

# High-power MIXSEL: an integrated ultrafast semiconductor laser with 6.4 W average power

B. Rudin, V. J. Wittwer,\* D. J. H. C. Maas, M. Hoffmann, O. D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller

*Department of Physics, Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland*

*\*vwittwer@phys.ethz.ch*

**Abstract:** High-power ultrafast lasers are important for numerous industrial and scientific applications. Current multi-watt systems, however, are based on relatively complex laser concepts, for example using additional intracavity elements for pulse formation. Moving towards a higher level of integration would reduce complexity, packaging, and manufacturing cost, which are important requirements for mass production. Semiconductor lasers are well established for such applications, and optically-pumped vertical external cavity surface emitting lasers (VECSELs) are most promising for higher power applications, generating the highest power in fundamental transverse mode ( $>20$  W) to date. Ultrashort pulses have been demonstrated using passive modelocking with a semiconductor saturable absorber mirror (SESAM), achieving for example 2.1-W average power, sub-100-fs pulse duration, and 50-GHz pulse repetition rate. Previously the integration of both the gain and absorber elements into a single wafer was demonstrated with the MIXSEL (modelocked integrated external-cavity surface emitting laser) but with limited average output power ( $<200$  mW). We have demonstrated the power scaling concept of the MIXSEL using optimized quantum dot saturable absorbers in an antiresonant structure design combined with an improved thermal management by wafer removal and mounting of the 8- $\mu\text{m}$  thick MIXSEL structure directly onto a CVD-diamond heat spreader. The simple straight cavity with only two components has generated 28-ps pulses at 2.5-GHz repetition rate and an average output power of 6.4 W, which is higher than for any other modelocked semiconductor laser.

©2010 Optical Society of America

**OCIS codes:** (140.3460) Lasers; (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (140.7090) Ultrafast lasers; (140.7270) Vertical emitting lasers.

---

## References and links

1. J. J. Plant, J. T. Gopinath, B. Chann, D. J. Ripin, R. K. Huang, and P. W. Juodawlakis, "250 mW, 1.5- $\mu\text{m}$  monolithic passively mode-locked slab-coupled optical waveguide laser," *Opt. Lett.* **31**(2), 223–225 (2006).
2. M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, "High-Power ( $>0.5$ -W CW) Diode-Pumped Vertical-External-Cavity Surface-Emitting Semiconductor Lasers with Circular TEM<sub>00</sub> Beams," *IEEE Photon. Technol. Lett.* **9**(8), 1063–1065 (1997).
3. M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, "Design and Characteristics of High-Power ( $>0.5$ -W CW) Diode-Pumped Vertical-External-Cavity Surface-Emitting Semiconductor Lasers with Circular TEM<sub>00</sub> Beams," *IEEE J. Sel. Top. Quantum Electron.* **5**(3), 561–573 (1999).
4. B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A.-R. Bellancourt, E. Gini, T. Südmeyer, and U. Keller, "Highly efficient optically pumped vertical-emitting semiconductor laser with more than 20 W average output power in a fundamental transverse mode," *Opt. Lett.* **33**(22), 2719–2721 (2008).
5. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE J. Sel. Top. Quantum Electron.* **2**(3), 435–453 (1996).
6. U. Keller, "Recent developments in compact ultrafast lasers," *Nature* **424**(6950), 831–838 (2003).
7. A. Aschwanden, D. Lorenser, H. J. Unold, R. Paschotta, E. Gini, and U. Keller, "2.1-W picosecond passively mode-locked external-cavity semiconductor laser," *Opt. Lett.* **30**(3), 272–274 (2005).

8. D. Lorenser, D. J. H. C. Maas, H. J. Unold, A.-R. Bellancourt, B. Rudin, E. Gini, D. Ebling, and U. Keller, "50-GHz passively mode-locked surface-emitting semiconductor laser with 100 mW average output power," *IEEE J. Quantum Electron.* **42**(8), 838–847 (2006).
9. A. H. Quarterman, K. G. Wilcox, V. Apostolopoulos, Z. Mihoubi, S. P. Elsmere, I. Farrer, D. A. Ritchie, and A. Tropper, "A passively mode-locked external-cavity semiconductor laser emitting 60-fs pulses," *Nat. Photonics* **3**(12), 729–731 (2009).
10. D. J. H. C. Maas, A.-R. Bellancourt, B. Rudin, M. Golling, H. J. Unold, T. Südmeyer, and U. Keller, "Vertical integration of ultrafast semiconductor lasers," *Appl. Phys. B* **88**(4), 493–497 (2007).
11. A.-R. Bellancourt, D. J. H. C. Maas, B. Rudin, M. Golling, T. Südmeyer, and U. Keller, "Modelocked Integrated External-Cavity Surface Emitting Laser (MIXSEL)," *IET Optoelectron.* **3**(2), 61–72 (2009).
12. A.-R. Bellancourt, Y. Barbarin, D. J. H. C. Maas, M. Shafiei, M. Hoffmann, M. Golling, T. Südmeyer, and U. Keller, "Low saturation fluence antiresonant quantum dot SESAMs for MIXSEL integration," *Opt. Express* **17**(12), 9704–9711 (2009).
13. G. H. C. New, "Modelocking of quasi-continuous lasers," *Opt. Commun.* **6**(2), 188–192 (1972).
14. H. A. Haus, "Theory of Mode Locking with a Slow Saturable Absorber," *IEEE J. Quantum Electron.* **11**(9), 736–746 (1975).
15. R. Paschotta, R. Häring, U. Keller, A. Garnache, S. Hoogland, and A. C. Tropper, "Soliton-like pulse-shaping mechanism in passively mode-locked surface-emitting semiconductor lasers," *Appl. Phys. B* **75**(4-5), 445–451 (2002).
16. D. Lorenser, H. J. Unold, D. J. H. C. Maas, A. Aschwanden, R. Grange, R. Paschotta, D. Ebling, E. Gini, and U. Keller, "Towards Wafer-Scale Integration of High Repetition Rate Passively Mode-Locked Surface-Emitting Semiconductor Lasers," *Appl. Phys. B* **79**(8), 927–932 (2004).
17. E. U. Rafailov, S. J. White, A. A. Lagatsky, A. Miller, W. Sibbett, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, "Fast quantum-dot saturable absorber for passive mode-locking of solid-state lasers," *IEEE Photon. Technol. Lett.* **16**(11), 2439–2441 (2004).
18. D. J. H. C. Maas, A. R. Bellancourt, M. Hoffmann, B. Rudin, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller, "Growth parameter optimization for fast quantum dot SESAMs," *Opt. Express* **16**(23), 18646–18656 (2008).
19. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, "Scalable Concept for Diode-Pumped High-Power Solid-State Lasers," *Appl. Phys. B* **58**, 365–372 (1994).
20. R. Häring, R. Paschotta, A. Aschwanden, E. Gini, F. Morier-Genoud, and U. Keller, "High-power passively mode-locked semiconductor lasers," *IEEE J. Quantum Electron.* **38**(9), 1268–1275 (2002).
21. W. J. Alford, T. D. Raymond, and A. A. Allerman, "High power and good beam quality at 980 nm from a vertical external-cavity surface-emitting laser," *J. Opt. Soc. Am. B* **19**(4), 663–666 (2002).
22. J. E. Hastie, J.-M. Hopkins, S. Calvez, C. W. Jeon, D. Burns, R. Abram, E. Riis, A. I. Ferguson, and M. D. Dawson, "0.5-W single transverse-mode operation of an 850-nm diode-pumped surface-emitting semiconductor laser," *IEEE Photon. Technol. Lett.* **15**(7), 894–896 (2003).

## 1. Introduction

High-power ultrafast lasers are important for numerous industrial and scientific applications in areas as diverse as biology, communication, metrology or material structuring. Until now, multi-watt power levels have required ion-doped dielectric laser materials in combination with additional cavity components for pulse formation, resulting in high complexity and costs. Ultrafast semiconductor laser have the potential for a higher level of integration which reduces packaging and manufacturing cost, important requirements for mass production. Modelocked edge-emitters achieve up to 250 mW of average power with 10-ps pulses [1], but dispersion, nonlinearities and end facet damage are severe challenges for achieving multi-watt power levels. Vertical external cavity surface emitting lasers (VECSELs) [2, 3] appear better suited for high power applications [4], because the pulses propagate mostly in an external cavity and experience only low dispersion and nonlinearities from the vertical propagation through the epitaxial semiconductor layers of only a few micrometer thickness. Ultrashort pulses have been demonstrated using passive modelocking with semiconductor saturable absorber mirrors (SESAMs) [5, 6], achieving picosecond pulses with up to 2.1-W average power [7], up to 50-GHz pulse repetition rate [8] and sub-100-fs pulse durations with average power well below 100 mW [9]. In 2007, the integration of gain and absorber elements into a single semiconductor structure was demonstrated with the MIXSEL (modelocked integrated external-cavity surface emitting laser) concept [10]. The limitations in terms of average power were due to the high thermal impedance the GaAs substrate left underneath the MIXSEL structure. Even at  $-50^{\circ}\text{C}$  heat sink temperature, heating limited the average power of the first MIXSEL to only 195 mW [11]. Furthermore the design relied on a strong field

enhancement in the absorber section for achieving stable modelocking, which led to high demands on the semiconductor growth accuracy (better than 1%).

In this paper we present a novel MIXSEL design based on a low saturation fluence quantum dot (QD) absorber [12] in an antiresonant structure, which substantially improves the growth tolerances. The 8  $\mu\text{m}$  thick structure is directly mounted on a CVD (chemical vapor deposition) diamond heat spreader, allowing for power-scaling with mode size. The simple straight cavity consisting only of two cavity components generates 28-ps pulses with 6.4 W average power which is higher than for any ultrafast semiconductor laser up to date.

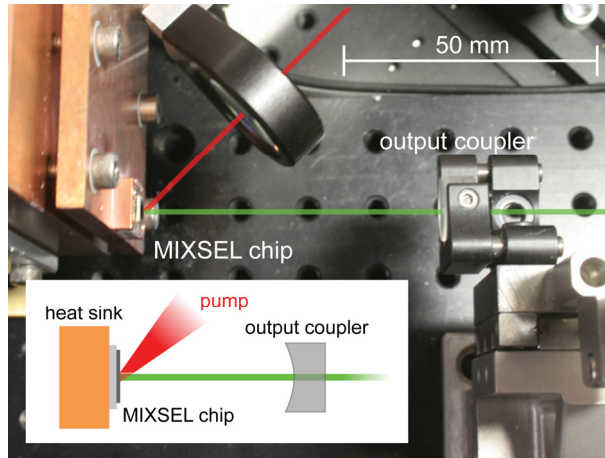


Fig. 1. Photograph and sketch of the MIXSEL cavity: The simple linear cavity is formed by the MIXSEL chip and an external output coupler. The MIXSEL structure is optically pumped under an angle of 45°.

## 2. MIXSEL concept, structure and growth

The MIXSEL is optically pumped and the cavity consists of only two elements: the MIXSEL semiconductor chip and an external output coupler (see Fig. 1). The key challenge was the integration of both laser gain and saturable absorber into a single semiconductor structure (Fig. 2) [10]. The MIXSEL structure was grown in reverse order on an (100) undoped GaAs substrate, using a VEECO GEN III (Veeco instruments Inc., Plainview, New York) molecular beam epitaxy (MBE) machine. The growth temperature was 600°C, except for the QD absorber, which was grown at 430°C.

The MIXSEL semiconductor structure consists of five main sections. The incident laser and pump beam enter the gain section through an anti-reflection (AR) coating, a numerically optimized structure of alternating AlAs and  $\text{Al}_{20}\text{Ga}_{80}\text{As}$  layers. The gain region consists of 7  $\text{In}_{13}\text{Ga}_{87}\text{As}$  quantum wells (QWs) separated by GaAs pump absorbing spacer layers and placed at the antinodes of the electric field. The compressively strained QWs were not strain balanced. In the adjacent intermediate dichroic distributed Bragg reflector (DBR) (the 9 pairs of AlAs/ $\text{Al}_{20}\text{Ga}_{80}\text{As}$  result in 93% reflectivity at the pump wavelength) the residual pump beam is reflected back into the gain region, while the laser beam propagates into the saturable absorber section, thus 90% of the pump light is absorbed in the active region. The dichroic intermediate DBR prevents the pump light from saturating the absorber. This mirror is followed by the saturable absorber section, consisting of a single layer of self-assembled InAs QDs embedded within a 20 nm thick GaAs layer surrounded by AlAs. The GaAs layer was kept as thin as possible to minimize the absorption of the residual pump light. The indium monolayer coverage was 2.0. Finally the laser beam is reflected by a highly reflective bottom mirror consisting of a 29-pair AlAs/GaAs DBR with 99.97% reflectivity at the laser wavelength.

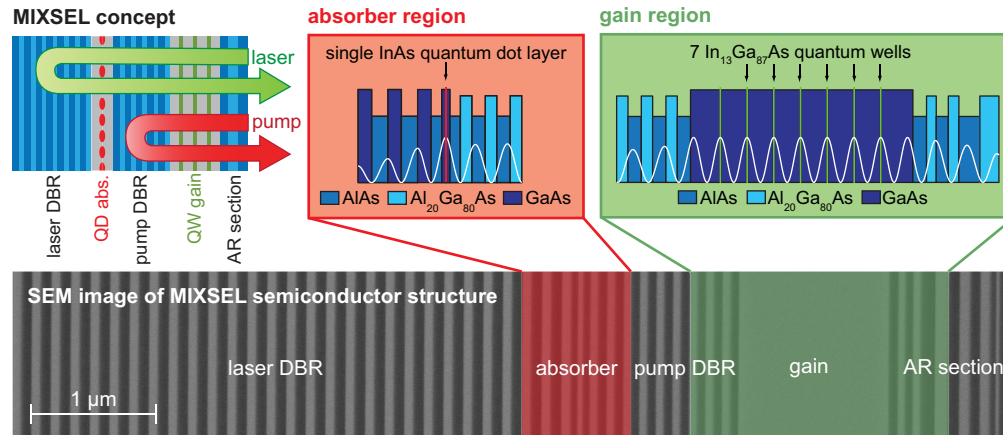


Fig. 2. MIXSEL concept and design: The MIXSEL semiconductor structure contains two highly reflecting distributed Bragg reflectors (DBRs), a quantum dot (QD) saturable absorber layer, a quantum well (QW) gain section and an anti-reflective (AR) coating. The laser DBR reflects the laser light and forms the laser cavity together with the external output coupler. The pump DBR is placed between the QD saturable absorber and the QW gain layers to prevent bleaching of the saturable absorber by the pump light. The white oscillations in the upper sketches represent the square of the electric field of the laser light. The QD layer as well as the QWs are placed in antinodes.

### 3. MIXSEL design

Stable modelocking requires the absorber to saturate faster than the gain [13–15], which translates into a lower saturation energy in the absorber than in the gain. In the MIXSEL, the beam diameters in the gain and the absorber layers are identical, because the total thickness of the semiconductor structure (i.e. the MIXSEL chip) (Fig. 2) is less than  $10\ \mu\text{m}$ , i.e. several times smaller than the mode areas of pump and laser beam and therefore well within the confocal parameter of the focused laser beam. The saturation fluence in the absorber section has to be in the order of or less than  $10\ \mu\text{J}/\text{cm}^2$  for a typical QW-based gain region [16], which can be achieved in quantum dot (QD) absorbers. QD absorbers in comparison to QW absorbers have potentially a faster relaxation response time [17] and provide more growth parameters, which is advantageous for the MIXSEL integration [10]. A detailed study on the effects of growth parameters on the macroscopic optical properties of QD absorbers showed that the modulation depth is proportional to the QD density, while the saturation fluence stays constant [18]. In the first MIXSEL [10], we made use of this property to independently optimize saturation fluence and modulation depth. We achieved low saturation fluence by placing one QD saturable absorber layer within a resonant structure. Unfortunately, this absorber saturation enhancement came at the trade-off of high group delay dispersion (GDD) and a high sensitivity towards MBE growth errors. A recent study showed that the saturation fluence can be substantially reduced by post-growth annealing [12, 18]. This enabled the design of a fully antiresonant MIXSEL.

In Fig. 3a, we compare the original resonant MIXSEL design (upper red graphs) with the novel antiresonant design (lower blue graphs). The resonance in the absorber layer was achieved by a 5-pair intermediate DBR at the laser wavelength, enhancing the electric field by almost a factor of 5 compared to the field in the new antiresonant design. Figure 3b shows the electric field enhancement in the absorber as a function of the wavelength, and Fig. 3c the calculated wavelength dependence of the GDD. The red and blue lines represent the values for the designed structures assuming no growth errors, whereas for the gray lines, we applied random errors of less than 1% for the growth rates (i.e. layer thicknesses) of the different materials for 50 structures. The antiresonant design has a substantially higher growth error tolerance, which makes it suitable for high-volume wafer-scale fabrication (1% error is a

typical value for high-quality MBE growth). In addition, the GDD was found to be smaller and less wavelength dependent.

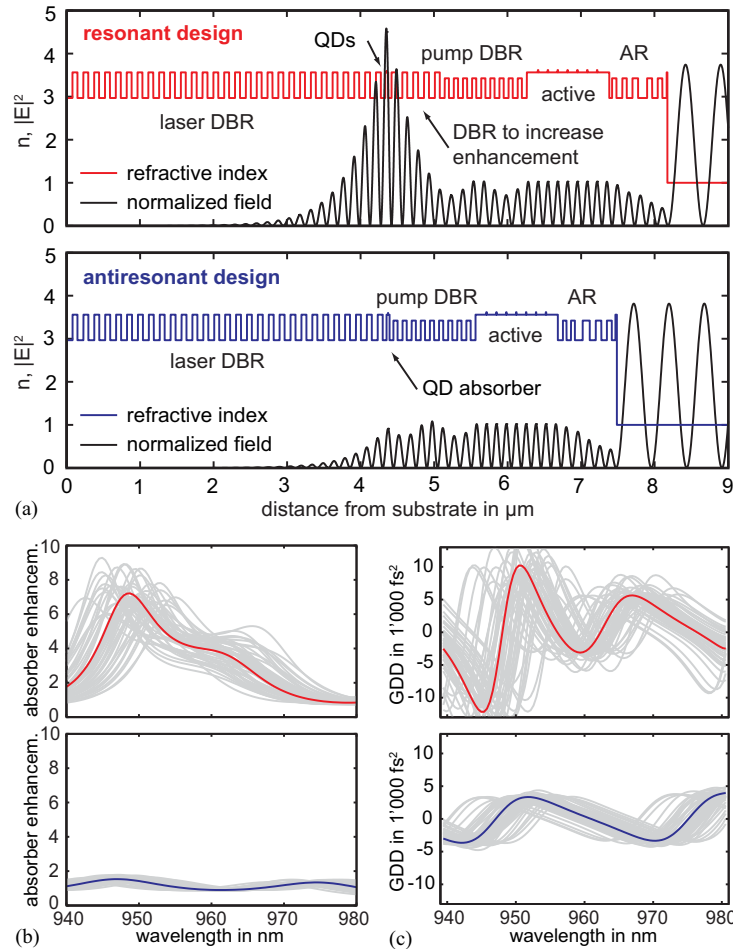


Fig. 3. Comparison between a resonant and an antiresonant MIXSEL design: (a) Resonant (red) and antiresonant (blue) MIXSEL design given by the refractive index pattern. The difference between the two structures is the lack of the laser DBR on top of the QD layer for the antiresonant structure. The calculated standing wave intensity pattern for the design laser wavelength is shown in black. (b) The corresponding field enhancements in the absorber and (c) the group delay dispersion (GDD) are displayed as function of wavelength. The red and blue lines show the values for the designed structure assuming no growth errors, whereas the gray lines show the values for 50 random structures, where growth errors of less than 1% have been applied to the different materials.

#### 4. MIXSEL power scaling

An important advantage of optically-pumped MIXSELS and VECSELS is their thin disk geometry allowing for power scaling with mode size [19]. The one-dimensional heat flow from the thin gain region into the heat sink enables efficient heat dissipation such that the output power can be doubled with twice the pump power applied to twice the mode area, while the temperature in the gain structure remains constant. For earlier MIXSELS the average output power was limited by the low thermal conductivity of the 600- $\mu\text{m}$  thick GaAs wafer, on which the structure was grown, thus, only 40 mW output power could be extracted from the first MIXSEL [10]. Higher output power levels of up to 195 mW could only be reached by massive cooling to  $-50^\circ\text{C}$  [11].

Better thermal management is typically achieved by either replacing the wafer substrate by a high thermal conductivity material [20], or by bonding a transparent heat spreader on top [21, 22]. We have chosen the first approach, as the modelocking is not affected by possible parasitic reflections at the heat spreader/air interface. We replaced the 600- $\mu\text{m}$  thick GaAs wafer by a CVD diamond heat spreader with a thermal conductivity higher than  $1800 \text{ WK}^{-1}\text{m}^{-1}$ . Therefore the structure was grown in reverse order (i.e. AR-coating first). Pieces of 5 mm x 5 mm were cleaved from the wafer, metalized with Ti/Pt/In/Au and soldered onto the CVD diamond heat spreaders (metalized with Ti/Pt/Au) using a fluxless indium soldering process under vacuum. The substrate and the etch stop layers were then removed using a selective wet etching procedure [20].

We confirmed the power-scaling procedure by increasing the pump spot radius from 80  $\mu\text{m}$  to 215  $\mu\text{m}$  corresponding to approximately a factor 7 in mode area, which increased the average output power by a factor of approximately 9.

## 5. MIXSEL results

The MIXSEL cavity (Fig. 1) was a 60 mm long straight cavity, formed by the MIXSEL semiconductor chip and an output coupler with 500 mm radius of curvature and 0.7% transmission. The chip was optically pumped at a wavelength of 808 nm under an angle of  $45^\circ$  and with a pump spot radius of 215  $\mu\text{m}$  using a fiber-coupled laser diode array (LIMO AV5 series 100 W, Lissotschenko Mikrooptik GmbH, Dortmund, Germany). The maximum pump power applied was 37 W. The curvature of the output coupler and the cavity length were chosen such, that the laser mode size on the MIXSEL structure was slightly bigger than the pump spot size, i.e. a radius of 223  $\mu\text{m}$ . This enabled fundamental transverse mode operation, which is necessary for stable modelocking. The MIXSEL structure was mounted on a heat sink, which was temperature stabilized with a Peltier element and was kept at a constant temperature of  $-15^\circ\text{C}$ . The MIXSEL chip was purged with dry nitrogen to prevent condensation of air humidity on the surface.

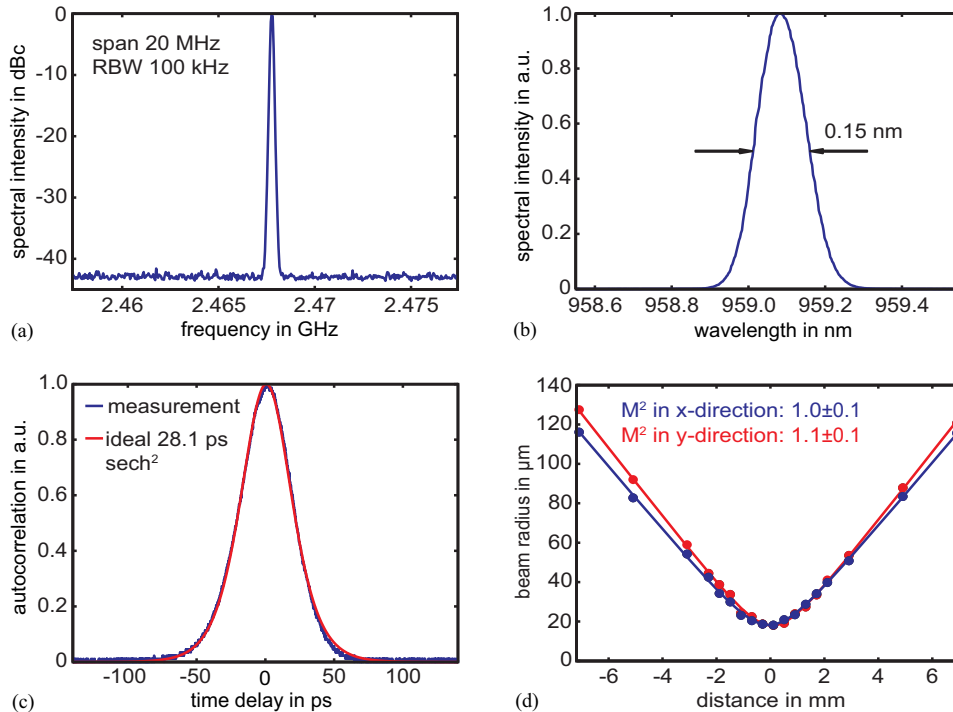


Fig. 4. Characterization of the MIXSEL lasing performance: (a) Microwave spectrum, (b) optical spectrum, (c) intensity autocorrelation and (d) beam quality measurement.

At the maximum applied pump power of 37 W, stable and self-starting modelocking was obtained with an average output power of 6.4 W (Fig. 4). This output power is 160 times higher than the output power of the first MIXSEL [10]. The optical-to-optical efficiency was 17.3%. The microwave spectrum of the optical pulse train confirms a pulse repetition rate of 2.47 GHz (Fig. 4a). The optical spectrum is centered at 959 nm with a width of 0.15 nm (FWHM) (Fig. 4b) and the intensity autocorrelation corresponds to an ideal  $\text{sech}^2$ -pulse of 28.1 ps duration (Fig. 4c). The time-bandwidth product is approximately 4.5 times the transform-limit. The beam quality was measured for an average output power of 5.3 W (Fig. 4d): Excellent  $M^2$  values of 1.0 and 1.1 in two orthogonal lab frame directions have been obtained.

The MIXSEL geometry is well-suited for repetition rate scaling. In an initial proof-of-principle experiment, we increased the repetition rate to 10 GHz with a shorter cavity of a length of 15 mm generating pulse durations of 22 ps. Using an output coupler with 38 mm radius of curvature, we obtained a 75  $\mu\text{m}$  mode radius, 3 times smaller than for the high power MIXSEL. This limited the average output power to 189 mW at a pump power of 8.7 W.

## 6. Conclusion

In summary, we have demonstrated the first multi-Watt power scaling of an optically pumped picosecond MIXSEL. The antiresonant design was found to substantially relax the demands on the semiconductor growth accuracy. We have achieved 6.4 W average output power, which is higher than for any other ultrafast semiconductor laser to date. Further increase of mode size and pump power should enable power levels well above 10 W. Better dispersion management of the MIXSEL structure should allow for transform-limited pulses, while femtosecond pulse durations might be achieved using saturable absorbers with shorter recovery times. The MIXSEL resonator is a linear resonator with only two end mirrors, the MIXSEL chip and the output coupler. The linear cavity geometry will support different pulse repetition rates by simply adjusting the distance between output coupler and semiconductor chip without altering the nonlinear interaction within the MIXSEL for the same peak power. Up to now, we achieved pulse repetition rates up to 10 GHz, which were limited by the pulse duration. The simplicity of the MIXSEL concept will enable more compact, robust and cost-effective ultrafast lasers in the multi-Gigahertz pulse repetition rate regime for applications, for which the current ultrafast laser technology is too expensive.

## 7. Author information

The first two authors contributed equally as first authors.

## Acknowledgements

This work was supported by ETH Zurich with the FIRST clean room facility and was financed by the Intel Corporation through a university sponsored research agreement and by the Swiss Confederation Program Nano-Tera.ch which was scientifically evaluated by the SNSF.