Precision Threshold Current Measurement for Semiconductor Lasers Based on Relaxation Oscillation Frequency

D. M. Kane and Joshua P. Toomey

Abstract—**The soft turn-ON of semiconductor lasers leads to uncertainty in defining and measuring the laser threshold injection current, I_{th}. Previously, practical calculation algorithms have been developed to achieve high-accuracy measurement of a clearly defined and reproducible quantity which is called I_{th}. We demonstrate a new and higher accuracy measurement of I_{th} using the dependency of the relaxation oscillation frequency on injection current, as compared to the existing standardized approaches. Further, if it is accepted that relaxation oscillations do not occur below laser threshold, this may be regarded as a more fundamentally based definition and measurement method to determine the laser threshold injection current in a semiconductor laser. The method may also be applicable to other types of lasers.**

Index Terms—**Laser threshold, relaxation oscillations, semiconductor lasers, threshold current.**

I. Introduction

A semiconductor laser operates as a light-emitting diode (LED) below the laser threshold current. Thus, the output power versus injection current has an approximately linear slope efficiency, as a LED, below laser threshold, and a much larger, linear, lasing slope efficiency above it. Kinks in this lasing slope efficiency have been common historically, but a linear region occurs for index-guided, commercial devices, and indeed, most semiconductor lasers fabricated using state-of-the-art approaches. In the LED-to-laser transition region of the output power versus injection current graph (also commonly called the light--current characteristic) a smooth curve is typically observed. This "soft" laser threshold for a semiconductor laser [1] introduces uncertainty into defining the onset of laser oscillation and the corresponding laser threshold injection current. Measuring a threshold current from such a characteristic has been thoroughly addressed in a practical manner for industry standardization of the measurement and a quantity that is called the laser threshold injection current results [2], [3]. A collective of four calculation algorithms are applied—the linear line fit, the two segment line fit, the first derivative, and the second derivative threshold calculations. Intercomparison of the results from the four calculations, and the graphs generated in each analysis, give further insight into the impact of measurement noise and sensitivity to any nonlinearities in the laser output. None of these algorithms can be claimed as a definitive calculation of a fundamentally defined laser threshold injection current. But, being able to systematically and reproducibly make such a measurement, so that lasers within a single "batch" and different device designs can be reliably compared, is important.

The method of measuring the laser threshold current herein is based on precision measurement of the frequency of the relaxation oscillations of the free running laser as a function of injection current. From theory [4], [5], the relaxation oscillation frequency (ROF) scales with the square root of the injection current above threshold. The laser threshold injection current is determined as the "test" value, which gives the best linear fit of ROF versus injection current above threshold.

Herein, we show that using this high-precision technique to measure the ROF as a function of injection current, for a range of injection currents where the relaxation oscillation dominates the RF spectrum of the output, enables the threshold injection current to be calculated with improved accuracy over the four calculation algorithms of the Bellcore standard [2], [3]. Thus, this can be a useful extension to the Bellcore standard for achieving improved precision and accuracy in laser threshold current measurements, as and when needed. The method is experimentally more involved and requires more equipment than generating a light--current characteristic and analyzing it using the Bellcore standards. However, there are contexts, such as lasers with very low threshold currents, where this extra effort is warranted to achieve a high-precision measurement. Additionally, if it is accepted that no relaxation oscillations occur below laser threshold, a correct interpretation from the standard rate equations for a free running semiconductor laser [1], then this is also a definition of the laser threshold injection current, I_{th}, for a semiconductor laser, which has some basis in fundamental laser physics. This interpretation will need to be considered in depth in the future in the context of the many complexities that do arise in describing semiconductor laser gain media.

It is timely to note that the standard calculation algorithms of laser threshold current are not systematically applied and reported to measurement of laser threshold injection currents in the semiconductor laser research literature, even when ultralow-threshold injection currents are being reported. A

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review of recent and early research papers, in which low laser threshold current, or current density, is a feature of the results being presented, shows that it is a common practice to omit details of the method used to make the threshold measurements (e.g. [6]–[10]). In one early report of achieving ultralow laser threshold injection current [11], the linear line fit was used. This method is acknowledged as the least accurate of those available [3]. It underestimates I_{th}. However, it may be the most commonly applied method still, but in the absence of specific information in research papers it is unknown which methods are in use. It can be argued that the semiconductor laser threshold current is highly temperature dependent and can also change quite significantly over time in devices fabricated in research facilities that do not meet standard manufacturing specifications. Even commercial devices are usually subject to a "burn-in" processing step to stabilize their operating conditions. Hence, high-accuracy measurements may not be repeatable over time in the devices, and this may be used to justify the lack of specificity in technique and precision in reported measurements by many researchers. For those wanting to apply good scientific principles to such measurements, this reminder about the Bellcore standard, the need to quote experimental uncertainties, and the potential to improve upon precision and accuracy using ROF-based measurements will be relevant. In any research that will claim a record low laser threshold current for a particular type of semiconductor laser, the method used to calculate the threshold, and the uncertainty in the value obtained, should be reported as part of a valid claim.

A. Precision Measurement of ROF

A technique has been developed to measure the ROF with high precision [4]. It uses averaging of large numbers of individual relaxation oscillation events (typically 1024) captured using a multi-GHz bandwidth photodetector connected to a multi-GHz bandwidth digital signal oscilloscope (DSO). A typical accumulated RO event, and its fast Fourier transform (FFT), as generated using the FFT function of the DSO, from the study herein, is shown in Fig. 1. Direct analysis of the RO event, by measuring its period from the time trace, allows the ROF to be measured with the smallest percentage error. Using the FFT function of the oscilloscope results in about a two-fold increase in percentage error [4]. However, the latter measurement is simpler and quicker and has been used in the results reported herein. This FFT approach, when contrasted with using an RF spectrum analyzer to measure the ROF from the photodetected laser output, demonstrated accuracy improvements of up to sixfold (0.3–0.5% precision with the new technique as compared to 2%–6.4% error in the ROF using RF spectral analysis). A percentage error of 0.3% in the ROF is the best precision that has been demonstrated to date.

II. Experiment and Results

In demonstrating the ROF based technique for measuring laser threshold current with high precision, the laser used was an STC multiple quantum-well semiconductor laser (LT50-03U) operating at 850 nm. The temperature of the device was held constant using a Melcor TEC, and both the TEC current and laser injection current were supplied by a Profile Laser Diode Combi Controller (ITC-510). The injection current supply has a specification of being stable to 100 μA for 20 s but performed better than this in practice. The output power was detected using a fast photodiode (Alphalas UPD-40-VSI-P) with a rise time of less than 40 picoseconds and a detection bandwidth of 12 GHz. This signal was captured by a 4 GHz digital sampling oscilloscope (Agilent Infiniium 54854A) capable of capturing 20 GSa/s. The oscilloscope was setup to capture and average 1024 trigger events. The trigger level was set above the noise level, but low enough to allow the device to trigger on small changes that lead to a small amplitude relaxation-oscillation-event, which decays back to steady state. Fig. 1(a) shows an averaged RO event obtained at an injection current of 51.8 mA. The amplitude of the averaged RO event is $\sim$3 mV. An FFT was then performed on the time trace [Fig. 1(b)] and the first peak was located, measured, and recorded as the ROF. This was done for many injection currents above threshold. Computer control of the experiment and data collection were implemented using LabView. It is important to check that the ROF follows the expected linear dependence on the square root of the injection current above threshold (any of the four calculation methods for the initial estimate of the laser threshold current can be used) [4]. It is linear regression analysis of this graph that is used to calculate the laser threshold current. Deviations from linearity of this graph can occur for data at injection currents that are too

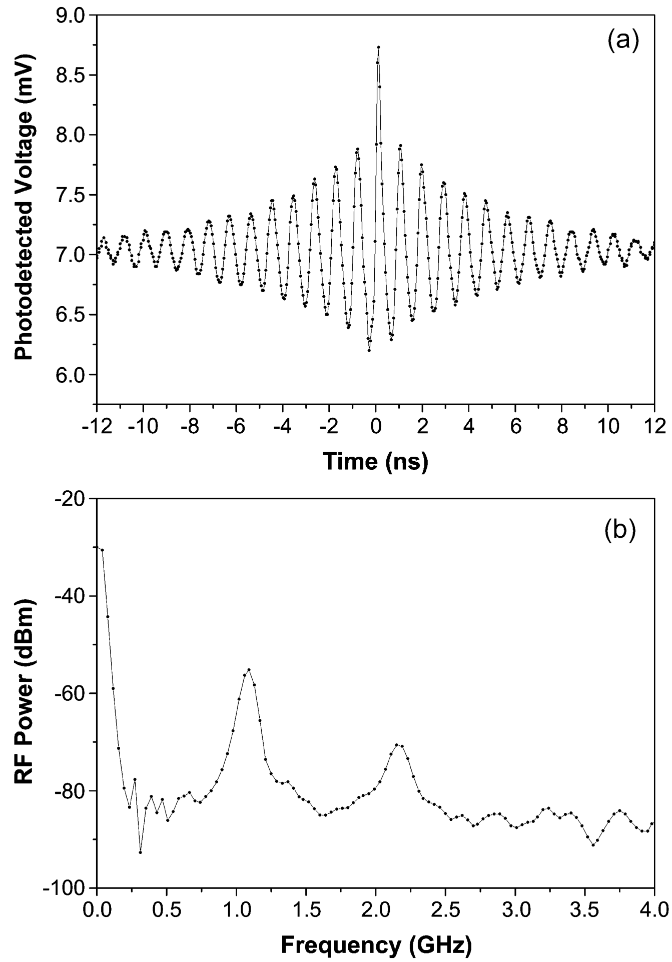

Fig. 1. (a) Averaged RO event and (b) its FFT, obtained at an injection current of 51.8 mA, from a STC LT50-03U MQW laser.

close to threshold and hence impacted by laser noise and other resonances associated with the packaging etc. Also, at higher injection currents the relaxation oscillations are more damped and hence the amplitude and the number of periods of the oscillation that can be recorded are both reduced. Observation of the averaged ROF event and its FFT spectrum informs judgement of the range of injection currents that should be included in the fit. An averaged ROF event where several complete oscillation cycles are captured is required [see Fig. 1(a)]. The corresponding FFT spectrum then has a symmetrically shaped ROF peak as the clearly dominant spectral component (apart from the dc component) [see Fig. 1(b)]. Such results are not obtained over the full range of injection current in general. An appropriate lower and upper bound for the injection current range, that is used in the fit, is set from the range that give RO events with an FFT spectrum of the type shown in Fig. 1. It should be noted that the STC LT50-03U laser is regarded as one having heavy damping of relaxation oscillations (as required for semiconductor lasers used in telecommunications networks) and the technique has been successfully applied to this laser. Heavy damping means that the ROF is not able to be determined from the RF spectrum of the photodetected output, nor is it measurable on the optical frequency spectrum at high resolution, such as by using a high-finesse Fabry--Perot interferometer. Averaging large numbers of RO events is the method by which the ROF is able to be detected. It may be the case, however, that the technique may not be applicable to some lasers with even higher RO damping coefficients. Also, in applying the ROF technique, care must be taken at higher output powers that no laser output is reflected back into the laser device from the photodetector surface or any other optical surface in the laser beam path. Any such optical feedback can increase the ROF relative to that for the free running solitary laser [12]. Once a valid range of injection current over which the ROF can be accurately measured has been determined (typically a range of 10 mA for a MQW laser of the type used here), a Matlab implemented analysis is completed to evaluate the laser threshold injection current that leads to the largest linear regression coefficient in the ROF versus square-root-of-injection-current-above-threshold graph. Typical values of R^2 for lines of best fit are of order 0.993. The most computationally convenient and accurate way to calculate $I_{\rm th}$ is to plot the line of best fit using linear regression without fixing the intercept at 0. Then the intercept may be calculated from the equation of the line for many different values of $I_{\rm th,trial}$. The value that puts the intercept closest to zero indicates the best value for $I_{\rm th}$. Fig. 2 shows this graph for the STC laser. The uncertainty in $I_{\rm th}$ is the range of injection current, which gives no change in the y-intercept value in Fig. 2. Table I summarizes the $I_{\rm th}$ values for this device obtained by the five calculation methods along with the uncertainty. The second derivative method gives the highest precision of the four methods included in the Bellcore standard. The ROF fit technique gives an order of magnitude improvement in precision over the second derivative fit.

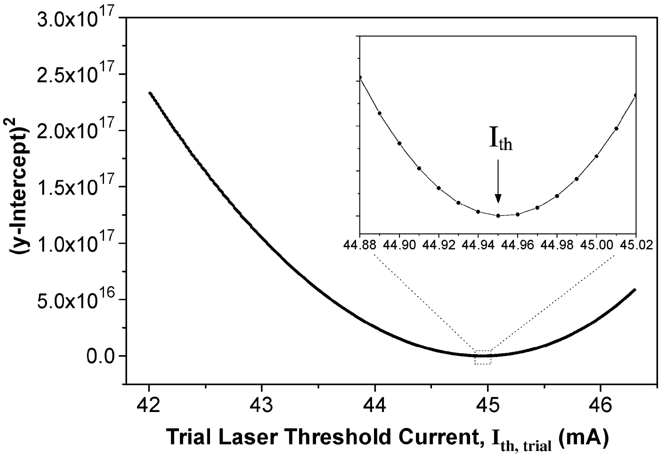

Fig. 2. Plot of the square of the y-intercept value obtained by varying the "$I_{\rm th,trial}$" value used for calculating injection current above threshold, that in turn is used in evaluating the line of best fit of the ROF against injection current above threshold. The "$I_{\rm th,trial}$" injection current, which gives the intercept value closest to zero corresponds to the $I_{\rm th}$ calculated using the ROF data.

TABLE I
COMPARISON OF LASER THRESHOLD CURRENT CALCULATIONS, AND THEIR UNCERTAINTY, FOR AN STC LT50-03U LASER, USING FIVE CALCULATION METHODS

Laser Threshold Current Calculation Method	I_{th} for STC LT50-03U (mA)
Linear Line Fit	43.9 ± 0.1
Two-segment Line Fit	44.1 ± 0.1
First Derivative Fit	44.5 ± 0.1
Second Derivative Fit	44.70 ± 0.05
Relaxation Oscillation Frequency Fit	44.950 ± 0.005

III. CONCLUSION

Thus, an order of magnitude improvement in the precision of the value of the laser threshold injection current of a semiconductor laser, calculated using the functional dependency of ROF on injection current above threshold, has been achieved, relative to standard calculations [3]. The laser threshold injection current is defined as that current that corresponds to a ROF of zero. This is obtained by extrapolating from precision, experimental measurements of ROF measured over a mid-range of injection currents of order 10 mA. This is a definition of threshold injection current for a semiconductor laser, which has its basis in laser physics.

The method described requires more time and equipment than the Bellcore standard methods and therefore we are not advocating its use as a common standard. It will be a useful additional technique in applications such as high-precision measurement of low threshold currents, where a record is being claimed, for example. A timely reminder is issued of the need to report the method used for measuring semiconductor laser threshold currents and the associated uncertainty that results.

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