# Disentangling gain, distributed losses and end-facet losses in freestanding nanowire lasers using automated high-throughput micro-spectroscopy

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**Abstract:** Optimizing nanowire laser performance is challenging due to wire-to-wire variation of the gain and cavity properties. Our data-led experimental approach harnesses this variation, demonstrating that the gain is the factor limiting the lasing thresholds. 

## 1. Introduction

Semiconductor nanowires (NWs) act as a gain medium and a Fabry-Perot cavity, facilitating room temperature lasing with sufficient optical pumping [1]. These structures can be used as directional, monochromatic and coherent light sources for photonic circuits [1]. However, bottom-up grown NWs typically demonstrate variation in the material and cavity properties that influence the lasing performance [2]. These effects are difficult to study experimentally, as it is not possible to vary a single NW property in isolation. This paper tackles this problem by developing a data-led approach to draw correlations between multiple independent measurements. We have applied this approach to 5195 GaAs/GaAsP multiple quantum well (QW) NWs that have record low-thresholds at room temperature [3] and we establish the most important factors that limit their performance.

## 2. Experimental approach

The data-led approach used machine-vision automated microscopy to perform 5 independent experiments on each NW. The key functional metric was laser threshold, measured using power-dependant spectroscopy under pulsed conditions (Fig. 1(a)). Time-resolved photoluminescence (PL) was used to determine the carrier dynamics below threshold (Fig. 1(b)).

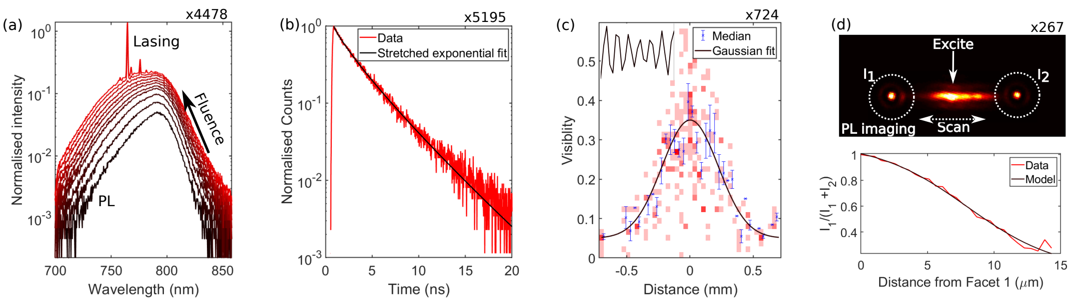


Fig. 1. Results for a single NW. (a) Power dependent PL spectra showing sharp lasing peaks above a threshold fluence. (b) Time-resolved PL histogram below the lasing threshold. (c) Interferometric visibility used to determine the coherence length of a NW laser. (d) Imaging of the sub-threshold emission of a NW, and the variation of output coupling with distance from facet.

Interferometry measurements were also performed on each NW using an approach reported previously [3]. A Gaussian fit was applied to the fringe visibility to extract the coherence length, $L_{\mathrm{coh}}$, of the laser (Fig. 1(c)). This had a median value and standard deviation of $(0.67 \pm 0.37)$ mm, which is orders of magnitude longer than the cavity length ($\approx 10\,\mu$m). $L_{coh}$ was then used to calculate the geometric mean of the end-facet reflectivities $R$ [3].

The distributed losses, $\alpha$, in the laser cavity were measured using an approach similar to [4]. The sub-threshold excitation spot was scanned along the length of each NW, whilst monitoring the intensity of light coupling out of each end-facet (Fig. 1(d)). $\alpha$ was then obtained using the Beer-Lambert Law.

## 3. Results and discussion

The lasing threshold when directly pumping the QWs was measured for 4478 NWs, with a median of $(178 \pm 80)\,\mu\mathrm{J\,cm^{-2}}$, and a best-in-class threshold of $51\,\mu\mathrm{J\,cm^{-2}}$. The threshold variation can be analysed with respect to changes in the laser cavity and the gain medium, using equation 1:

$$B_0(N_{th} - N_0) = \alpha - \frac{1}{L}\ln R \tag{1}$$

where $N_{th}$ is the threshold carrier density in the QW, $B_0$ is the differential gain and $N_0$ is the transparency carrier density. The initial value of $N_{th}$ was obtained by fitting the photoluminescnce spectrum with the Lasher–Stern–Würfel model [5]. $N_{th}$ has a median value of $3.5 \times 10^{15}\,\mathrm{cm^{-2}}$ and a strong linear relationship was observed with the independently-measured threshold fluence, confirming that this model is a realistic way of probing the carrier density.

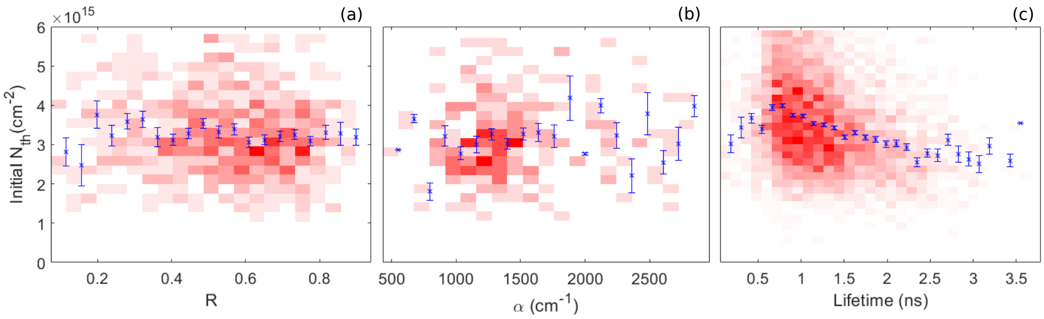


Fig. 2. 2D histograms showing distributions of parameters with initial $N_{th}$. The blue points show the median and standard deviation in each x-axis bin. (a) $R$ shows no correlation. (b) $\alpha$ shows no correlation. (c) Carrier lifetime shows a negative linear correlation coefficient (r = -0.29, $p < 0.001$).

$R$ was determined for 724 NWs, with a median value of $(0.60 \pm 0.18)$ This is enhanced above Fresnel reflection, 0.3, and corresponds to a median cavity loss coefficient of $(314 \pm 210)\,\mathrm{cm^{-1}}$. Fig. 2(a) shows that, despite a large degree of variation, $R$ does not correlate with $N_{th}$.

The distributed losses, $\alpha$, was found for 267 NWs, with a median value of $(1380 \pm 450)\,\mathrm{cm^{-1}}$. This is the largest source of loss in the cavity and originates from a combination of re-absorption into the QWs and the loss of light into the substrate. However, no correlation is observed with $N_{th}$ in Fig. 2(b), and so the performance of the NW lasers is insensitive to changes in the cavity properties.

A negative correlation is observed between lifetime and threshold carrier density (Fig. 2(c)). The lifetime is strongly related to changes in the non-radiative carrier recombination rate, and hence efficiency. Lasing in these NWs occurs on the ns timescale [3], so non-radiative recombination can compete and reduce the instantaneous carrier density, resulting in a higher lasing threshold. The lasing performance is therefore limited by the gain medium: optimisation of the QW efficiency will be crucial to achieving the highest possible lasing performance.

## References


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