Energy Efficiency Analysis of Frequency Comb Sources for Silicon Photonic Interconnects

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***Abstract*—We present a procedure for modeling the energy efficiency of frequency comb sources based on empirical device measurements. The proposed methodology allows for rapid exploration of the joint source-link design space to identify valid configurations that minimize the energy consumption of the link.**

I. Introduction

With the ever-growing need for higher bandwidth interconnects in data center and high performance computing systems, low-cost, low-energy and ultra-high bandwidth transceivers are becoming critical to meet performance demands [1]. Silicon photonics provides a promising platform to satisfy these metrics by leveraging the inherent low energy dissipation and large bandwidth potential of optical communications.

Channels for wavelength-division multiplexed (WDM) systems are typically produced by an array of continuous-wave (CW) lasers which must be independently tuned to maintain the desired channel spacing. Frequency combs are becoming a promising candidate to replace CW lasers in optical interconnects as they provide many different tones from a single source [2]. Each of these tones can be used as an individual WDM carrier, which enables enormous channel counts without the scalability issue associated with adding additional lasers. Frequency combs provide another major advantage over CW arrays since they have a precise, intrinsic spacing between lines corresponding to the laser cavity modes. Furthermore, quantum dot comb lasers are particularly well-suited as optical interconnect sources due to their relative maturity, small footprint, and cost-effectiveness [3].

Compact models have been widely used to explore the design space of photonic links and identify the optimal parameters that yield the highest bandwidth and lowest energy per bit [4]. However, formulating compact models for the light source is difficult for complex devices such as comb lasers which exhibit dependencies that cannot be described analytically. Thus, without compact models for the source, it is prohibitively inefficient to scan the joint design space of the comb and the link. Here, we propose a statistically-driven methodology for modeling comb sources and apply it to commercial quantum dot comb lasers. We then use the derived models to identify optimal design points for photonic links which minimize the energy consumption per bit of the laser source.

II. Modeling Methodology

All possible comb laser parameters (supplied current, temperature, and saturable absorber bias) were scanned to create a database of spectra and LIV curves. For each database entry, the output spectrum from an optical spectrum analyzer (OSA) was searched using a peak finding algorithm to identify the optical power and center wavelength for each comb line. The regions around each line were then separated and the center wavelength and optical power from peak finding were used as initial guesses to fit each comb line to the spectral line shape with the smallest fitting error (approximated as Lorentzian). The regions were recombined to recreate the full fitted spectrum, entirely characterizing it by a set of Lorentzians.

The link design space is highly dependent on the capability of the source. Two key considerations are: (i) how many channels the source can provide that overcome the power penalty of the link and (ii) the line spacing provided by the source. The line spacing of a particular comb laser is fixed since the lines correspond to modes of the laser cavity, which poses a restriction on the channel spacing of the link and can introduce added crosstalk for particular architectures.

For a given channel count and data rate per channel, the energy consumption per bit for the laser can be calculated by scanning the database to find all possible configurations that satisfy the channel count (lines above the power penalty of link) and then analyzing the corresponding IV curves to calculate the total power consumption for the given configuration. From this set of satisfying configurations, the one with the lowest power consumption yields the optimal energy per bit for the entire link. However, the power consumption of the laser contributes disproportionately to the total power consumption of the link [5], so choosing a particular link configuration and then searching for the most energy efficient source does not guarantee that the energy consumption per bit is a global minimum. Rather than beginning with the link configuration and searching for a satisfying source, it is useful to first define a metric that encompasses the potential aggregate bandwidth

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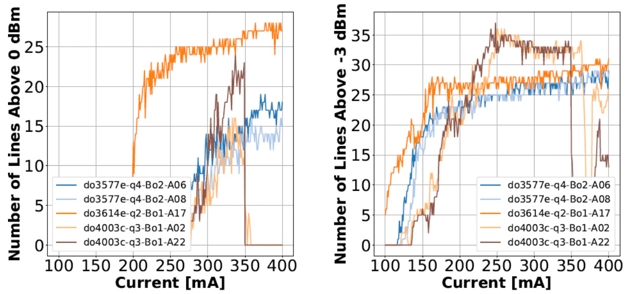

(a) (b)

Fig. 1. Fluctuation in the number of consecutive comb lines above (a) 0 dBm and (b) -3 dBm as a function of supplied current for various comb laser modules.

and energy efficiency of a particular comb configuration. The effective wall plug efficiency (EWPE) is then defined as

$$\mathrm{EWPE} = \frac{\sum_{\mathrm{lines}} \mathrm{P_{optical}}}{\mathrm{P_{electrical}}} \quad (1)$$

where $\mathrm{P_{electrical}}$ is the total electrical power consumption of the laser and thermoelectric cooler (TEC) and $\sum_{\mathrm{lines}} \mathrm{P_{optical}}$ is the sum of the optical powers over all comb lines above the given power budget. In our modeling framework, the optical power of the individual comb lines can be quickly obtained by integrating the Lorentzian fits over each region. In the design space of a low-power consumption photonic link with a comb source, the EWPE provides an advantage over the WPE since the electrical to optical conversion for comb lines below the link power budget yields unusable carriers and therefore the conversion efficiency is only of interest for lines above the budget. The EWPE acts as a proxy for the total possible energy per bit of the source (for a given modulation rate) if all potential carriers are used.

III. Analysis of Innolume Comb Lasers

Various parameters (supplied current, saturable absorber bias voltage, and temperature) were scanned for multiple Innolume comb laser modules to create a database of spectra and IV curves for analysis. The dependence of comb lines above a specified link power budget with respect to current and temperature were analyzed to identify ideal regions of operation (Fig. 1). The steep regions of the curves show unfavorable operation points as small current or temperature fluctuations can dramatically change the number of available carriers. For stable regions of operation, we then analyzed the energy efficiency to find configurations that yielded the lowest energy per bit by scanning the database over all valid configurations for various channel counts (Fig. 2). Multiple configurations with sub-pJ/bit laser energy consumption were identified in the stable regions of operation. It is clear that the highest EWPE yields the lowest energy per bit and that there is a trade-off between the number of channels that a given comb can provide and its efficiency. The optimal point of this trade-off is captured by the EWPE, as it eliminates the

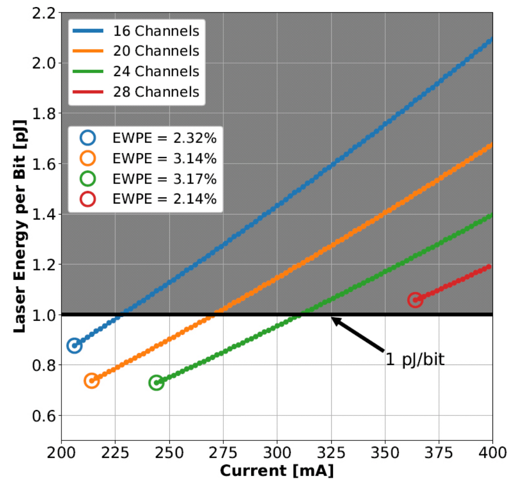

Fig. 2. Dependence of Innolume comb laser (DO4003c-q3-Bo1-A02) energy consumption per bit on current for various channel counts with a fixed bitrate per channel of 25 Gb/s and a 0 dBm power threshold. Only currents that can provide enough lines above the threshold for each channel count are shown. Circled points indicate optimal energy efficiency for each channel count.

ambiguity associated with increasing the laser supply current (and therefore the electrical power consumption) to get more comb lines above the threshold (which increases the potential aggregate bandwidth) by assigning relative weights to each configuration which reflect the ratio of potential channel count to electrical power consumption.

IV. Conclusion

We present a procedure for creating compact models for frequency combs that allows for co-optimization in the joint source-link design space. The effective wall plug efficiency is defined as a key figure of merit that determines the potential aggregate bandwidth and energy efficiency of the configuration for a given data rate and channel count. Applying the methodology to commercial, low-cost comb sources shows a promising path towards fully characterizing the design space for near-term implementation in energy efficient optical transceivers.

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