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Spectral density contrast in DPSS and ECD lasers for quantum and other narrow-linewidth applications

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ABSTRACT

With increasing demand for narrow-linewidth lasers for applications such as atom cooling, metrology and sensing, the research community has centred its focus around locking and referencing the lasing wavelength with the highest stability achievable. The two main platforms emerging to accommodate for such specific needs are diode pumped solid-state (DPSS) and external cavity diode lasers (ECDL). Being in the early stages of their product life cycles, both platforms are seeking ways to provide users with reasonably high and stable output powers. Our paper looks into the details of the performance differences between the two platforms. Primarily it shows that whilst similar output powers can be achieved using both platforms within Sub-GHz bandwidths, due to additional spontaneous emission noise terms, encountered in ECDLs, there exists a difference in the spectral density contrast. In fact, these noise terms, being detectable by power meters for output power specifications, compromise on the spectral density contrast within the linewidth of interest, which can be critical for narrow-linewidth applications. We have compared some of the most recently reported ECDL spectra to a standard Nd:YAG DPSS laser to show that in case of both platforms specified for the same output power, a DPSS laser can provide at least 3-times more useful output power, within the specified narrow spectral linewidth, than an ECDL, which puts the feasibility of these platforms into a new perspective.

Keywords: Spectral density contrast, Narrow-linewidth, Quantum Technology, DPSS, ECDL, lineshape

1. INTRODUCTION

Narrow-linewidth lasers are now highly demanded in various applications from atom cooling and trapping to high-resolution spectroscopy. These light sources can be achieved using different gain media, such as solid-state crystals, semiconductors or even fibre sources. These systems might be compared upon the specified output power, the specified linewidth and the overall system footprint.

With current endeavours in the UK and around the world to foster the development of new Quantum-based technologies (QT) to sense and detect previously unreachable interactions, such as underground structures or gas leakages, the generation of light sources with highly stabilised output wavelengths have become critical. The difference in technologies, particularly focusing on diode-pumped solid-state (DPSS) and external cavity diode (ECD) lasers, have advantages in various respects. With this paper we aim to give a consideration of the differences in the performance of these two platforms.

This report will give a general introduction to the fundamental lifetime broadening of ECD and DPSS laser sources. It will illustrate the different gain factors that will lead to a broadened lineshape for semiconductor lasers. The lineshape difference can lead to discrepancies in the performance of these two platforms, even when the quoted system properties seem identical. We base our argument on the sometimes misleading power measurement conventions. With power detector spectral bandwidths rated to $>100\text{nm}$, we can assume that most of the noise terms are detected, suggesting that quoted power readings are not fully reflecting the power enclosed in the specified linewidth of the system. Therefore, it is important to define and quantify the losses associated with technology-specific characteristics and so these terms should be carried forward for the specification of future Quantum Technology applications. Consequently, we will introduce the term spectral density contrast as a ratio between the application-specific useful and overall output power.

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2. LIFETIME BROADENING IN DPSS AND ECD LASERS

In this section we give a brief summary of the development of the spectral lineshape in DPSS and ECD lasers. Laser operation is generally supported for multiple lasing modes with a given cavity geometry and gain medium. In fact, the cavity itself can support billions of modes. The excitation is therefore distributed amongst the supported modes. The multi-mode operation can be characterised as the superposition of the lasing modes, each specified with a certain coupling constant K_i and number of atoms n_i . Equation 1 describes the multi-mode rate equations.

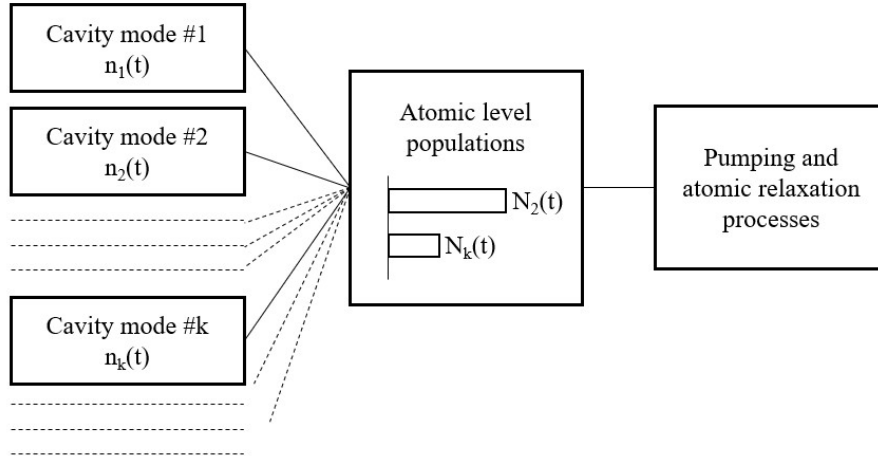


Figure 1: Recreated from Siegman's book,¹ illustrating the coupling of a set of atoms to the supported cavity modes.

$$\begin{aligned} \frac{dN_2(t)}{dt} &= \sum_i K_i n_i(t) [N_1(t) - N_2(t)] + [pumping \ terms] + [relaxation \ terms] \\ \frac{dN_1(t)}{dt} &= - \sum_i K_i n_i(t) [N_1(t) - N_2(t)] + [pumping \ terms] + [relaxation \ terms] \end{aligned} \quad (1)$$

In order to achieve single-mode operation, it is required to ensure that only one mode can reach threshold conditions to lase. It shall be noted that some of the incident power is still coupled into spontaneous emission terms. By assuming a quick relaxation rate, hence $N_1 = 0$, we can simplify the above equations to the well-known form:

$$\begin{aligned} \frac{dn(t)}{dt} &= \sum_i K N_2 (n_i + 1) - \gamma_{c,i} n \\ \frac{dN_2(t)}{dt} &= R_p - K N_2 n - \gamma_2 N_2 \end{aligned} \quad (2)$$

In equation 2 we assumed single mode operation to achieve an upper-state population of N_2 and a significant photon number n , R_p is the pump rate, γ_c is the cavity decay rate and γ_2 is the spontaneous decay rate. Thus one can see that the power in the lasing mode P_0 is proportional the the number of photons associated with the spectral position of that mode. While, the total power is given as the sum of the power stored in the lasing mode, P_0 , and the additional spontaneous terms.

Theoretically, atomic transitions occur at exact frequencies, however, the tiny fluctuations in the phase of the optical field result in additional phase and intensity noise in the emitted laser field, which eventually broadens the lineshape. We differentiate between homogeneous and inhomogeneous (or technical) broadening. These disturbances might arise from environmental factors such as temperature fluctuations, mechanical vibrations or electrical noise encountered in the control system. The theoretical minimum of the instantaneous linewidth of the simulated emission in a laser is given by the Schawlow-Townes limit.² The first estimate for a semiconductor laser linewidth was derived by Fleming and Mooradian,³ whilst similar characterisation was done previously for gas lasers with a certain focus on lifetime broadening by Lax.^{4,5}

$$\Delta f = \frac{\nu_g^2 h \nu g n_{sp} \alpha_m (1 + \alpha^2)}{8\pi P_0} \quad (3)$$

Equation 3 describes the Schawlow-Townes limit. In this equation Δf is the instantaneous linewidth, ν_g is the group velocity, g is the gain, n_{sp} is the spontaneous emission factor, α_m is the facet loss and α is the detuning term first introduced by Lax. Note here that the instantaneous linewidth is inversely proportional to the power stored in the given mode. Whilst the above formula gives an accurate estimate for the linewidth of each system, Henry⁶ showed that for a semiconductor-based system the linewidth can be at least 50-times broader than previously expected. This was explained by the increased spontaneous emission factor, n_{sp} , relevant to semiconductor lasers. While for solid-state lasers it can be assumed that spontaneous emission related losses equal the gain or that $n_{sp} = r/g = 1$, hence $\alpha = 0$, this is not true for semiconductor-based systems and an additional term shall be included in the equation, so that $r = g + \alpha$. This ultimately couples back to the rate equations 2 with a higher relaxation rate and an increased spontaneous emission factor.

Following the theoretical introduction of the lineshape development specific to both DPSS and ECD lasers, we can analyse some of the experimental results to show that these platforms might perform differently for QT applications.

3. METHODOLOGY AND RESULTS

We compared the spectral purity in some of the most recently published narrow-linewidth ECDL sources to industry-standard DPSS lasers including Coherent's Mephisto (Nd:YAG) and Cobalt's Samba (Nd:YVO₄). This report does not give a full-extent analysis to the noise-terms and performance indications specific to the gain types. But, it intends to illustrate the implications and future challenges associated with spectral performance differences in between the two platforms. We also want to show how these differences might be reflected in commonly used performance specifications.

3.1 Spectral density contrast

In the following analysis we use the term *spectral density contrast* (s.d.c.) to illustrate the ratio of effective power achievable with the analysed laser platforms. We define s.d.c. as the percentage ratio of the useful power, i.e. the power enclosed in the Gaussian fit of the specified linewidth of the system, to the overall power emitted by the laser. In figure 2 we illustrate some of the reference DPSS lasers including Coherent's Mephisto⁷ and Cobalt's Samba.⁸ The above illustrated DPSS laser models show similar characteristics. As the figure shows, a spectral suppression of at least -70dB is achievable with these systems within 1MHz of spectral width. The linewidth in most of these systems is defined as below 500kHz, with Coherent's Mephisto platform capable of achieving an FWHM of below 1kHz with the active noise eater.⁹ Comparable performance can be achieved with our QT ranges, including the Solo 780 QT and Solo 698 QT, results from this analysis will be communicated in a later paper.

$$s.d.c. = \frac{P_{useful}}{P_{measured}} \cdot 100\% \quad (4)$$

There is a broader lineshape and hence a weaker suppression of power outside the specified linewidth in ECD lasers. This is shown in figure 3. Whilst, narrower linewidths can be achieved, the maximum side-mode suppression is found to be -60dB in these examples. Hence, comparatively less power is emitted within the specified linewidth of this laser type.

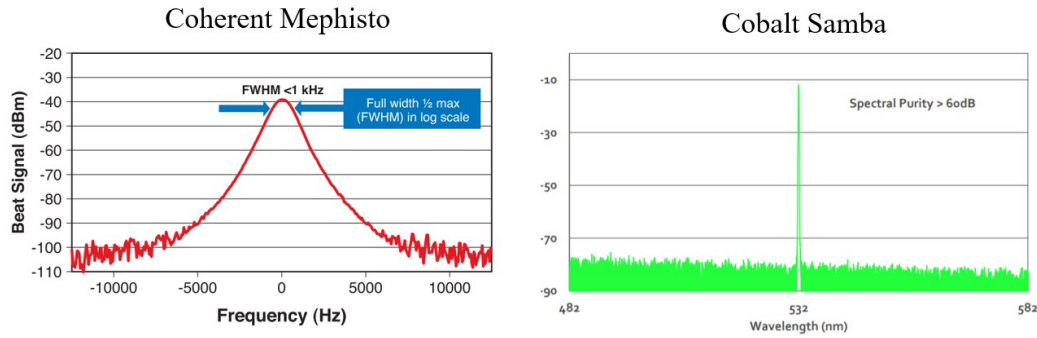


Figure 2: Illustrating the spectra of some of the industry-standard narrow-linewidth DPSS lasers including Coherent's Mephisto⁷ and Cobalt's Samba.⁸

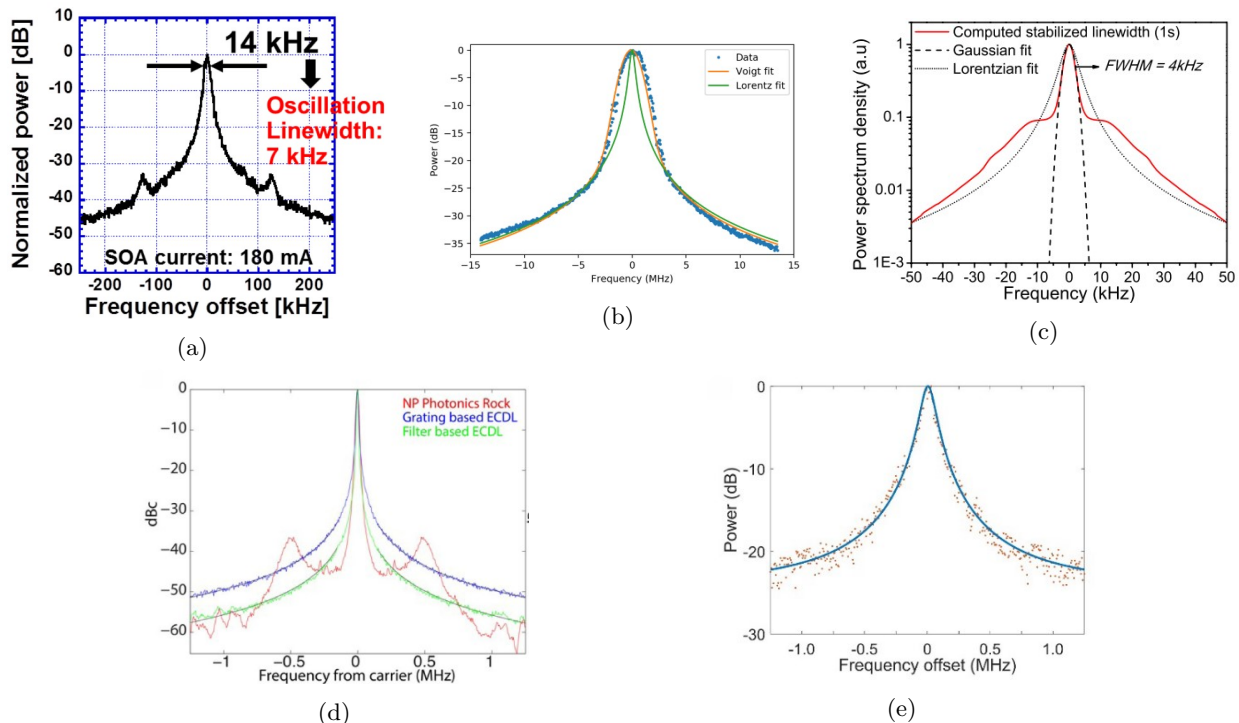


Figure 3: Illustrating some recently published ECDL spectra (a) Kasai et al.,¹⁰ 14kHz linewidth, (b) Schkolnik et al.,¹¹ 88kHz linewidth, (c) Laurain et al.,¹² 4kHz linewidth, (d) Bennets et al.,¹³ 5.2kHz linewidth, (e) Zhu et al.,¹⁴ 70kHz linewidth.

3.2 Numerical measurement of the s.d.c.

We did a numerical analysis to calculate the spectral density contrast for the previously mentioned ECDL platforms, we then compared that to our reference DPSS laser. In this analysis we recreated the spectral graphs provided in the individual papers. It shall be noted that these figures are only estimates representing some of the key characteristics of the respective systems. Furthermore, since the spectral data was only provided for a given spectral width (this ranged from 50kHz up to 15MHz), we calculated the s.d.c. for the spectrum provided by each paper. This indicates that on the assumption of further noise terms encountered outwith the provided spectral ranges, which is evident from the weak side-mode suppression, the s.d.c. calculated here is the highest value, hence the best-case scenario for these systems.

The spectra are conventionally reported as logarithmic power density functions. As a first step, we converted

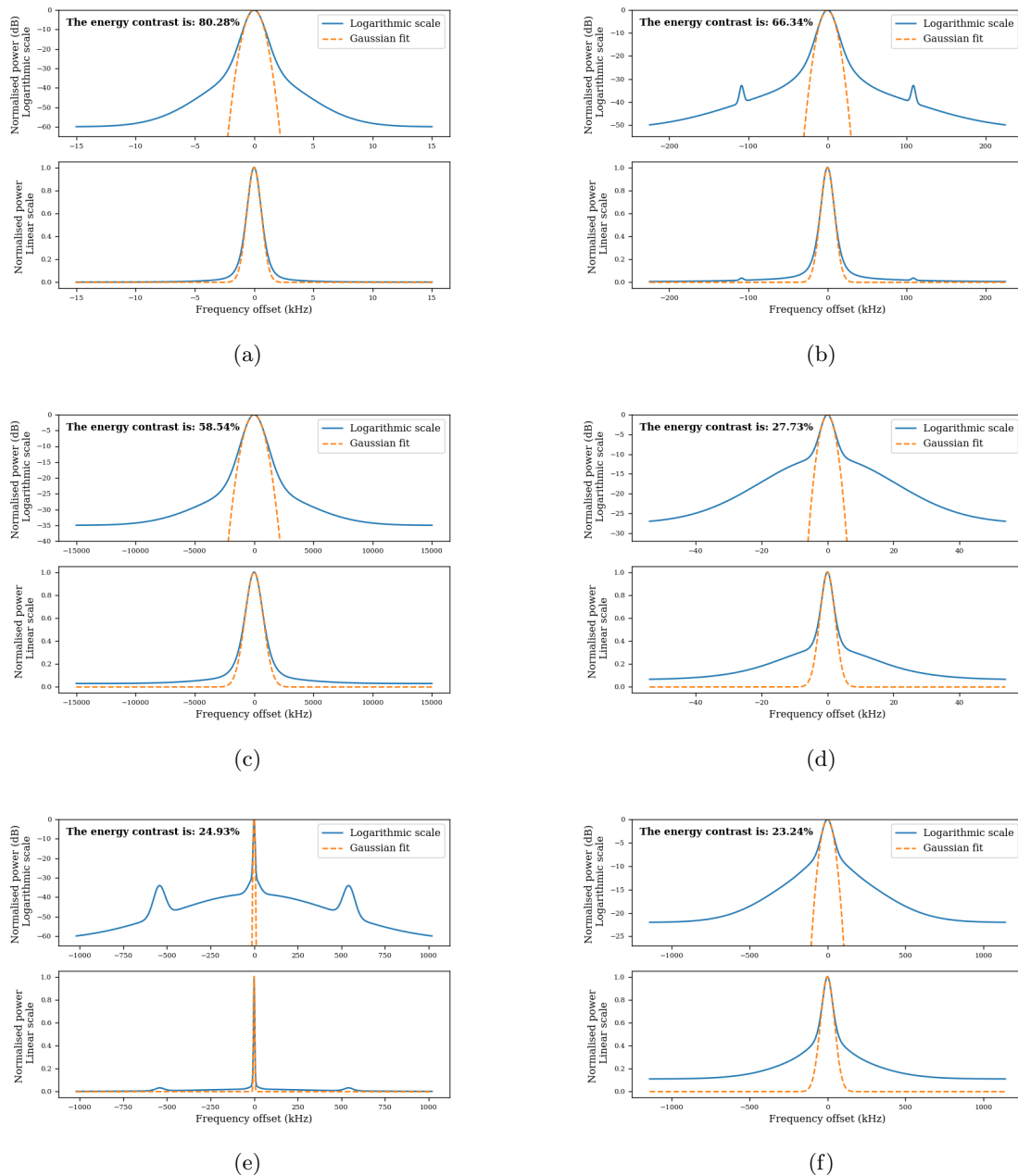


Figure 4: Illustrating the spectral density contrast estimates for the analysed systems, in each subfigure the top graph is presented in the logarithmic scale, while the bottom graph shows the linear scale of the same data. (a) Coherent's Mephisto DPSS laser,⁷ 1kHz, 80.28%, (b) Kasai et al.,¹⁰ 14kHz, 66.34%, (c) Schkolnik et al.,¹¹ 88kHz, 58.54%, (d) Laurain et al.,¹² 4kHz, 27.73%, (e) Bennets et al.,¹³ 5.2kHz, 24.93%, (f) Zhu et al.,¹⁴ 70kHz, 23.24%.

the logarithmic scale into a linear representation. We used a Gaussian fit to estimate the specified linewidth region of each system. We assumed that at a minimum of 4kHz linewidth, reported in the outlined papers, the platforms would exceed the Schawlow-Townes limit of the instantaneous linewidth by at least 10^6 times, therefore we considered technical, hence Gaussian-shape, broadening being dominant in the development of the lineshapes. As a last step, we integrated the normalised power enclosed in the Gaussian fit, which was then

compared to the power enclosed in the reported spectrum. This gave us a normalised and unitless figure to show the spectral density contrast or the ratio of useful to overall power.

From the results it is clear that DPSS lasers can achieve a better spectral density contrast. In our analysis Coherent's Mephisto came first with an s.d.c. of >80%. Whilst, for some of the analysed ECDL platforms we calculated an s.d.c. of <25%. This means that when compared against our reference DPSS laser, these lasers might provide 3-times less useful power.

4. DISCUSSIONS AND IMPLICATIONS

The above estimates show that compared to a standard DPSS source, ECD lasers might not be able to provide the same amount of useful power given an identical output power specification. This is mainly due to the added detuning term to the spontaneous emission factor, which in turn broadens the lineshape. This ultimately can imply differences in the performance of ECD lasers compared to solid-state platforms. We base this assumption on the fact that most of the noise terms are picked up by a power detector and hence the output power specification for an ECD laser might not prove to be as efficient as the same specification quoted for a DPSS laser. We also believe that these differences might only be relevant to high-precision applications such as in Quantum Technologies for atom trapping or cooling or high-resolution spectroscopy including Raman and Brillouin where a specified linewidth below 1MHz is required.

Narrow-linewidth lasers are essential for Quantum applications, for example in optical clocks. Apart from frequency stability, another important requirement is the portability and robustness of such devices that will enable the transition of these systems from the laboratory into field applications. A figure often used when comparing such devices is the SWaP-C or size, weight, power and cost. We have previously discussed that both ECD and DPSS lasers are capable of achieving similar powers and linewidth specifications. Whilst, DPSS lasers are normally considered more expensive, with this analysis we intended to show that their useful-power-respective cost might be favourable compared to ECDLs. Another implication of the additional noise terms encountered in ECDLs can be found in their overall footprint. While a typical DPSS laser takes up a few litres of volume (the Mephisto is 3.4l, the Samba is 0.25l and the Solo 780 is 1.1l), most of the ECD platforms are in the range of 3 to 8 litres of volume due to the additional cooling solutions they require. Considering their lower s.d.c. figures we can also assume that in order to achieve an equivalent useful power compared to DPSS sources, the overall volume of an ECDL can be significantly larger. All of these aspects would have an impact on the corresponding SWaP-C figures, which should be considered by the user before committing to either of these platforms.

5. CONCLUSIONS

In this paper we showed that due to the dissimilarities in the lifetime broadening between semiconductor-based ECD and DPSS lasers, there exists a difference in the spectral density contrast. This consequently indicates that given the same output power specification, the two platforms might provide different levels of useful power. For the examples illustrated in this paper, we found that while an s.d.c. of above 80% can be achieved in the DPSS case, for ECDLs this figure can be as low as 25%, meaning that only a quarter of the emitted power is contained within the specified linewidth of the system. This contrast might stay unnoticed, as power meters detect the additional spontaneous noise terms encountered in ECDLs. In fact, the difference in performance can be critical for narrow-linewidth applications such as in Quantum Technologies or high-resolution spectroscopy. Furthermore, we believe that these discrepancies between DPSS and ECD lasers might alter the corresponding SWaP-C figures and hence could have significant implications in terms of the feasibility of the two laser platforms.

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