Nonlinear Lensing in an Unpumped Antiresonant Semiconductor Disk Laser Gain Structure

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***Abstract*— We characterize the nonlinear lens in an antiresonant 11 quantum well InGaAs/GaAsP semiconductor disk laser gain structure designed for operation at 1035 nm using a reflection-type z-scan technique. We probe at a wavelength of 1035 nm and with a sub-picosecond pulse duration. The measured n_2 was within the range of -5.6×10^{-13} cm^2/W < n_2 < -3.1×10^{-13} cm^2/W.**

***Index Terms*— Semiconductor lasers, quantum well lasers, nonlinear optics, ultrafast optics.**

I. INTRODUCTION

SEMICONDUCTOR disk lasers (SDLs), also known as vertical-external-cavity surface-emitting lasers (VECSELs), have been the subject of considerable interest in recent years due to flexibility in their design and low cost. This has led to steady improvements in average powers up to 106 W [1] in continuous-wave (CW) operation and kilowatt peak powers in mode-locked (ML) operation with sub-picosecond pulse durations typically at gigahertz repetition frequencies [2], [3].

Most ML-SDLs have used semiconductor saturable absorber mirrors (SESAMs) to initiate mode-locking [4], [5]. Recently, there have been reports of SDLs operating in a pulsed regime without a saturable absorber in the cavity, so called self-mode-locking (SML) [6]–[15]. It has been suggested that Kerr lensing in the gain medium [7], [8] or saturable absorption in unpumped quantum wells (QWs) causes the observed pulsation [6]. However, there has not yet been sufficient characterisation or modelling to determine what the causal effect is.

To understand the observed lasing behavior of self-mode-locked SDLs it is important to characterize nonlinear lensing in a SDL gain structure. The magnitude of the nonlinear lensing would influence the cavity design of SML-SDLs and it may also need to be considered when designing SESAM ML-SDL cavities.

SDL gain chips are multilayer structures with scope for large variation in composition, thickness and number of layers. The complexity of their design makes modeling the nonlinear response challenging. The nonlinear response of semiconductors is highly dependent on the photon energy of the incident light as compared to the band gap energy of the semiconductor [16]. There are many different physical mechanisms that could affect lensing in the gain chip, including carrier and thermal effects, the strength of which are not well known and may occur on very different time scales [17], [18]. The relative contribution to the nonlinear lens from QWs and barriers is not well understood and is further complicated by the E-field standing wave formed by the microcavity.

In order to obtain representative values of the lensing it is essential to replicate laser operating conditions when characterising the nonlinear lens. The structure must be probed at a wavelength on resonance with the quantum well emission, where the SDL gain chip would naturally lase, and with a pulse duration that is comparable to reported self mode-locking (<1 ps).

The first z-scan characterisation of an SDL gain structure detected a nonlinear lens that was potentially large enough to perturb an SDL cavity [19]. The probe laser used in this experiment, however, had a pulse duration of 10 ps, more that an order of magnitude longer than the pulse duration typical of femtosecond ML-SDL. Furthermore, the wavelength of the probe laser was 1064 nm, outside the 1025-1040 nm range over which the gain chip was observed to lase.

In this letter we present z-scan measurements made on the same SDL gain structure as in Ref. [19], using a 1035 nm probe laser emitting a train of pulses of 230 fs duration. We treat the SDL chip as a black box optical component and directly measure the nonlinear lens produced without making assumptions as to relative contributions to the lensing from different elements within the structure. We observe a self-defocussing lensing effect that varies linearly with the average power of the probe beam.

II. METHOD

The nonlinear response of the SDL gain chip was measured using a reflection-type z-scan setup, similar to that demonstrated in Ref. [16], shown in figure 1.

The probe beam is focused onto the sample using an aspheric lens (Thorlabs A280TM-B), producing a focused spot

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Manuscript received January 19, 2016; revised March 1, 2016; accepted March 10, 2016. Date of publication March 24, 2016; date of current version April 29, 2016. This work was supported in part by the U.K. Engineering and Physical Sciences Research Council under Grant EP/J017043/2 and in part by U.K. Quantum Technology Hub for Sensors and Metrology Grant EP/M013294/1.

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Digital Object Identifier 10.1109/LPT.2016.2543302

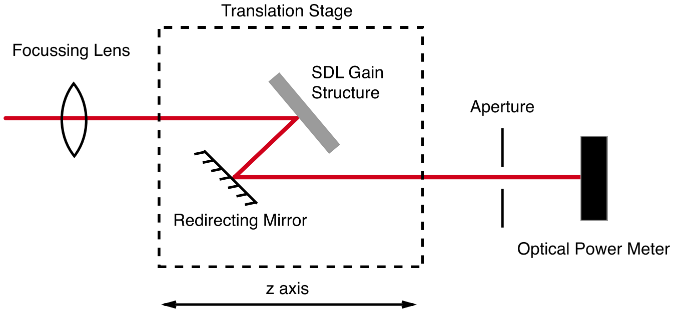

Fig. 1. Schematic of the reflection z-scan setup. The incident intensity on the sample is varied by changing the position of the sample along the axis of the focusing probe beam (z-axis). Mounting the sample and a redirecting mirror on a translation stage maintains a constant optical path length to the aperture.

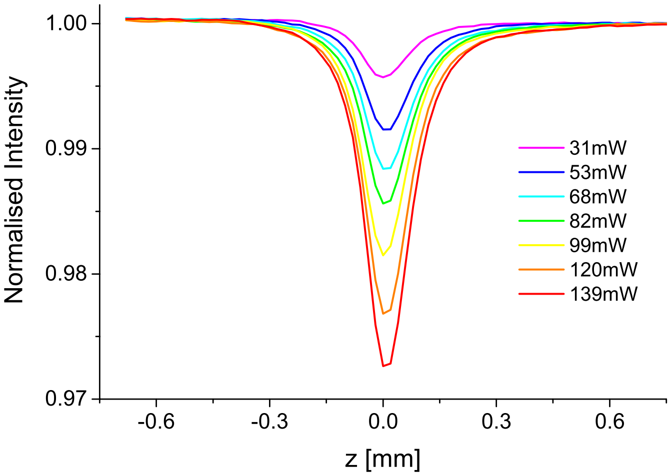

Fig. 2. Normalised "open" scan data showing a large absorption feature, centered at z_0, that increases with increased average power of the pump beam.

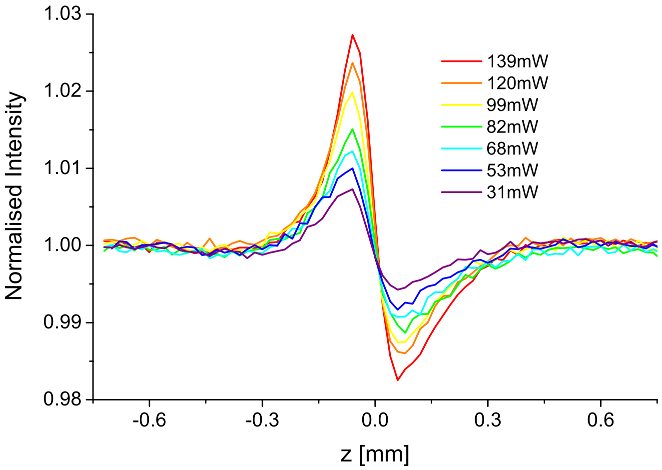

Fig. 3. Normalised z-scan curves showing the deviation in transmission through an aperture as a result of nonlinear lensing in the SDL gain chip.

radius of ~ 5 μm. This spot size allows us to reach pulse fluences of up to 3 mJ/cm^2 on the sample, which is comparable to those found in ML-SDLs.

To control the incident spot size, the sample is translated along the z-axis through the focus of a Gaussian beam. The sample and a redirecting mirror are mounted together on a motorized translation stage to maintain a constant optical path length between the lens and the aperture.

Collecting the whole beam onto a power meter (Thorlabs SC120) enables the detection of any change in intensity of the beam on reflection by the sample due to intensity dependent absorptions ("open" scan). Closing an aperture on the reflected beam causes the collected power to be dependent on any change in beam size, due to nonlinear lensing, as well as intensity dependant absorptions ("closed" scan). If the input and output beams are parallel, the "closed" and extracted z-scans have a flat background, providing a sensitive test of beam alignment.

Extracted z-scan curves, showing only the effect of nonlinear lensing are obtained by dividing the "closed" by the "open" scan and normalizing so that for distances far away from the focus, z_0 there is no deviation from 1. The aperture size was set to give a 50% transmission for large z magnitude, where no lensing effect is observed.

The probe laser used in these measurements was a 63.4 MHz repetition rate, Yb:glass laser producing 230-fs FWHM pulses with a Gaussian temporal profile and an available average power of up to 140 mW at the sample. The M^2 value was less than 1.1 on both axes.

The SDL gain chip used in this work is a multi-layer stucture containing a distributed Bragg reflector (DBR), active region and carrier confining window layer. The DBR consists of 22 pairs of AlAs/GaAs quarter wave layers with a center wavelength of 1035 nm. The active region is a resonant periodic gain (RPG) structure also with a design wavelength of 1035 nm. The active region contains 11 InGaAs quantum wells (QW), positioned with one QW per antinode of the E-Field standing wave. The spacer layers between the QWs consists of GaAsP, with a low phosphorous concentration chosen to compensate for the strain of the QWs. The sample is completed by an InGaP$_{0.5}$ window layer which is etched to a quarter wavelength thickness at a wavelength of 1035 nm using wet chemical etching during the flip-chip bonding process, to make the structure antiresonant. The structure is grown in reverse order and is flip chip bonded onto a 300-micron thick diamond heat-sink which then is mounted into a Peltier controlled copper heat sink. When lasing in CW operation with a 20 degree heat sink temperature, the emitted center wavelength ranged between 1025 nm and 1040 nm.

III. RESULTS

Z-scan measurements were performed for a range of incident probe powers up to the maximum average power of 140 mW. Below 30 mW the signal-to-noise ratio was too low for data extraction. "Open" scans show a large absorption feature at the z_0-position as shown in figure 2 which was not discussed in previous measurements [19]. The effect is likely to be dominated by two photon absorption (TPA).

The extracted z-scan curves for the various probe powers are shown in figure 3. The change in normalised intensity from

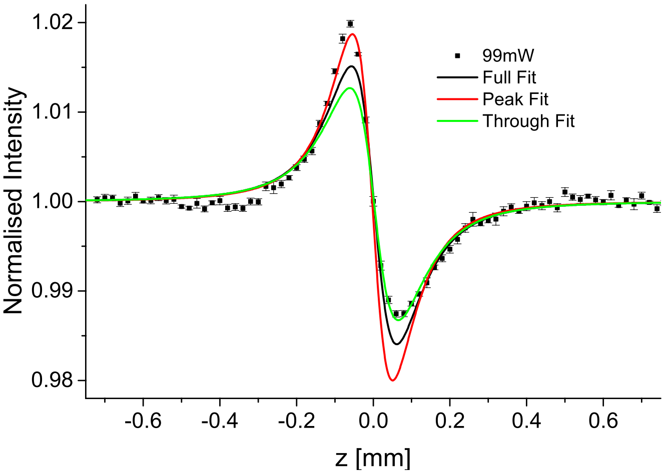

Fig. 4. Fitted curves, calculated using the method described in Ref. [20], to the normalized z-scan response for 99 mW incident probe power. Fitting to the whole data set [black], fitting to the peak only [red] fitting to the trough only [green].

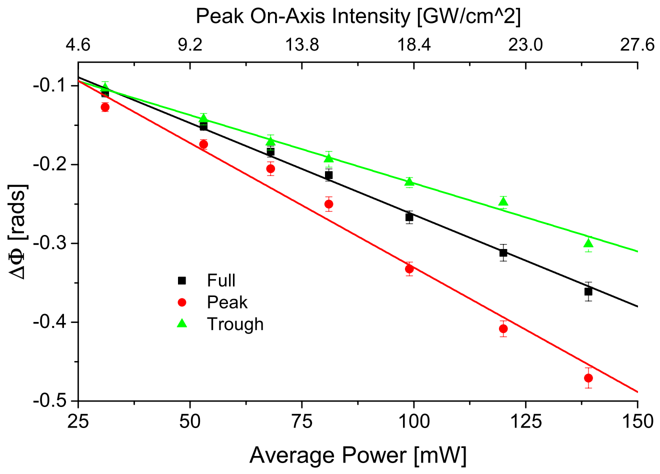

Fig. 5. Peak on-axis phase shift ($\Delta\Phi$) extracted from fitting to the z-scan. The variation of $\Delta\Phi$ with peak on-axis intensity would be linear for nonlinear lensing dominated by χ^3 effects. Extracted phase shifts with linear fits are shown for fits to the whole curve [black], fits to the peak only [red], and fits to the trough only [green].

a value of 1, about the z_0-position, is evidence of a nonlinear lensing effect in the SDL gain structure.

To extract a value for the lens strength, the data is fitted using the method described in Ref. [20] for z-scan responses using Gaussian beams in which χ^3 effects dominate. Peak on-axis phase shift ($\Delta\Phi$), focused spot size (ω_0) and z_0 are left as free fitting parameters. An example fit is shown as the black line in figure 4.

The form of the theoretical z-scan curve differs from our data as the peak and trough deviate from the normalized transmission by different amounts. The source of this asymmetry in our data is unclear at present. Assymetry leads to uncertainty in the extracted phase shifts. By fitting to only the peak or only the trough we achieve good fits to these sections of the data, providing upper and lower bounds to the extracted values, shown as the green and red curves in figure 4.

The extracted spot width was 5.0 ± 0.5 μm for all of the data analysed. The variation in the value of the zero offset between fits was much less than the step size of 20 μm.

The variation in extracted values of $\Delta\Phi$ with average probe power is shown in figure 5. The negative gradient of the change in $\Delta\Phi$ with incident power indicates that the sign of the lens is negative, acting to defocus the incident beam.

The linear trend of the change in peak on-axis phase shift ($\Delta\Phi$) suggests that the dominant mechanisms driving the changes in refractive index are due to third-order nonlinear effects [20]. We calculate an effective n_2 value using equation 6 in Ref. [20]. Fits to the peak and trough provide upper and lower bounds of -5.6×10^{-13} cm^2/W $< n_2 < -3.1 \times 10^{-13}$ cm^2/W.

The negative sign measured for n_2 corresonds to a defocussing lens, consistent with the observations reported for the same chip in Ref [19]. The lens that we observe here is, hovever, weaker: Ref [19] reports a value for n_2 of $-1.5 \pm 0.2 \times 10^{-12}$cm^2/W. It therefore appears that the nonlinear effect is weaker for 230 fs pulses at 1035 nm than for 10 ps pulses at 1064 nm. In both experiments the temperature of the chip was maintained at 20 °C.

The authors in Ref. [8] state that the value of n_2 for an SDL gain structure is expected to be in the range -1×10^{-13} cm^2/W to -10×10^{-13} cm^2/W based on a review of a number of experimental and theoretical publications [17], [18], [21]–[23]. A measured value of n_2 in bulk GaAs has been reported by Ref. [22] to be 3×10^{-13} cm^2/W at a wavelength of 1060 nm.

Given the measurements here and those reported in Ref. [19] it is evident that there is a measureable nonlinear refractive index in this SDL gain structure. It remains unclear if the nonlinear lensing this will cause in SDLs will be sufficient to explain self-mode-locked operation.

IV. CONCLUSIONS

The nonlinear lensing response of a semiconductor disk laser (SDL) gain structure has been characterised with a probe beam that has a center wavelength, pulse duration and pulse fluence comparible with the intracavity field in a ML-SDL. The phase shift is shown to vary linearly with incident power, consistent with a third order nonlinearity. The value of n_2 is in the range of -5.6×10^{-13} cm^2/W $< n_2 < -3.1 \times 10^{-13}$ cm^2/W.

ACKNOWLEDGMENTS

The authors wish to acknowledge Mr. D. Grimsey for technical support, Vasilis Apostolopoulos for the use of the probe laser, and Wolfgang Stolz, Bernadette Kunert, and Bernd Heinen of NAsP III-V GmbH for sample fabrication and processing.

The data shown in this letter is openly available in DOI:10.15132/10000109.

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