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Quantum dot membrane external-cavity surface-emitting laser at 1.5  $\mu\text{m}$

## Quantum dot membrane external-cavity surface-emitting laser at 1.5 $\mu\text{m}$

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A membrane external-cavity surface-emitting laser (MECSEL) with an InAs/InP quantum dot (QD) based gain region is demonstrated. The pumping scheme employs a 90° off-axis parabolic mirror to focus the diode laser pump beam to a nearly circular pump spot. With this pump arrangement, the QD MECSEL with SiC heat spreaders produced 320 mW output power at room temperature with direct emission in the near-infrared at 1.5  $\mu\text{m}$ . We report a record value of 86 mW for the tuning range at this wavelength region, owing to a broad QD gain bandwidth and wide tunability in MECSELS.

Vertical-external-cavity surface-emitting lasers (VECSELS)<sup>1</sup> have emerged as a versatile platform for high-power coherent light sources with high beam quality. In terms of operation principles and cavity architecture, VECSELS integrate the major benefits of thin-disk solid-state lasers as well as semiconductor lasers. The high-quality beam is rendered possible by the external cavity, while the semiconductor bandgap engineering enables wavelength versatility in a broad range. The key element of a VECSEL is the semiconductor gain mirror, which typically consists of a multi quantum well (QW) or multi quantum dot (QD) gain structure and a monolithically integrated distributed Bragg reflector (DBR). To achieve gain and enable lasing, such a gain mirror which is incorporated in the external cavity configuration is typically pumped optically. Although semiconductor gain media ensure a much broader wavelength coverage compared to solid-state lasing materials, the power capability and wavelength coverage of VECSELS are neither equally distributed nor available at all possible wavelengths covered by typical III-V compound semiconductors. There are various reasons behind this state of fact, ranging from the maturity of technology at certain wavelengths to more profound ones related to intrinsic features of the material systems used.

For example, owing to the mature development stage of the InGaAs/AlGaAs material system, ensuring a high reflectivity, high carrier confinement, and relatively good thermal conductivity, the highest power VECSELS have been demonstrated at around 1  $\mu\text{m}$ .<sup>2,3</sup> But if one moves away from this wavelength range requiring different material systems<sup>4</sup>, either the DBR, the carrier confinement, thermal conductivity, or a combination of these features will become increasingly difficult to manage. Simplifying this analysis, we can point out the limitation arising from the DBR, which requires specific layers with a reasonable high refractive index contrast and also being compatible in terms of lattice constant with the QW or QD gain heterostructure. These features are readily available for the 1  $\mu\text{m}$  region but become an issue when targeting lasing in the 1.3-1.5  $\mu\text{m}$  region,

where the QWs are InP-based rendering impossible the use of GaAs/AlGaAs DBRs. To overcome the spectral limitations of the DBR and to some extent also improve the operation of the gain heterostructure by better thermal management, an alternative laser concept has emerged, the membrane external-cavity surface-emitting laser (MECSEL)<sup>5-7</sup>. In a MECSEL the gain medium is comprised only of the thin QW or QD heterostructure (without a DBR), which is then used in an external cavity architecture. Moreover, in MECSELS, the thermal management is more efficient as the active structure can be bonded between two intra cavity heat spreaders<sup>8</sup>, i.e. it is cooled from both sides with heat spreaders in the close proximity of the gain region. In turn, this enables to use heat-spreading materials with lower conductivity but more cost-effective as silicon carbide (SiC). Owing to these advantages, recent efforts have led to the demonstration of MECSELS emitting in the red and near-infrared<sup>9-15</sup>.

In this paper, we focus our attention on the important 1.5  $\mu\text{m}$  telecom region, where the DBR technology is particularly difficult due to the low refractive index contrast of InP-based materials. For the sake of generality, we point out that although 1.5  $\mu\text{m}$  monolithic InP-based VECSELS have been demonstrated<sup>16-19</sup>, the highest output power reported at room temperature operation is only 140 mW<sup>16</sup>, which is a small fraction of what would be available at 1  $\mu\text{m}$ . We note here that the thermal resistance of this VECSEL measured under laser operation, is as high as 470 K/W<sup>17</sup>. To have a better thermal resistance of 34 K/W, a hybrid metal-metamorphic AlAs/GaAs DBR has been implemented<sup>18</sup>. Alternative demonstrations involving GaInAsN/GaAs QWs and AlAs/GaAs DBR pairs grown on GaAs, have also resulted in rather low output power in the 80 mW range<sup>19</sup>. An alternative solution to the monolithic approach is to grow the InP-based active structure and the AlAs/GaAs DBR separately on two different types of substrates, and afterwards combining them via wafer-fusion<sup>20-22</sup>. This involves a higher level of complexity. Nevertheless, this technique has enabled to fabricate high-power VECSELS exceeding 3.65 W at 1.55  $\mu\text{m}$ .<sup>23</sup> In this Letter, we demonstrate a MECSEL with InAs QDs at an emission wavelength of 1.5  $\mu\text{m}$ . In particular, we demonstrate wavelength tuning over a large bandwidth. The laser implemented an optical pumping scheme<sup>24</sup> to favor an almost circular pumping.

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The QD MECSEL structure was grown by gas source molecular beam epitaxy (GSMBE) on a  $300 \mu\text{m}$  thick InP substrate with a (311)B crystal orientation. First, a  $100 \text{ nm}$  thick InGaAs etch stop layer was fabricated. The gain structure consisted of 20 InAs QD layers separated by  $15 \text{ nm}$  thick GaInAsP barrier layers and distributed over groups of five QD layers with InP cladding layers as schematically illustrated in Fig. 1.

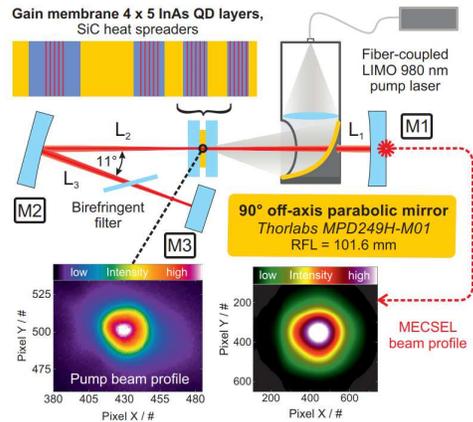


FIG. 1. Experimental setup of the MECSEL employing  $4 \times 5$  InAs/InP QD layers and a V-cavity. By using a  $90^\circ$  off-axis parabolic mirror with a high-reflection protected gold coating, the pump beam is focused down to a nearly circular pump spot onto the laser-active membrane as illustrated. This also favours an almost round beam profile of the MECSEL as captured by a scanning slit beam profiler.

The structure has been designed with a fixed number of QD layers per groups. To optimize the structure in terms of charge carrier distribution, an increase of the thickness of the GaInAsP barrier absorbing layers compensated for the exponential decrease of the input pump absorption. As a consequence, the total thicknesses of the absorbing layers from the back up to the front side are as follows:  $240 \text{ nm}$ ,  $160 \text{ nm}$ ,  $120 \text{ nm}$ , and  $90 \text{ nm}$ . The whole structure appears thus as asymmetric, but is still resonant with a  $2.5\lambda$  design because of the InP/SiC interface. Here, the InP cladding layer between the first and second QD layer is more than twice thicker than the other InP cladding layers in the gain structure. The antinode between these two QD layers is practically left out, such that each QDs group is carefully positioned at stationary field antinodes. Details of the QD fabrication by the Stranski-Krastanow growth mode, the gain structure and its laser performance as a VECSEL at  $14^\circ\text{C}$  employing intra cavity diamond heat spreaders have been described elsewhere<sup>22</sup>.

After the growth was completed, the substrate was mechanically thinned before being removed wet-chemically with an HCl solution. An  $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$  solution was applied to

eliminate the InGaAs process layer. After the etching process, the membrane was bonded between two uncoated 4H SiC heat spreader pieces, and mounted into a copper heat sink. During all operation conditions, the membrane heat spreader sandwich was cooled in a heat sink mount via water/glycol cooling at a temperature of  $19^\circ\text{C}$ . A schematic illustration of the V-cavity for the output power and wavelength tuning experiments performed is shown in Fig. 1. The V-cavity consisted of a plane outcoupling mirror M3, and two curved high-reflecting mirrors M1 and M2, which both had the same reflectivity of  $R_{M1, M2} > 99.8\%$  and the same radius of curvature of  $r_{M1, M2} = 200 \text{ mm}$ . The mirror distances of M1 and M2 to the gain membrane sandwich were adjusted to  $L_1 = 195 \text{ mm}$  and  $L_2 = 199 \text{ mm}$ . M3 was positioned under an opening angle of  $11^\circ$  between  $L_2$  and  $L_3$ . The distance between M2 and M3 was  $L_3 = 199 \text{ mm}$ . The calculated cavity mode diameter on the gain membrane was about  $200 \mu\text{m}$  using the ray transfer method for a Gaussian beam. A  $980 \text{ nm}$  LIMO diode laser coupled into a multi-mode fiber with a  $200 \mu\text{m}$  core diameter and a numerical aperture of 0.22 was used as a pump source. The fiber output was collimated by a  $f = 100 \text{ mm}$  plano-convex lens, and focused onto a spot size of about  $360 \mu\text{m}$  in diameter by a  $90^\circ$  off-axis parabolic mirror (MPD249H-M01 from Thorlabs) with a protected gold reflection coating ( $R_{980\text{nm}} > 98\%$ ) and a reflected focal length of  $101.6 \text{ mm}$ . Thus, the ratio between the cavity and pump mode diameter was about 0.56. It is lower than the suggested optimum from 0.65 to 0.82 simulated by Laurain *et al.*<sup>25</sup>. The parabolic mirror used in these experiments has a diameter of  $50.8 \text{ mm}$  as well as a hole with a diameter of  $3 \text{ mm}$  that is large enough and does not cut the laser mode. The pump beam covered almost the whole area of the parabolic mirror. For the pump beam, the losses caused by this  $3 \text{ mm}$  hole were investigated and were below  $1\%$ , and therefore negligible. With an angle of incidence of the pump laser ranges from almost  $0^\circ$  to less than  $15^\circ$ , this pump approach enables a nearly circular pump spot with  $D_{p, \text{sag}}/D_{p, \text{tan}} > 0.96$  in the focus. In particular, the pump efficiency can be enhanced by having similar mode shapes (see Fig. 1).

Following the Fresnel equations, approximately  $20\%$  of incident pump power was reflected at the SiC heat spreader front surface for incident angles between  $0^\circ$  and  $15^\circ$ . Pump transmission measurements revealed an absorption by the gain membrane of about  $65\%$  of the incident pump power.

The QD MECSEL output characteristics are shown as a function of the absorbed pump power in Fig. 2 and include the transmission from M1, M2, and M3 with an outcoupler reflectivity of  $R_{M3} = 99\%$ .

Lasing was achieved with a threshold pump power of  $P_{\text{pump, thr.}} = 4.7 \text{ W}$ . By increasing the pump power further to a value of  $22.6 \text{ W}$  of absorbed power, a maximum output power of  $320 \text{ mW}$  was obtained with a differential efficiency of  $2\%$ . As can be seen in Fig. 2, the output power was limited by thermal rollover, which was setting in at about  $22 \text{ W}$  absorbed pump power. The QD MECSEL produced a near diffraction limited fundamental transverse mode profile, in both, sagittal and tangential planes with an  $M^2$  value of less than 1.05, measured with a dual scanning-slit BP209-IR/M

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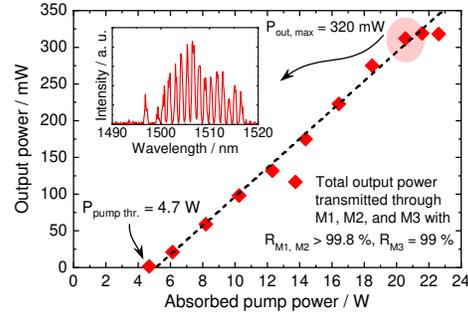


FIG. 2. Power performance of the 1.5  $\mu\text{m}$  QD MECSEL using SiC heat spreaders at 19°C cooling water temperature. The plotted output power is a sum of transmitted power from M1, M2, and M3. A spectrum at 21 W pump power absorption is illustrated in the inset.

beam profiler and a Thorlabs M<sup>2</sup> M2MS measurement system. As can be seen in Fig. 1, the MECSEL beam profile reproduced from the scanning-slit measurement was nearly circular, which is most likely favored by the circular pump approach.

A set of spectra was simultaneously recorded with an Ando AQ6317C optical spectrum analyzer with a resolution of 0.02 nm during the output power measurements. In addition to the spectral red shift, the emission spectrum widened with pump power. This was probably due to the state-filling effect in QDs<sup>26</sup>, as the threshold of higher emission energy modes could be reached at high excitation power and contribute to lasing. The inset in Fig. 2 shows an emission spectrum at 21 W absorbed pump power. It contained typical Fabry-Pérot resonances, related to the spectral filtering induced by the 350  $\mu\text{m}$  thick intra cavity SiC heat spreaders.

Furthermore, the spectral red shift by heating up the gain membrane by the pump source was determined as 0.16 nm/W. The emission spectra shifted on average by 0.07 nm/K with the heat sink temperature. Correspondingly, the thermal resistance<sup>27</sup> is obtained. The value of 2.3 K/W is more than one order of magnitude lower than in monolithic InP VECSELs<sup>17,18</sup> and rather in the same order of magnitude as the 1.77  $\mu\text{m}$ -emitting MECSEL with a QW-based active region<sup>14</sup>.

Tuning experiments have been conducted by inserting a birefringent filter within the cavity (see Fig. 1) using different output coupler reflectivities. This 1.5 mm thick filter enables to cover a large free spectral range of 180 nm. With a  $R_{M3} = 99\%$  outcoupler, the emission wavelength was tunable from 1474 nm to 1519 nm as illustrated in Fig. 3. The broader tuning range of 86 nm was achievable with a high-reflecting  $R_{M3} > 99.8\%$  outcoupling mirror. Compared to earlier 1.5  $\mu\text{m}$  VECSELs<sup>21,22</sup>, the highest tuning range has been achieved at the 1.5  $\mu\text{m}$  wavelength band here in this work.

The polarization behavior of the QD MECSEL was analyzed without any intra cavity elements inside a linear cavity to avoid any preferred polarization that would be given by a

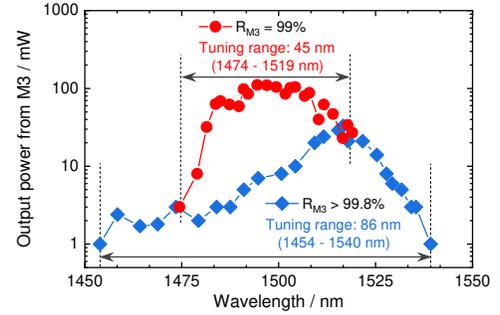


FIG. 3. Wavelength tuning results of the QD MECSEL by tilting a 1.5 mm thick intra cavity birefringent filter at 16.4 W absorbed pump power.

V-cavity. The mirrors M1 and M2 with the mirror distances of about  $L_1 = L_2 = 197$  mm were used. An ultra broad band wire grid polarizer from Thorlabs (WP25M-UB) with an extinction ratio of 1000:1 was set behind M2. With the transmission axis fixed at 0° (p-polarization) axis and 90° (s-polarization) axis, the measured output power curve was linearly increasing with pump power as shown in Fig. 4 without power drop. Also, the spectra taken at both polarization axes at an absorbed pump power of 16.4 W in the inset of Fig. 4 revealed that there was no wavelength hopping.

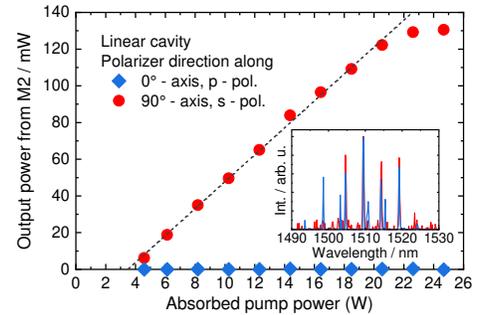


FIG. 4. Polarization output power characteristics recorded at two orthogonal angles of the polarizer transmission axis from a linear cavity with the corresponding spectra in the inset. The spectra are normalized in intensity and measured at an absorbed pump power of 16.4 W.

To determine the degree of linear polarization (DOP), the polarizer was rotated over a full cycle. The DOP was calculated with the maximum and minimum output power  $P_{\text{max}}$  and  $P_{\text{min}}$  from M2 transmitted through the polarizer by

$$DOP = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}$$

As can be seen in Fig. 5, the DOP was calculated to be larger

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than 99%, meaning that the MECSEL was almost fully s-polarized. In VECSELS, similar values have been obtained<sup>28</sup>. The preferential polarization state was fixed at lasing. No switching over the wafer and the whole output power characteristic was observed. This originates most likely from the QD anisotropy, similarly to the recently reported VCSELS integrating the same 1.5  $\mu\text{m}$  InAs QDs<sup>29</sup>.

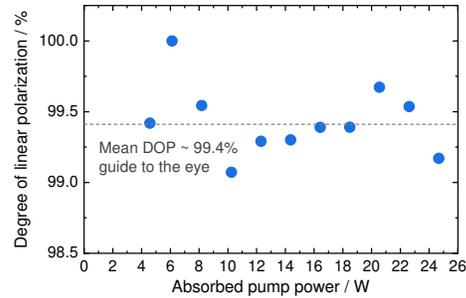


FIG. 5. Calculated degree of polarization of a QD MECSEL recorded in a linear cavity.

In conclusion, we demonstrated a QD MECSEL operating at 1.5  $\mu\text{m}$ . With the combination of the broad gain of InAs QDs, and the absence of the DBR<sup>30</sup>, the MECSEL has made a record tuning range of 86 nm, which is higher than the gain structure provides as a VECSEL<sup>21,22</sup>. Over 320 mW of output power was achieved at room temperature with relatively low cost SiC heat spreaders available in wafer quality. To optically pump the gain membrane under small pump incident angles below 15° with an almost circular pump spot, a 90° off-axis parabolic mirror was integrated in the pump optics. In the future, this pump approach could be extended by a second set of pump optics, positioned on the opposite side of the MECSEL for double-side pumping<sup>11</sup> or pump recycling<sup>31</sup> by reflecting the transmitted pump beam back to the MECSEL structure to increase the pump efficiency. Additionally, a high DOP larger than 99% was obtained where the s-polarized modes were far more prominent than the p-polarized ones which was reproducible across the sample. From the application point of view, QD MECSELS with a near diffraction limited beam with an  $M^2$  value of less than 1.05 and a broad gain bandwidth could be applied in coherent Doppler LIDAR<sup>32</sup> in the future for wind velocity sensing, wind turbulence measurements<sup>33</sup>, or wake vortices detection created by aircrafts in flight formations<sup>34</sup>.

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#### DATA OF AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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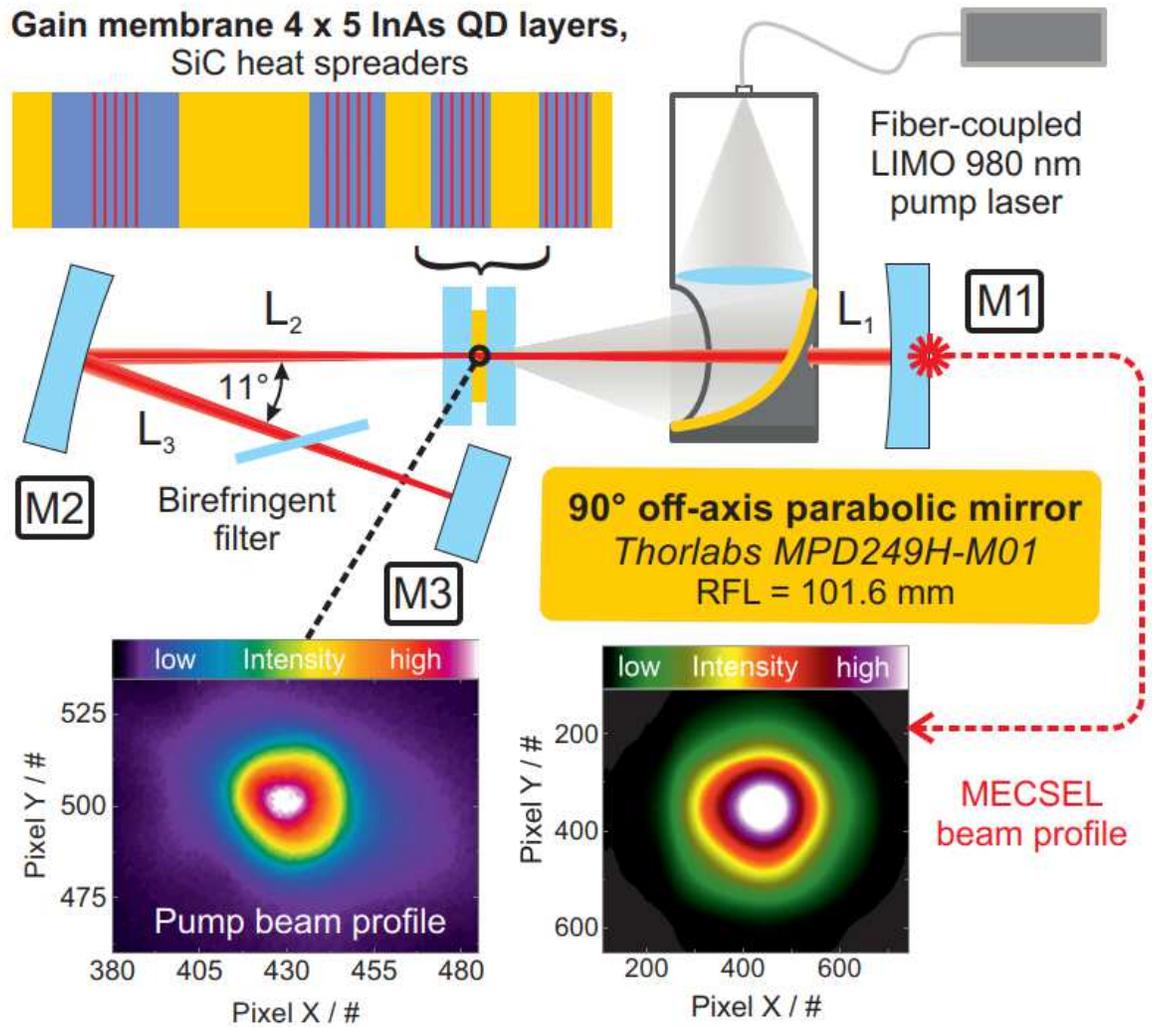
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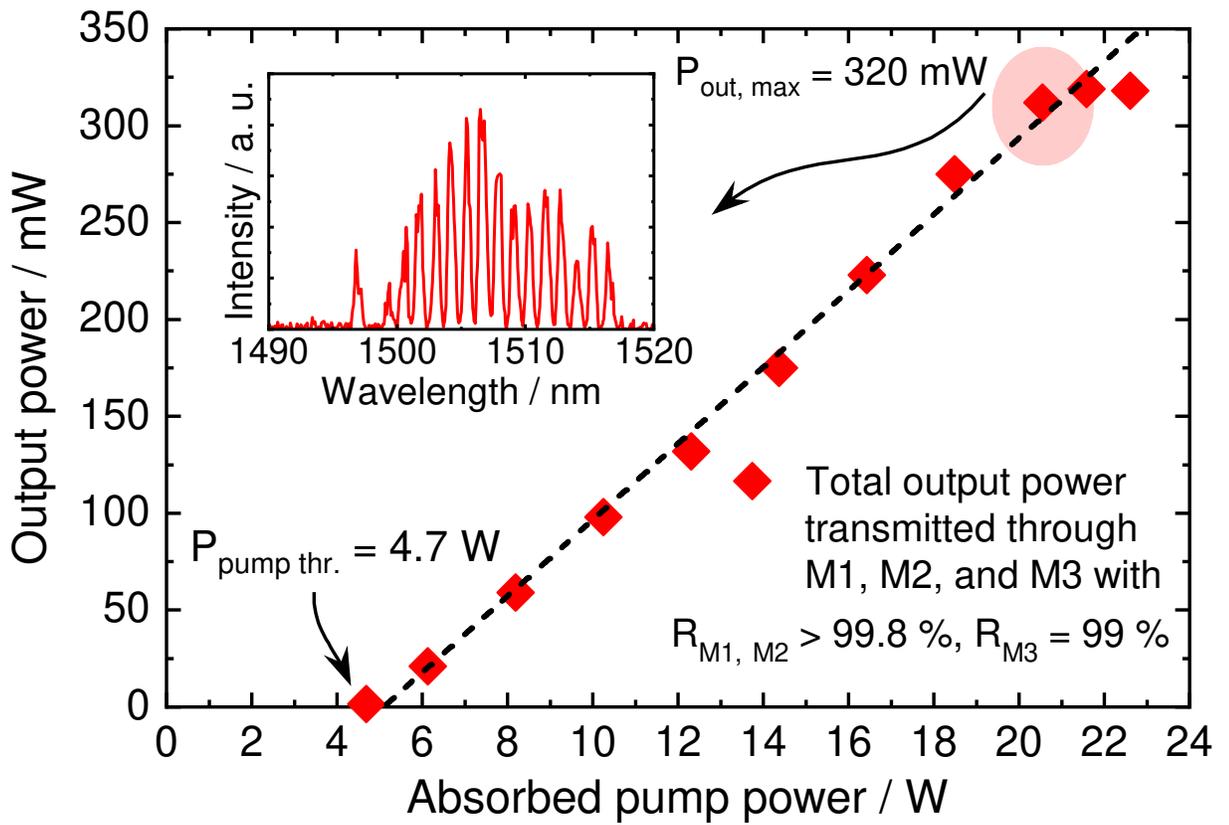
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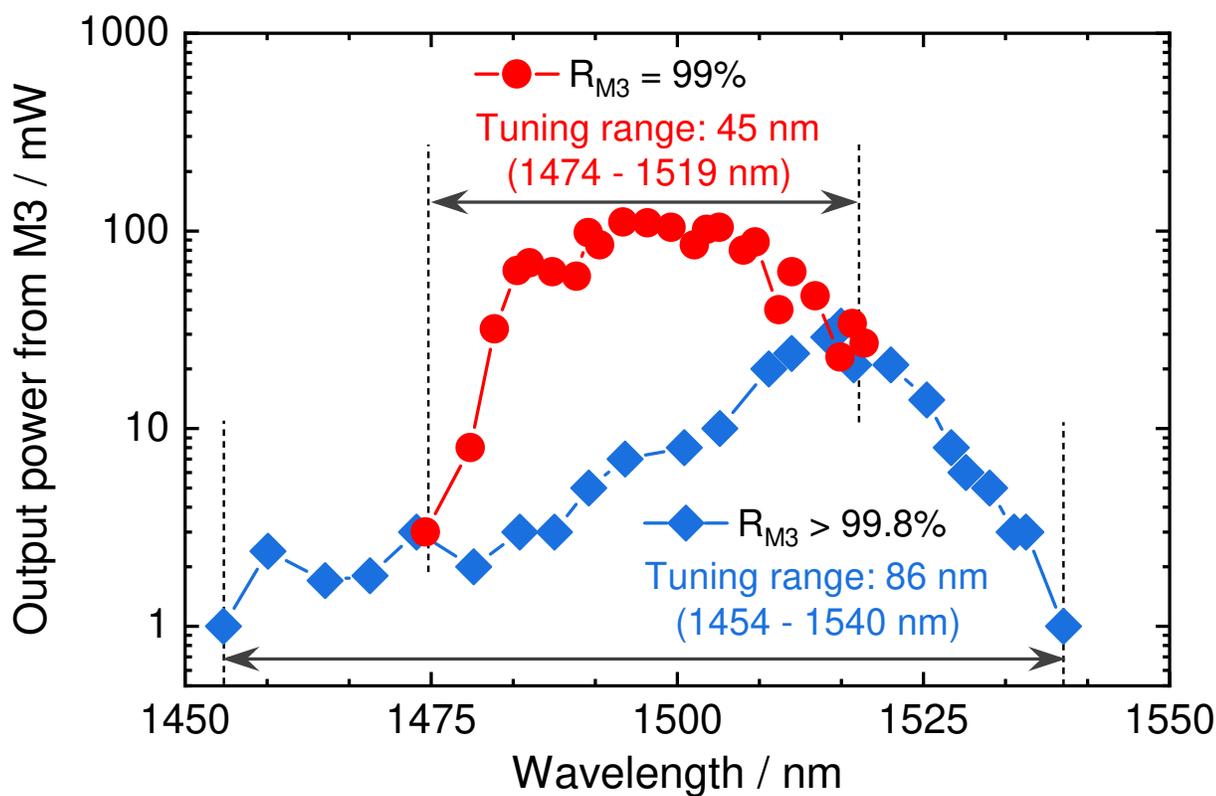
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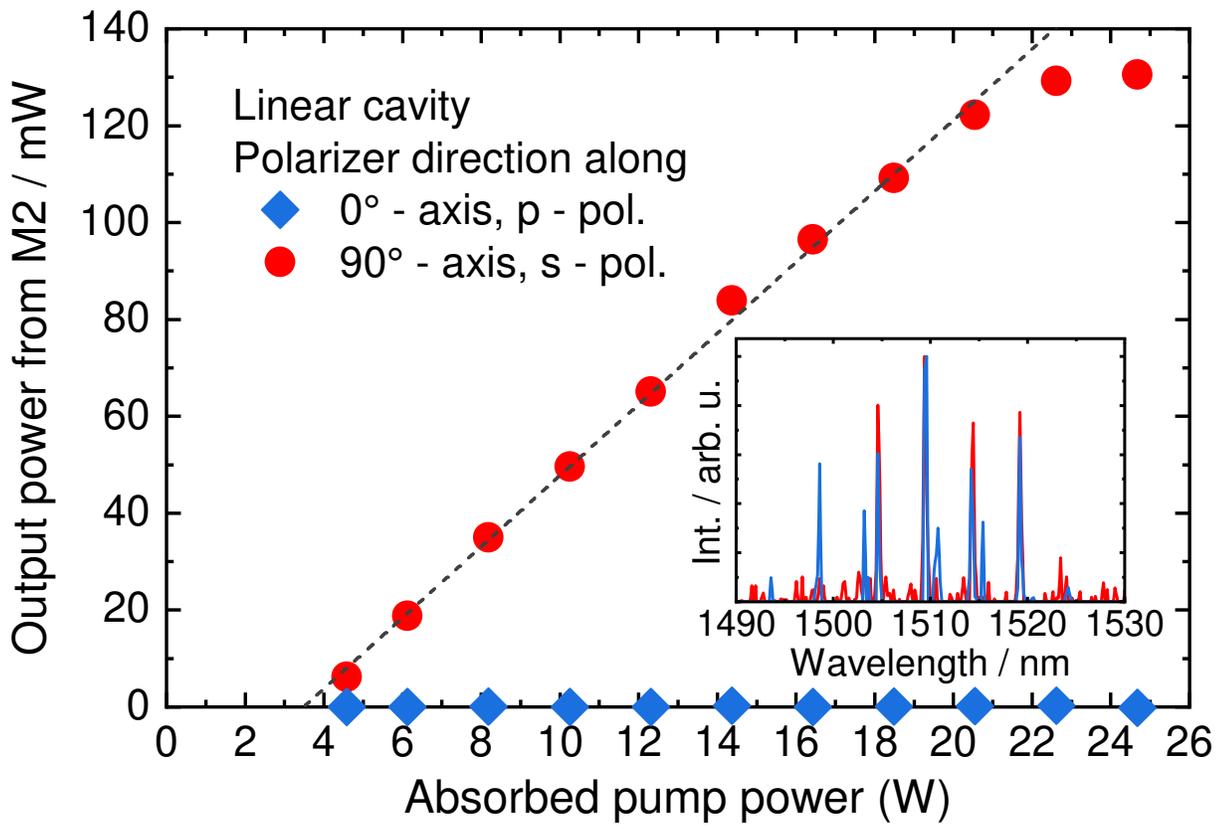
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