, **11** (5), 1126 (2005).
12. Lorenser D., Maas D., Unold H., Keller U. *IEEE J. Quantum Electron.*, **42** (8), 838 (2006).
13. Südmeyer T., Wittwer V.J., Rudin B., Maas D., Hoffmann M., Sieber O.D., Barbarin Y., Golling M., Keller U. *Proc. 19th Int. Laser Phys. Workshop 2010 (LPHYS'10)* (Brazil, 2010).

14. Rautiainen J., Lyytikainen J., Toikkanen L., Nikkinen J., Sirbu A., Mereuta A., Caliman A., Kapon E., Okhotnikov O. *IEEE Photon. Technol. Lett.*, **22**, 748 (2010).
15. Saarinen E., Puustinen J., Sirbu A., Mereuta A., Caliman A., Kapon E., Okhotnikov O. *Opt. Lett.*, **34** (20), 3139 (2009).
16. Saarinen E., Herda R., Okhotnikov O. *J. Opt. Soc. Am. B*, **24** (11), 2784 (2007).
17. Paschotta R., Aus der Au J., Spühler G., Morier-Genoud F., Hövel R., Moser M., Erhard S., Karszewski M., Giesen A., Keller U. *Appl. Phys. B*, **70** (7), 25 (2000).
18. Grange R., Rutz A., Liverini V., Haiml M., Schön S., Keller U. *Appl. Phys. Lett.*, **87**, 132103 (2005).