Thermally-Enabled Transmission Line Laser Model with Arbitrary Sampled Gain Spectra

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***Abstract*—In this paper we demonstrate a directly coupled opto-electro-thermal (OET) transmission line laser model (TLLM) for edge emitting laser simulations and its comparison to physical simulations and measurements. Our results show that the OET TLLM has comparable computational efficiency to the standard opto-electronic (OE) TLLM and can include self-heating effects with good accuracy. As such OET TLLM can be used as a flexible tool for reduced order physical modeling, as well as for photonic integrated circuit (PIC) simulation, including thermal and external feedback effects.**

Keywords—laser diodes, optoelectronics, heating, parametric macro-modelling, photonic integrated circuits

I. Introduction

TLLM [1] is a time-domain OE model widely used in academia and industry. In the previous work [2], it was shown that, for isothermal simulations, the OE TLLM compares well with rigorous physical simulations. Although some works discuss standalone thermal modeling using the transmission line approach [3], a fully coupled OET TLLM model has not been demonstrated and compared to physical simulations or measurements to the best of our knowledge. In this paper, we demonstrate a fully coupled OET TLLM with parameterized Lorentzian gain, implemented in the commercial photonic circuit simulator INTERCONNECT [4]. We show that it has good accuracy for modeling self-heating effects, and efficiency comparable to the standard OE TLLM for isothermal simulations. We also detail the extension of the model to incorporate arbitrary optical gain spectra as simultaneous functions of carrier density and temperature using a parametric macro-model.

II. The Opto-Electro-Thermal Transmission Line Laser Model

The self-consistent coupling between the optical, thermal, and laser rate and diffusion equations allows updating the temperature in each section of the laser considering all relevant heat sources (Fig. 1).

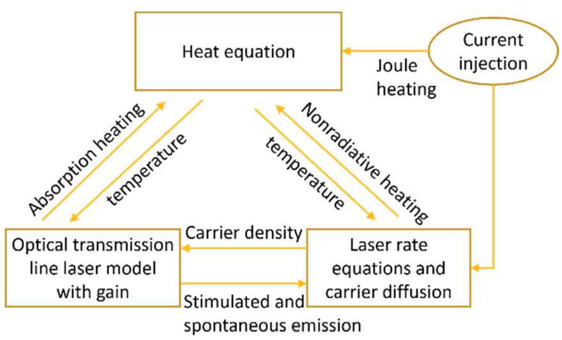

Fig. 1. Detailed coupling between the optical, electrical, and thermal subsystems, typical for physical simulations, can also be implemented in the time-domain transmission line laser model.

The inputs to the thermal model (Fig. 2) include thermal impedances (active layer and equivalent active-layer-to-ambient thermal resistivities); the equivalent electrical resistance between the contact and the active layer; the active layer bandgap; and the facet surface recombination velocity. The discretization of the spatial coordinate along the cavity enables calculating inhomogeneous temperature profiles.

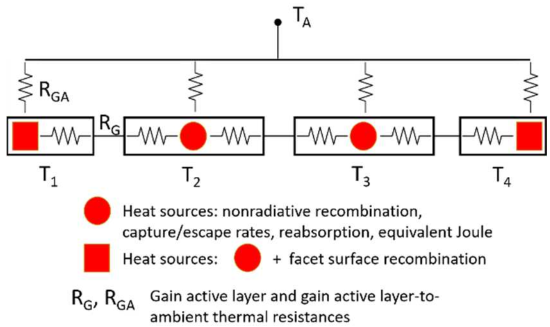

Fig. 2. Equivalent transmission line thermal model with a 4-section spatial laser discretization. The heat equation is self-consistently coupled to the OE equations to solve for section temperatures.

III. Comparison to Physical Simulations and Measurements Using Fitted Lorentzian Gain Spectra

In Fig. 3 we compare the OET TLLM with self-heating against measurements for an AlGaInAs/InP ridge waveguide edge emitting laser, where an independent physical simulation agrees with the measurement [5]. As can be seen, the OET TLLM provides a good match to the reference results, using similar material parameter fitting as done in the corresponding physical simulation from Ref. [5].

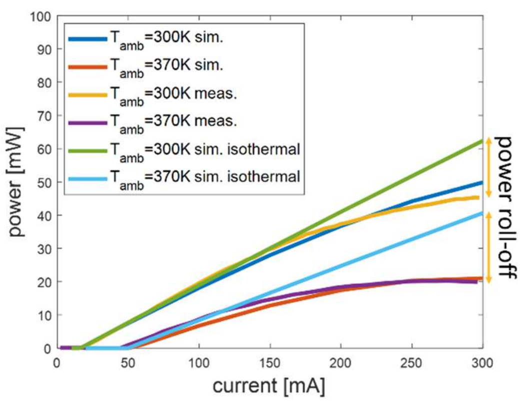

Fig. 3. OET TLLM simulated LI curves vs. measurements. The fitting of material parameters in the transmission line model is done in a similar way as in the physical simulation. The OET TLLM simulation provides good power roll-off accuracy using a fitted Lorentzian gain spectrum.

In Fig. 4 we show that it is also possible to obtain more detailed outputs, such as componentized contributions to the self-heating and the temperature profile along the cavity. The temperature profile appears uniform due to a dominant contribution of the Joule heating.

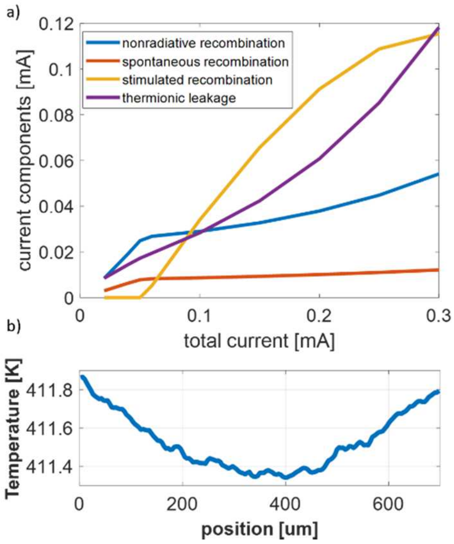

Fig. 4. OET TLLM also provides detailed outputs: a) contribution of different heat sources. b) position-dependent temperature profile along the laser cavity (small variation is due to the dominant contribution of Joule heating).

IV. Efficcient Parametric Macro-model for Arbitrary Optical Gain Spectra in OET TLLM

Realistic material gain spectra are non-Lorentzian and typically are non-linear functions of both temperature and carrier density, which are continuously varying solutions of the model. Efficient time-domain simulations require an accurate representation of an arbitrary gain spectrum with a digital filter and fast generation of new filter coefficients for arbitrary carrier densities and temperatures. To achieve this, the techniques of black box parametric macro-modelling [6] can be used to accurately represent the parametrized gain transfer functions and impulse responses.

We approach this multidimensional macro-modeling problem in state space [6]:

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

where A, B, C, and D are the state space matrices depending on carrier density and temperature, x is the state variable, and u and y are the input and output variables, respectively. A state space parametric macro-model for arbitrary optical gain spectra is identified and parameterized according to the following steps:

1. parameter selection: carrier density n and temperature T;
2. input corresponding measured or simulated optical gain transfer functions;
3. fit corresponding state space model matrices to optical gain transfer functions; and
4. build a parametric macro-model suitable for multi-dimensional interpolation (e.g. along n and T).

In Fig. 5a, we compare optical gain spectra calculated from physical simulation with the commercial material gain solver MQW [7] to gain spectra from the parametric macro-model. In Fig. 5b we show the relative RMS error of the optical gain spectra from the parametric macro-model across the entire 2D parameter space.

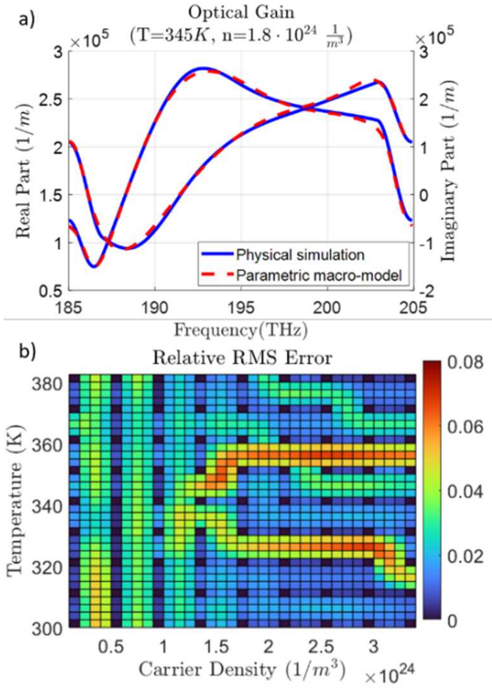

Fig. 5. Accuracy of the parametric macro-model for physical gain spectra: a) physical gain spectrum (solid) vs. parametric macro-model (dash) for a single (n, T) point. b) relative error of the parametric macro-model across the entire 2D parametric space (black squares indicate previously fitted training data).

V. Conclusion

Our implementation of a fully coupled OET TLLM in a commercial photonic circuit simulator [4], as well as the development of a multidimensional parametric macro-model for arbitrary sampled carrier density- and temperature-dependent gain spectra, shows that the OET TLLM can be used as an accurate and efficient tool for reduced order physical laser modeling, as well as for photonic integrated circuit (PIC) simulation.

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