Compact Tunable Diode Laser with Diffraction Limited 1000 mW in Littman/Metcalf configuration for Cavity Ring Down Spectroscopy

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ABSTRACT

High resolution spectroscopy of environmental and medical gases requires reliable, fast tunable laser light sources in the mid infrared (MIR) wavelength regime between 3 and 5 microns. Since this wavelength cannot be reached via direct emitting room temperature semiconductor lasers, additional techniques like difference frequency generation (DFG) are essential. Tunable difference frequency generation relays on high power, small linewidth, fast tunable, robust laser diode sources.

We report a new, very compact, alignment insensitive, robust, external cavity diode laser system in Littman/Metcalf configuration with an output power of 1000mW and an almost Gaussian shaped beam quality ($M^2<1.2$). The coupling efficiency for a optical waveguides as well as single mode fibers exceeds 70%. The center wavelength is widely tunable within the tuning range of 20 nm via remote control. This laser system operates longitudinally single mode with a mode-hop free tuning range of up to 150GHz without current compensation and a side-mode-suppression better than 50dB. This concept can be realized within the wavelength regime between 750 and 1060nm.

We approved this light source for high resolution spectroscopy in the field of Cavity-Ring-Down-Spectroscopy (CRDS). Our high powered Littman/Metcalf laser system was part of a MIR-light source which utilizes difference-frequency-generation in Periodically Poled Lithium Niobate (PPLN) crystals. At the wavelength of 3.3µm we were able to perform a high resolution absorption measurement of water with all resolved isotopic H_2O components. This application clearly demonstrate the suitability of this laser for high high-precision measurements.

Keywords: Tunable Laser, Diode Laser, Laserdiode, Tapered Lasers, External Cavity, Littman/Metcalf, Difference Frequency Generation, Mid Infrared, Cavity Ring Down Spectroscopy

1. INTRODUCTION

Using high power laser diodes directly in an external cavity configuration combines the high power of these diodes with the advantages of the external cavity: a narrow line width in the region of a MHz and good wavelength tunability[1] of more than 20 nm, in combination with ease of use and small dimensions. Within a ‘usual’ external resonator concept[1] only one side of the diode is useable. One side of the diode has a high reflectivity coating (HR) while the other side is antireflection coated (AR). In Littrow configuration the emitted light from the AR illuminates a low efficiency grating so that the –1st order is reflected back into the resonator and the 0th order is uses as the output beam. In the Littman/Metcalf configuration the –1st order is reflected to a mirror so that the HR facet and the mirror build the resonator. Such ‘usual’ external cavity diode lasers (ECDL) design has several drawbacks: In order to achieve high output power, there is the need for operating the grating in low efficiency mode. Gratings have a high reflectivity of 90 % for P-polarized light and a low reflectivity of 10 % for the S-polarized light. When using the grating for a high power ECDL this results in a poor polarization ratio between TE and TM emission. Furthermore, this non-optimized resonator quality leads to a poor side mode suppression in the order of 40 dB. Another drawback of the Littrow design is the beam walk of the out-coupled laser beam. During a 30 GHz wavelength scan, a parallel shift in the order of up to 10 µm appears, even with a beam correction mirror attached to the grating. This causes serious problems with the stability, e.g. when coupling into a single mode fiber or amplification stages.

With the new generation of diodes both facets can be used so that one faces can be used as the output beam and the other side is coupled to the external resonator. Our new design uses the rear facet of the diode laser chip for coupling the laser light out of the system. This has a number of advantages: We are able to design a high quality external cavity so there are no longer compromises required. The polarization ratio is now improved by the cavity and typical values are well above 1:200. The side mode suppression of the laser system has drastically improved with typical values being 55 dB and better. Also the total tuning range as well as the mode-hop free tuning range are drastically improved and there is no longer a beam walk when changing the wavelength with adjusting the grating angle.

Furthermore, the collimation insisde the resonator is independent from the collimation of the output beam. This has the big advantage that the collimation within the resonator can be optimize for best illumination of the grating while the collimation lens for the output beam can be optimized for the requirements of the experiment the laser will be used for- With such diodes it is also possible to build high power laser systems within a Littman/Metcalf configuration with an output beam up to 1000 mW. This makes this system a good replacement of common master-slave laser systems [2]. The combination of the Littman/Metcalf resonator concept with this new diode generation leads in a widely tunable laser system with maximum frequency stability and extremely small line width with maximum output power. The resonator quality is extremely improved which results in a higher sidemode suppression and a better tuning behavior. With this resonator concept an automated wavelength change with a motor system for coarse tuning and with piezo actuator for fine tuning is possible.

Here we demonstrate a novel external cavity diode laser (ECDL) employing Fabry-Perot diodes as well as high power tapered laser diode within the Littman/Metcalf configuration with computer controlled wavelength change over more than 20 nm. This system greatly simplifies the experimental setup while increasing the available laser power up to 1 W with all the advantages of an Littman/Metcalf design.

Our external cavity semiconductor laser system is designed to have a maximum mechanical stability and an optical power of up to 1000 mW, in addition to a small linewidth and good tunability. Fig. 1 shows schematic interior view of our tunable external cavity in Littman configuration. The laser source of the ECDL is a commercial laser diode where one of the facet is antireflection coated, which suppresses the reflectivity typically below 10^{-4}.

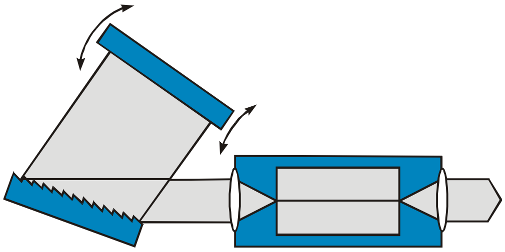


Fig. 1.Principle of the ECDL in Littman/Metcalf configuration. The external cavity is defined by a reflection element and the front facet of the laser diode. A diffraction grating inside the cavity is used for the wavelength selection. The –1st order of the grating is reflected back into the diode. Only a small part is coupled out via the 0th diffraction order of the grating. The main part of the laser light coming from the rear facet of the diode is collimated with a set of lenses.

The wavelength selectivity of the grating forces the laser to oscillate in one single longitudinal mode. Wavelength tuning is obtained by simultaneous rotating of the external mirror around the Pivot Point. The coarse tuning (>20 nm) can be done with a precision of 1 GHz using a stepper motor, fine tuning with a precision of 100 kHz using the piezoelectric transducer. For high speed locking techniques a high frequency Bias-tee is included in the laser head.

The presented results were measured around 800 nm. We also tested other wavelengths regimes at 770 nm, 830 nm, 850 nm, 920 nm, 960 nm, 1010 nm and 1060 nm and further wavelengths regions are under investigation. These results are presented elsewhere. DFG:

The capability of our motorized high power Littman/Metcalf ECDL was demonstrated within a difference frequency (DFG) based cavity ring-down spectrometer (CRDS)[3,4,5,6].. This ultra sensitive absorption technique is based on the

measurement of the decay rate of light confined in a high-finesse cavity. Cavity ring-down spectroscopy with cw lasers is an unique tool for trace gas detection because it combines high sensitivity and fast response. Our laser system was used as a light source within the DFG laser system which is used within the portable CRD-spectrometer. With our tuneable ECDL and a non tuneable Nd:YAG laser system such a DFG-laser source is tuneable between 3030 nm and 3570 nm (2800 cm^{-1} – 3300 cm^{-1}). The wavelength around 3 µm is ideally suited for this measurement technique since various atmospheric or medical relevant molecules show a characteristic fingerprint absorption. The combination of a compact light source with a suitable CRDS-set-up results in a portable trace-gas analyzer with high sensitivity and high specificity which is required for various environmental and medical applications[7].
As an example we measured an water spectrum around 2997 cm^{-1} where the different isotopomeres of water are visible within the spectrum. This shows the excellent tuneability behaviour of our ECDL as well as its perfect brilliance.

2. RESULTS AND DISCUSSION

We demonstrated the suitability of our high power Littman/Metcalf concept with two different types of diodes. For the power range up to 200 mW we use normal Fabry-Perot (FP) diodes where we optimize the output reflectivity especially for this concept. To reach power level up to 1000 mW we use tapered (TA) diodes within this concept. Both systems were designed with a stepper motor and a piezoelectric transducer. In this section we report our investigations of the most important characteristics of such a laser system with an external resonator. We discuss the spacial beam quality, the sidemode suppression, linewidth ,and tuning behavior of our high power laser. Furthermore we performed a high resolution absorption experiment (CRDS), which shows the excellent suitability of such high power ECDL for this kind of application.

1.1 Spectral Behavior

The total available tuning range of a laserdiode in an external resonator is determined by its gain profile. With an antireflection coated front facet, the high-power tapered diode can be tuned via grating-tuning from 764 nm to 795 nm with an output power from the rear facet of up to 200 mW with a standard FP diode and above 1000 mW and a side mode suppression better than 50 dB. Fig. 2 and Fig. 3 show the side mode suppression for both types of diodes, which we could achieve at lowest, center and highest wavelength, analyzed with an optical grating spectrometer (ANDO AQ6315A). We measured that more than 95 % of the emitted power is within the laser line and only about 5 % is due to spontaneous emission background, which can be decreased further by using an optical filter.

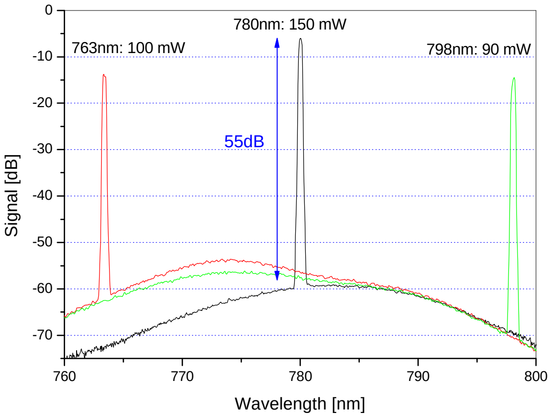


Fig. 2. Spectrum of our ECDL with a side mode suppression of 50 dB and an output power of 150mW for the Littman Laser with FP-Diode.

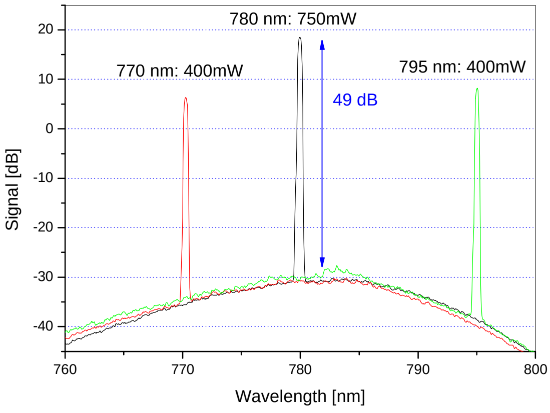


Fig. 3. Spectrum of our ECDL with a side mode suppression of 45 dB and an output power of 750mW for the Littman Laser with TA-Diode (Faraday isolator included).

1.2. Beam profile

The beam profile of the ECDL output light was analyzed by a CCD camera (Coherent, LaserCam II – 1/2). The collimation within the resonator can be aligned independent from the output beam. This gives us the possibility to use different optics for the output beam, for an example we can implement beam correction optic to produce a circular beam profile or an focus at a special distance from the laser head. Fig. 1 illustrates the beam profile of the high power laser ECDL in Littman/Metcalf configuration with and without beam correction optic. Without such an optic, which is used to compensate the astigmatism of the output beam, the aspect ratio is 1:3.

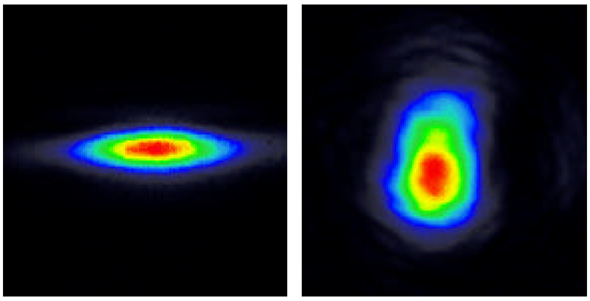
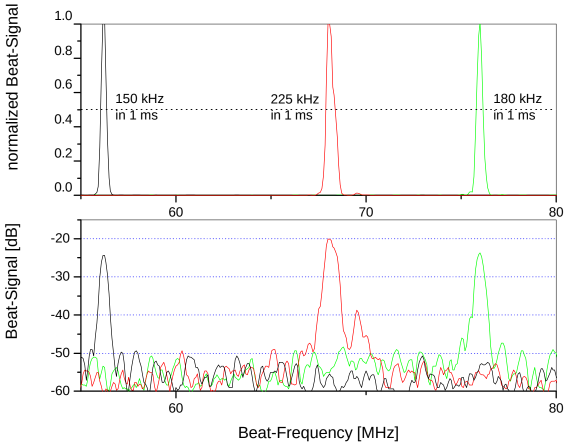


Fig. 4. The beam profile of the ECDL with an $M^2 < 1.2$. The fast axis is in the horizontal plane, while the slow is in the vertical. The right picture shows the beam with a beam correction optic to neglect the astigmatism of the laser beam. Without such an optic the laser beam has an aspect ration of 1:3.

The beam diameter is about 3 mm in slow- by 1 mm in fast-axis at a distance of 50 cm. The M^2 factor is better than 1.2 in both directions, as measured with a beam analyzer (Coherent, ModeMaster). With such a nearly Gaussian beam, coupling efficiencies of up to 75 % could be achieved into a single mode fiber for 780 nm for both types of diodes within the Littman/Metcalf resonator.

1.3 Line width

The linewidth of an ECDL is mainly determined by acoustic vibrations and the injection current noise of the current source. Acoustic vibration disturbances are present on a time scale of 10 s while injection current noise is determinable on a time scale of 10 ms$^{\textbf{Fehler! Textmarke nicht definiert.}}$. For high resolution spectroscopy or for laser cooling a small linewidth is essential. To keep the linewidth as small as possible, we performed a ultra-low-noise laserdiode current source with our ECDL and kept the whole setup on an optical table. We determined the linewidth of this laser system via a heterodyne experiment with two Littman/Metcalf laser systems.



Fig, 5. Linewidth in 1 ms sweep time: 1 MHz.. Three independent scans are shown here Resolution bandwidth: 100 kHz

In the lower parts of the Fig, 5 the beat signals of three independent measurements are shown. These measurements were linearized (upper parts) to determine the FWHM linewidth. Taking into account that the value is a result for both linewidths, the linewidth for one ECDL in Littman/Metcalf configuration is around 100kHz in 1 ms sweep time (for both types of diodes) and in the dimension of below 1 MHz (FP diode) below 10 MHz (TA diode) in 20 ms sweep time. In order to reach this excellent passive stability we developed a ultra-low noise 3A current source. These measurements demonstrate the excellent performance of our ultra-low noise 3 A current source.

1.4. Tunability

For many application it is essential to scan over a wide wavelength range. Therefore we implemented in our Littman/Metcalf laser system a stepper motor. With this the laser can be easily tuned over more than 30 nm. The other important thing is the fine wavelength tuning which is done with a piezoelectric actuator. Both scanning methods must have big overlap to guarantee that the laser can be used at any wavelength within the tuning range. Fig. 6 shows the coarse tuning with the stepper motor of a Littman/Metcalf ECDL (FP diode). It can be scan with a speed of 10nm/second. The minimum step at 780 nm is 1GHz (2 pm @ 78 nm). The tuning behavior of the TA-ECDL is similar.
The inlay in Fig. 6 shows a part of the coarse wavelength scan in more detail. The sinusoidal structure is a result of the internal longitudinal mode structure of the laser diode itself. The power fluctuation is in the order of 10%. There is no discontinuity visible, which is an indication that there was no modehop within this scanning region.

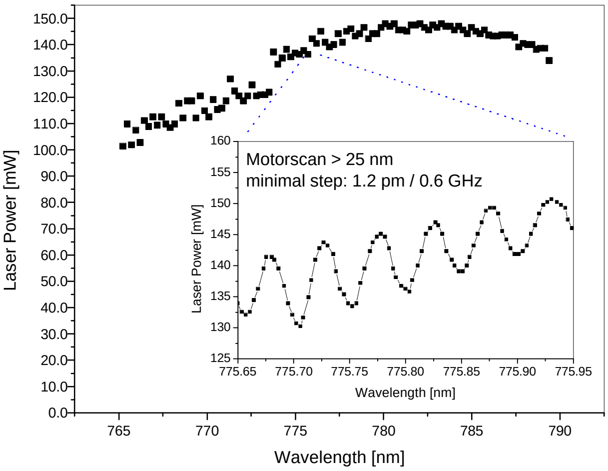


Fig. 6. Wavelength tuning with the servo motor. The maximal tuning range is 25 nm @ 780 nm. The inlay shows the power modulation in detail for a smaller region. The minimal step of the servo motor is 1.25 pm.

With the piezoelectric actuator the laser can be tuned over 0.6 nm @ 780 nm (300 GHz) with a resolution of 6 MHz. In Fig. 7 shows the measured wavelength tuning with the piezoelectric actuator. All measurements were done with a wavemeter (Burleigh, WA 1500) with a resolution of 30MHz, and a calibrated power meter (Coherent, LM2)With such a configuration we have a broad overlap for both tuning mechanism.

The scanning speed with the piezoelectric actuator is 1 kHz. For faster tuning speeds and smaller wavelength steps a bias-tee is included within the laser head. With this the laser can be tuned over 5GHz with a rate of 100kHz/mA and a speed of up to 100MHz. In Fig. 8 the transfer function for the bias-tee is shown. The inlay in the picture shows the power fluctuation during the piezo scan. It is in the oder of 10% without any discontinuity.

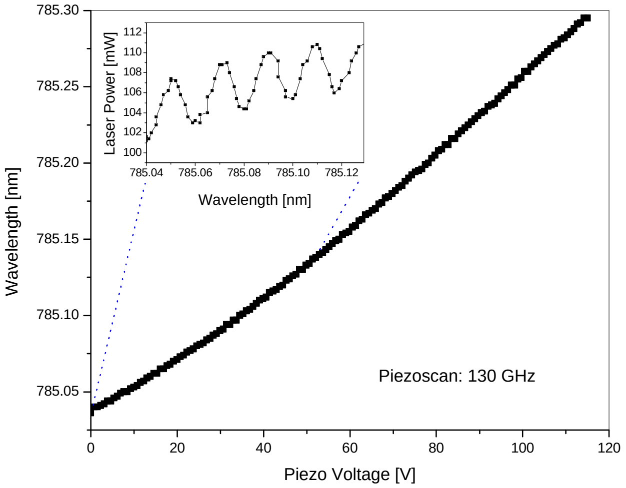


Fig. 7. Wavelength tuning with the piezoelectric transducer. The maximal tuning range with the piezo is 130 GHz @ 780 nm. The inlay shows the power modulation during the piezo scan.

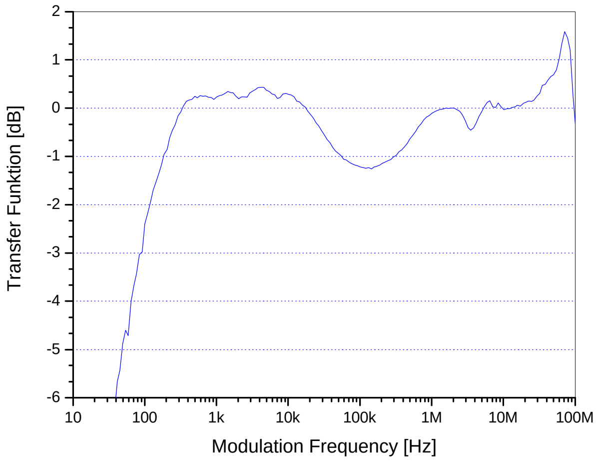


Fig. 8. Frequency response function of the current bias-tee modulation

Modulation Frequency (Bias-tee): 100 Hz … 10 MHz
Current transfer function: 20 mA/V
RF Input Resistance (Bias-tee): 50 Ohm
Laser frequency response: 0.25 GHz/V
Max. Voltage 2 $V_{p\text{-}p}$

All this measurements show the excellent single mode tuning behavior. The combination of high power and excellent tuneability in a compact setup offers the potential that such a laser system can be used in various applications. For example such a laser should be very suitable for difference frequency generation a light source for high resolution spectroscopy or in as a light source for THz generation.

1.6 The Cavity leak-out experiment

In order to demonstrate the suitability of this light source for high resolution spectroscopy, we tested our laser system in the ultra sensitive absorption technique called Cavity-Ring-Down-Spectroscopy. It is based on the measurement of the decay rate of light confined in a high-finesse cavity. Cavity ring-down spectroscopy with cw lasers is an unique tool for trace gas detection because it combines high sensitivity and fast response.

Our high power ECDL was part of a MIR-light source which utilizes difference-frequency generation (DFG) in a periodically poled LiNbO$_3$ (PPLN) crystal pumped by two single-frequency solid state lasers. Two solid state laser systems are used: our widely tuneable external-cavity diode laser and a diode-pumped monolithic Nd:YAG ring laser. Both laser beams are collinearly focussed into the non-linear crystal using several lenses. The PPLN crystal is 5 cm long and both sides AR-coated. The crystal is structured by 21 stripes, each 0.9X 0.5 mm^2 wide, with periods ranging from 20.6 µm to 22.6 µm. The generated DFG radiation is mode-matched to the ring-down cavity with two lenses. The mirrors of the cavity have a reflectivity of 99.985% at 3.3 µm wavelength.

The DFG laser beam is mode-matched to the TEM$_{00}$ mode of the ring-down cavity by means of two lenses. Since the DFG-frequency is modulated, the ring-down cell is periodically excited. Furthermore, we use the modulation to lock a signal TEM$_{00}$ cavity mode to the DFG by adjusting the length of the ring-down cell. As soon as the transmitted intensity exceeds a certain threshold, a trigger pulse is released, which shuts of the DFG via an electro optical modulator inside the beam of the Nd:YAG laser. The subsequent decay of the cavity field is monitored by the photo detector and transferred by a 12 bit analog-to-digital conversion card to the control computer. The decay time of the leak-out signal is determined by fitting a single exponential to the data[8].

1.7 Iostopomer selective water absorption measurement

The capability of the high power diode laser as pump source for the DFG-laser system proofed with an absorption spectrum measurement at a wavelength of 3.3 µm. In this spectral region water molecules show a characteristic fingerprint spectrum. For the absorption measurement the ring-down cell was flushed with a sample gas mixture consisting N$_2$ with an absolute humidity of 100%. The flow rate was controlled by an electronic mass-flow controller to be 100 cm^3/min^{-1} at standard temperature and pressure conditions (1013 mbar, 298 K). In order to reduce the pressure broadening of the spectral line the pressure inside the cavity was 100 mbar. The corresponding gas system is described in detail Reference[9]. Fig. 9 shows the measured water spectrum. The frequency of the DFG-laser system is tuned via the piezoelectric transducer at the mirror inside our the Littman/Metcalf ECDL.

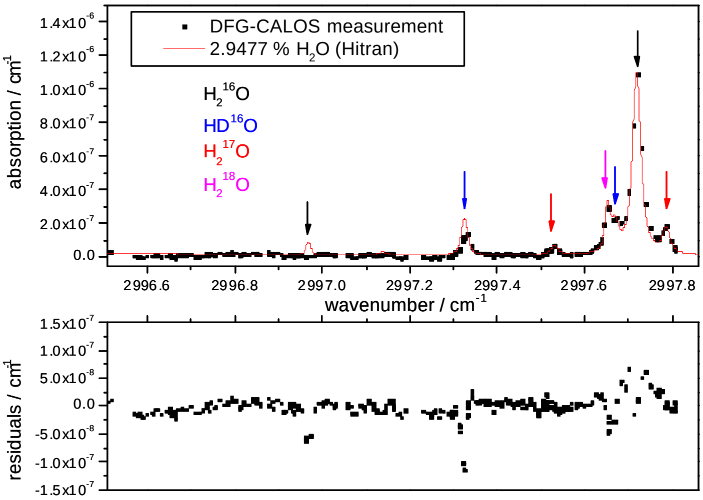


Fig. 9. Water spectrum at 3.392 µm. 100% humidity, 24 °C.

The discrepancies between the measured spectrum and the calculated spectrum with the database HITRAN is caused by errors within the database.

3. CONCLUSION

We reported a new principle of using high power laserdiodes in an external Littman/Metcalf cavity. The very compact design offers up to 1 W output power and an excellent beam propagation factor of $M^2 < 1.2$ in both directions. The laser system has a small linewidth in the 100 kHz regime and is tunable over more than 30 nm. Due to three different wavelength tuning mechanisms the laser can be automatically tuned over the complete tuning range without any discontinuities. We also demonstrated the high performance of the laser system in a CRDS-experiment. This study is a proof of the high potential of the ECDL as a cost effective alternative to amplified laser systems.

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