Femtosecond pulses from a modelocked integrated external-cavity surface emitting laser (MIXSEL)

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Abstract: Novel surface-emitting optically pumped semiconductor lasers have demonstrated >1 W modelocked and >100 W continuous wave (cw) average output power. The modelocked integrated external-cavity surface emitting laser (MIXSEL) combines the gain of vertical-external-cavity surface-emitting lasers (VECSELs) with the saturable absorber of a semiconductor saturable absorber mirror (SESAM) in one single semiconductor structure. This unique concept allows for stable and self-starting passive modelocking in a simple straight cavity. With quantum-dot based absorbers, record-high average output power was demonstrated previously, however the pulse duration was limited to 17 ps so far. Here, we present the first femtosecond MIXSEL emitting pulses with a duration as short as 620 fs at 4.8 GHz repetition rate and 101 mW average output power. The novel MIXSEL structure relies on a single low temperature grown quantum-well saturable absorber with a low saturation fluence and fast recovery dynamics. A detailed characterization of the key modelocking parameters of the absorber and the challenges for absorber integration into the MIXSEL structure are discussed.

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

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1. Introduction

Optically pumped vertical-external-cavity surface-emitting lasers (VECSELs [1]) are attractive laser sources for applications that require high-power operation combined with excellent beam quality. In continuous-wave (cw) operation, up to 20 W in a fundamental transversal mode [2] or 106 W in transversal multimode operation [3] were demonstrated. VECSELs can be passively modelocked with semiconductor saturable absorber mirrors (SESAMs [4]), generating ultrashort pulses in a repetition rate regime ranging from a few hundred MHz [5] up to several tens of GHz [6]. Femtosecond VECSELs passively modelocked with an intra-cavity SESAM have generated >1 W average output power for the first time in 2011 [7]. Since this first milestone result even higher multi-watt average output power was demonstrated [8, 9]. To date, the shortest pulses in fundamental modelocking with only one pulse per cavity round-trip are as short as 107 fs with 3 mW of average output power [10], whereas pulse durations of 60 fs were achieved in bursts of pulses [11]. Furthermore in contrast to standard semiconductor lasers, SESAM-modelocked VECSELs support very low-noise performance comparable to diode-pumped ion-doped solid-state lasers [12].

SESAM modelocked VECSELs are typically based on a V-shaped cavity design, which sets a fundamental limit to the packaging complexity, compactness and the repetition rate. To overcome these limitations the modelocked integrated external-cavity surface emitting laser

(MIXSEL [13]) combines the gain of the optically pumped VECSELs with the saturable absorber of a SESAM in one single semiconductor layer stack. This concept enables a higher level of integration to reduce complexity, packaging, and manufacturing cost, and allows for stable and self-starting passive modelocking in a simple straight cavity. The first MIXSEL generated 40 mW of average output power in 35-ps-pulses at 2.8 GHz [13]. With improved thermal management and carefully optimized quantum dot (QD) saturable absorbers [14], up to 6.4 W in 28-ps-pulses were obtained at a repetition rate of 2.5 GHz [15]. At 10 GHz, an average output power of 2.4 W in 17-ps-pulses was demonstrated [16].

The MIXSEL marked a milestone in the field of compact, gigahertz repetition rate, high-power ultrafast lasers, establishing an attractive source for applications such as optical clocking, communication or sampling. To date the >10 ps pulse durations with limited peak power prevented access to many other applications such as biomedical imaging or frequency metrology. Such applications would greatly benefit from the simple MIXSEL concept with very flexible operation wavelengths with semiconductor bandgap engineering [17] and femtosecond pulse generation.

However, pushing the pulse duration of the MIXSEL towards the femtosecond regime has been challenging because of the integrated saturable absorber parameters. Long annealing times during the molecular beam epitaxy (MBE) growth of the MIXSEL wafer structure degenerated the absorber parameters. Recent pulse formation simulations revealed a strong dependence of the minimum pulse duration on the recovery dynamics of the saturable absorber and the total intra-cavity group delay dispersion (GDD) [18]. In the previous MIXSEL structures, QDs were utilized as a saturable absorber (see Fig. 1(a)). They were optimized for a low saturation fluence, which enabled passive modelocking in an antiresonant MIXSEL [15]. However slow recombination times above 100 ps set a lower limit to the achievable pulse durations and prevented a further increase in repetition rate.

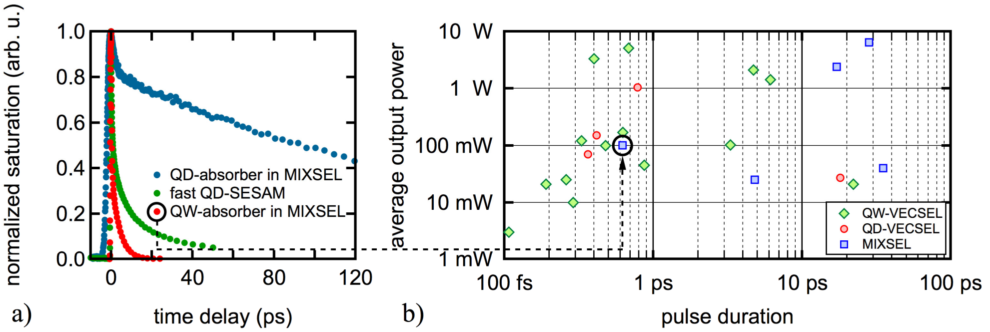

Fig. 1. a) Comparison of normalized recovery dynamics of different saturable absorbers: slow QD-absorber in previous MIXSEL [15, 16] (blue), fast QD-SESAM used in [7] (green) and novel fast QW-absorber (red); b) Overview of average output power versus pulse duration for different fundamentally modelocked VECSELs and MIXSELs: First femtosecond operation of MIXSEL (black circle) with fast QW-absorber (dashed black line) [19].

Therefore, a novel saturable absorber based on a single InGaAs quantum well (QW) was developed for the integration into the MIXSEL, offering fast recovery dynamics and low saturation fluences at the same time without any significant degradation during the long MBE growth. In addition an optimized top-coating for small and broadband GDD helps to support short pulse durations [20]. Subsequently, we were able to achieve a strongly reduced pulse duration of 4.8 ps in a preliminary experiment with a structure not yet optimized for high-power operation [21].

Here, we present a novel high-power MIXSEL that relies on an InGaAs QW saturable absorber. The low temperature grown QW absorber is embedded in AlAs spacers and carefully characterized and optimized for achieving low saturation fluences and fast recovery dynamics. These improvements of the structure and the saturable absorber then has allowed us to obtain the shortest pulse durations from a MIXSEL to date, generating 620-fs-pulses at a repetition rate of 4.8 GHz with an average output power of 101 mW (see Fig. 1(b)).

2. MIXSEL concept and design

The MIXSEL combines the QW-based gain of a VECSEL with the saturable absorber of a SESAM in one single semiconductor structure. This concept enables stable and self-starting passive modelocking in a simple straight cavity with no other optical elements than a standard curved output coupler and the MIXSEL-chip (see Fig. 2(a)). In principle, arbitrarily short distances between the two cavity elements are possible, which should enable pulse repetition rates from 1 GHz to >100 GHz. The MIXSEL is optically pumped by a commercially available diode array coupled into a multi-mode fiber with an M^2 of ≈75.

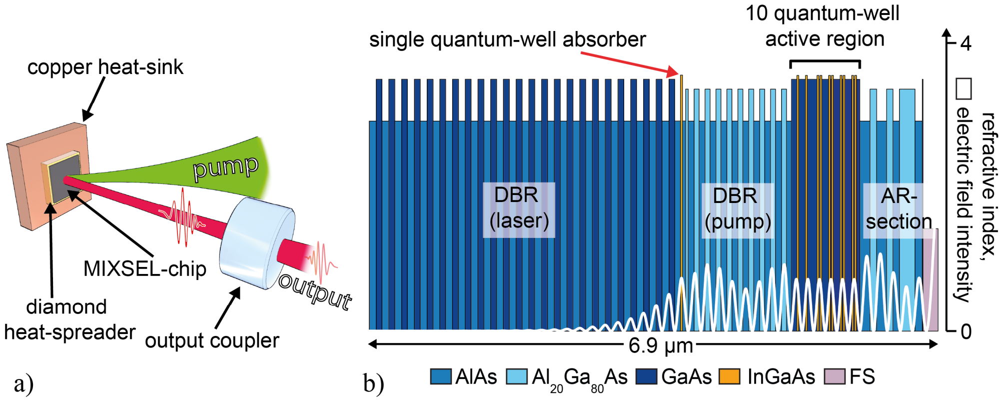

Fig. 2. MIXSEL concept: a) The straight cavity is formed by the MIXSEL chip and a curved output coupler. The flip-chip processed MIXSEL-chip is optically pumped under an angle of 45°. b) The 6.9-µm-thick MIXSEL semiconductor layer stack consists of a 24-pair distributed Bragg reflector (DBR) for the lasing wavelength and a 9-pair DBR for the pump wavelength. In between the DBRs, we placed a single InGaAs quantum well (QW) saturable absorber. The active region consists of 10 compressively strained InGaAs QWs embedded in GaAs for pump absorption. On top, a hybrid semiconductor/fused silica anti-reflection mirror section ensures low pump light reflection and optimized group-delay dispersion (GDD).

The full MIXSEL structure is only about 7 µm thick (see Fig. 2(b)) and was grown in a single run, using a VEECO GEN III (Veeco instruments Inc., Plainview, New York) MBE machine in the FIRST cleanroom facility at ETH Zurich. For subsequent flip-chip bonding, the structure was grown in reverse epitaxial order with a single etch-stop layer placed between the undoped GaAs (100) substrate and the structure. The whole structure was grown at a temperature of 580°C, except from the absorber section that was grown at 280°C. After the epitaxy, the structure is metallized and flip-chip bonded on a metallized diamond heat-spreader for optimum thermal management. The 600-µm-thick diamond is grown by chemical vapor deposition and has a thermal conductivity exceeding 1800 $Wm^{-1}K^{-1}$. After bonding, the GaAs substrate and the etch-stop layer are removed by chemical wet-etching as described in detail in [22].

The MIXSEL structure layout and the material composition are schematically shown in Fig. 2(b). The incident laser light at a wavelength of around 960 nm is reflected by a 24-pair AlAs/GaAs distributed Bragg reflector (DBR), while the pump light is reflected by a dichroic 9-pair AlAs/$Al_{0.2}Ga_{0.8}As$ DBR for the pump wavelength of 808 nm. The pump DBR inhibits a pre-saturation of the absorber by residual pump light. Between the two DBRs, a single quantum-well absorber is placed at the antinode of the standing wave pattern of the electric field intensity. The field intensity enhancement at the absorber is designed to be around 1.2 (normalized to 4 outside the structure coming from a close to 100% reflection). A detailed characterization of the absorber is presented in Section 3.

The active region consists of ten compressively strained 4.8-nm-thick $In_{0.12}Ga_{0.88}As$ QWs embedded in 6 λ/2-layers of GaAs. The room-temperature photoluminescence of the QWs is intentionally blue-shifted to allow for spectral overlap of the intrinsic QW emission with the structural resonance under lasing conditions at an elevated operation temperature of ≈80°C. The optimum operation temperature of 80-90°C (corresponding to a red shift of 26-29 nm) was calculated by performing finite element temperature simulations inside the structure. The first eight QWs (from top) are positioned pairwise on adjacent sides of the antinodes of the standing wave pattern of the electric field with a GaAs-spacing of 30 nm. Absorption of the pump light in GaAs results in decreased pump intensities in the active region further afar from the top. In order to compensate that, the last two QWs (from top) are placed in separate antinodes to ensure a more homogeneous excitation of all QWs. The arrangement of the QWs in the active region was chosen to achieve a relatively low average field intensity enhancement in the QWs of around 0.95, thus increasing the gain saturation fluence [23]. Furthermore, compared to the standard arrangement of a single QW in each antinode, this configuration leads to an average field enhancement in the QWs with weaker dependence on the laser wavelength. Therefore a broader and more homogeneous gain bandwidth can be achieved.

On top of the active region, a numerically optimized anti-reflection (AR) section is grown. It consists of 3.5-pairs of $AlAs/Al_{0.2}Ga_{0.8}As$ and ends with a layer of fused silica (FS). The FS layer was deposited after flip-chip bonding and substrate removal by plasma enhanced chemical vapor deposition (PEVCD). The anti-reflection section is not only designed for a minimum pump reflection at the interface air/MIXSEL-chip, but also for achieving a flat and slightly positive GDD of ± 100 fs^2 in the range of ± 15 nm around the design wavelength of 960 nm. Small values of positive total intra-cavity GDD were found to be ideal for achieving short pulse durations with passively modelocked VECSELs [7, 18, 24]. These considerations apply for both SESAM modelocked VECSELs and MIXSELs since their modelocking mechanism relies on the same parameters and theory.

3. Characterization of important modelocking parameters

The integration of the saturable absorber into the MIXSEL structure has been challenging since key absorber parameters such as low saturation fluence and fast recovery need to be maintained with integration. In SESAM-modelocked VECSELs the mode sizes in the gain and absorber layers can be adapted individually by different cavity configurations. In a MIXSEL however they are identical because the <10-µm MIXSEL chip thickness is well within the confocal parameter length of the cavity laser mode, given that the overall cavity length is in the multi-millimeter to centimeter range (i.e. a 10 GHz pulse repetition rate corresponds to a cavity length of 1.5 cm in air). Therefore an absorber with low saturation fluence is needed in order to saturate the absorber before the QWs in the active gain region. In the previous MIXSEL structures, low saturation fluences of the absorber were achieved by adapted self-assembled InAs QDs [14, 15]. Those absorbers only show a weak dependence of the absorption wavelength on temperature and can be designed for a desired modulation depth of 1-2%. However, our attempts to integrate QD-based saturable absorbers into a MIXSEL structures have shown limited success so far, because the recovery time degraded towards a rather long time (see Fig. 1(a)) limiting our efforts towards shorter pulse generation.

For this novel MIXSEL structure we employed a single low-temperature grown InGaAs QW embedded in AlAs spacers as saturable absorber that is operated close to the QW band-edge. Low-temperature grown QW absorbers are easier to fabricate than QD-based absorbers and the fast recovery dynamics even after annealing make them highly interesting for the generation of short pulses. For the absorber characterization we have grown a SESAM with the identical absorber properties and field enhancement as in the MIXSEL. In addition the SESAM was annealed in the MBE with arsenic over-pressure at 580°C for 8 hours to emulate the additional annealing that the absorber undergoes during the actual MIXSEL growth. The room-temperature absorption is blue-shifted compared to the design wavelength, hence a temperature of 60-80°C at the absorber position shifts the QW absorption to the desired

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operation wavelength regime of around 960 nm (see Fig. 3(a)). The absorption wavelength shifts at a rate of $d\lambda/dT \approx 0.32$ nm/K and the actual temperature strongly depends on pump intensities and heat-sink temperature.

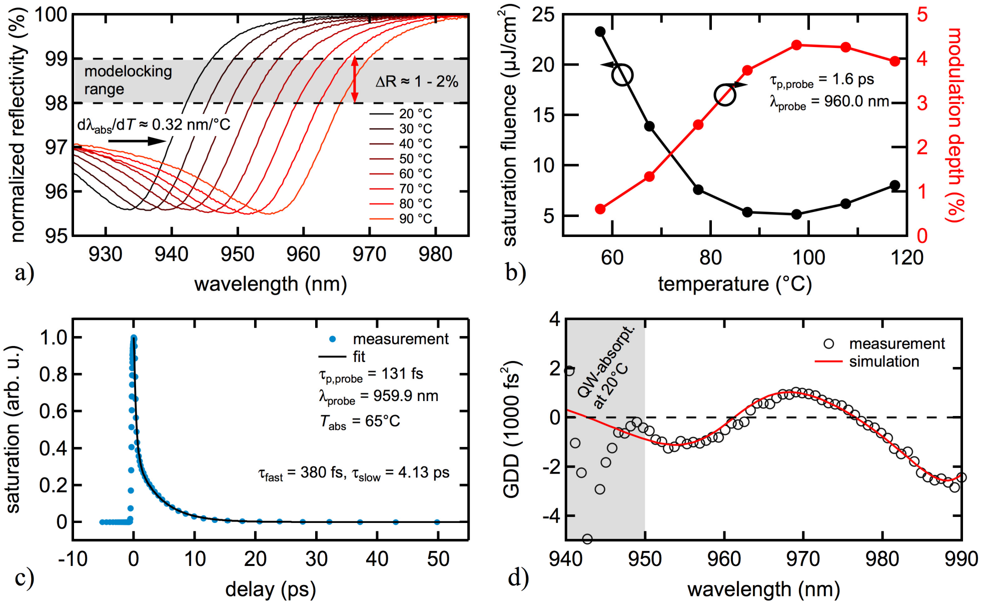

Fig. 3. Key modelocking parameters: a) Characterization of saturable absorber in SESAM: detuned single QW is designed for operation temperatures of 60-80°C to achieve 1-2% modulation depth near the bandedge at 960 nm; b) Nonlinear characterization of the absorber with 1.6-ps-pulses at 960 nm: elevated temperatures result in desired regime of modulation depths ΔR≈1-2%, with decreasing saturation fluences from 17 to 7 µJ/cm^2; c) Measurement of the bitemporal recovery dynamics of the absorber at 65°C and with 131-fs-pulses near 960 nm: fast recovery time $\tau_{\mathrm{fast}} \approx 380$ fs with amplitude of 62% compared to slow recovery time $\tau_{\mathrm{slow}} \approx 4.1$ ps; d) measurement of group delay dispersion (GDD) of the MIXSEL chip around operation wavelength of 960 nm (dots) compared to simulation (solid line) based on the designed structure with a slightly thicker fused silica (FS) layer of a few percent; positive GDD-regime favors stable modelocking with short pulse durations [18].

Temperature dependent nonlinear SESAM reflectivity measurements were performed at a wavelength of 960 nm and a pulse duration of 1.6 ps (see Fig. 3(b)) with a setup described in [25]. In the temperature range between 60 and 80°C the modulation depth ΔR increases into the desired regime of 1-2%, whereas the saturation fluences are decreased from 20 µJ/cm^2 to 7 µJ/cm^2. At higher temperatures the unsaturated absorber losses become comparable to the small-signal gain which completely stops the MIXSEL from reaching the laser threshold.

With a time-resolved differential reflectivity measurement setup, the recovery dynamics of the SESAM were measured for a temperature of 65°C with 130-fs-pulses at a wavelength of 960 nm (see Fig. 3(c)). We applied a double exponential fit to the measurement with a fast recovery time of $\tau_{\mathrm{fast}} \approx 380$ fs and an amplitude of 62%, and a slow recovery time of $\tau_{\mathrm{slow}} \approx 4.1$ ps. This means this integrated saturable absorber should be more than 40 times faster than the 188 ps measured for the QD-based MIXSEL (see Fig. 1) [16].

As mentioned in the previous section, an AR-coating was placed on top of the structure to achieve a flat GDD around the lasing wavelength. With a setup based on white-light interferometry, the GDD of the MIXSEL chip was evaluated. In order to only measure the GDD of the structure, the measurement was performed at 20°C without optical pumping (see Fig. 3(d)) [26] to avoid contributions of the blue-shifted QW absorption to the dispersion. The relatively large range of ± 1000 fs^2 is found to be in agreement with the simulation when considering a fused silica (FS) layer that is slightly too thick compared to the initial design. For wavelengths above 962 nm the structural GDD is in the positive regime, which should favor the generation of short pulses [24].

4. Experimental results

We inserted the MIXSEL chip into a straight cavity (see Fig. 2(b)) with a length of 31 mm and used an output coupler with 200 mm radius of curvature and 0.35% transmission. The MIXSEL chip was optically pumped under an angle of 45°C by a fiber-coupled commercial diode array at a wavelength of 808 nm. The cavity mode radius of 149 µm was chosen to be slightly larger than the pump spot radius of 144 µm. The MIXSEL chip was kept at a constant temperature of 11°C by a water-cooled Peltier element. At a pump power of 24.9 W stable and self-starting modelocking was achieved.

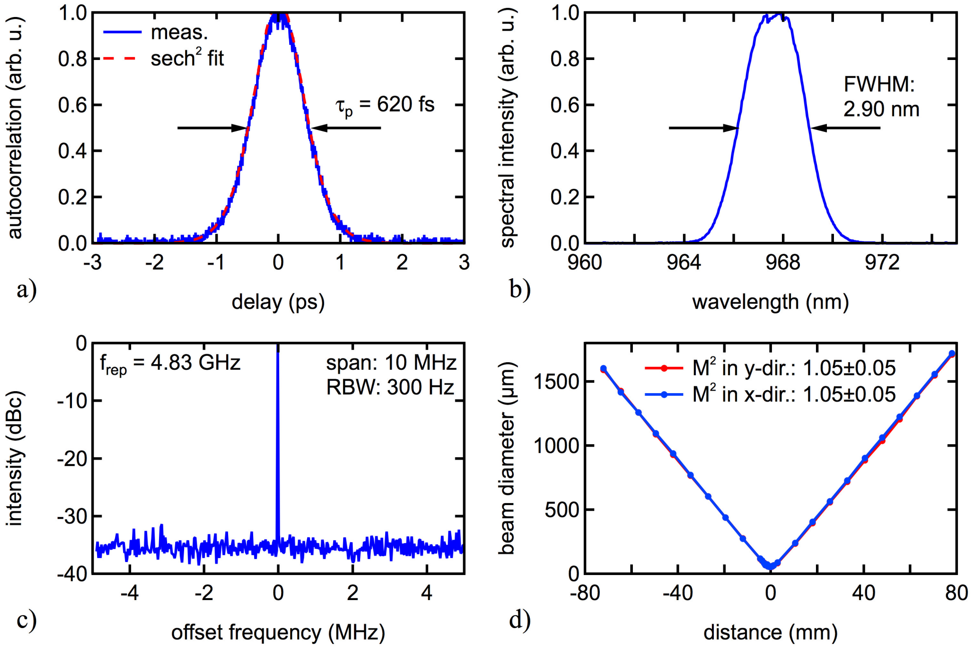

Fig. 4. Femtosecond operation of a MIXSEL: a) intensity autocorrelation with sech^2-fit yields a pulse duration of 620 fs; b) optical spectrum with a resolution bandwidth (RBW) of 0.5 nm centered at a wavelength of 967.7 nm with a bandwidth of 2.90 nm (FWHM), c) microwave spectrum with RBW of 300 Hz at repetition rate of 4.83 GHz and d) beam quality measurement confirming operation in fundamental transverse mode with M^2 values of 1.05 ± 0.05 in two orthogonal lab frame directions.

The intensity autocorrelation with a corresponding fit to the autocorrelation of a sech^2-pulse (sech^2-fit) yields a pulse duration of 620 fs (see Fig. 4(a)). This is a 27-fold reduction in pulse duration compared to the previously published pulse duration of 17.1 ps [16]. The optical spectrum is centered at a wavelength of 967.7 nm with a bandwidth of 2.9 nm (FWHM) (see Fig. 4(b)). Therefore, the time-bandwidth product is about 1.8 times the transform limit of an ideal sech^2 pulse. The microwave spectrum of the optical pulse train with a resolution bandwidth of 300 Hz in a 10 MHz span indicates stable modelocking at a repetition rate of 4.83 GHz (see Fig. 4(c)). At the same laser configuration a beam quality measurement confirmed operation in a fundamental transverse mode with M^2 values of 1.05 ± 0.05 in two orthogonal lab frame directions (see Fig. 4(d)).

5. Conclusion and outlook

We have demonstrated the first femtosecond operation of a modelocked integrated external-cavity surface-emitting laser (MIXSEL). An adapted single quantum-well saturable absorber was developed and characterized for integration into the MIXSEL structure. Low saturation fluences and fast recovery dynamics of the absorber in combination with an anti-reflection top-coating that minimizes the GDD around the lasing wavelength are the main parameters for achieving record short pulse durations. By implementing those improvements in a novel MIXSEL structure, we were able to decrease the minimum pulse duration of a MIXSEL by over an order of magnitude to 620 fs at 101 mW of average output power at a repetition rate of 4.83 GHz.

The novel MIXSEL is a unique high-power ultrafast laser source in the gigahertz regime that can be beneficial for applications such as biomedical imaging or frequency metrology. Further optimization of the structure and absorber together with mode-size power scaling should enable femtosecond operation and watt-level average output power levels in the near future.

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