Ultrafast and Low-power-consumption Membrane Lasers on Si with Integrated Optical Feedback

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Abstract

We developed energy-efficient membrane III-V distributed-reflector lasers on silicon-based substrates for ultrafast short-reach communication links and neuromorphic computing applications. By leveraging high-speed photon-photon interactions enabled by integrated optical feedback and a high-optical-confinement membrane structure, we demonstrated record-fast directly modulated laser bandwidths and spike-processing rates with ultralow operating energies. This is a step towards our goal of reducing the carbon footprint of information and communication technology and artificial intelligence hardware, while keeping pace with the increasing demand of processing speeds.

Keywords: integrated photonics, membrane lasers, neuromorphic photonics.

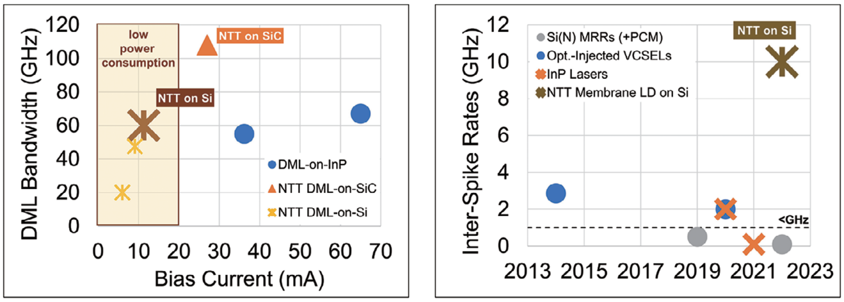
1. Introduction

The advent of modern artificial intelligence and machine learning (AI/ML) applications and cloud services have led to tremendous information and communication technology (ICT) growth, enabling unprecedented processing capabilities. However, as processing and datacenter communication speeds continue to increase, so do their power consumption and associated CO_2 (carbon dioxide) emissions [1, 2]. To support ultrahigh speeds but at reduced power consumption, we developed membrane distributed-reflector lasers with integrated optical feedback for energy-efficient photonics-electronics convergence within NTT's Innovative Optical and Wireless Network (IOWN) project [3, 4].

With our membrane lasers with integrated optical feedback on silicon dioxide/silicon (SiO_2/Si) substrates, we could achieve unprecedented directly modulated laser (DML) bandwidths of ~60 GHz [5, 6] and spike-processing rates (i.e., inter-spike rate) of 10 GHz [7, 8] with sub-pJ/bit and ~pJ/spike laser-operating energies (see **Fig. 1**). We also achieved the world's fastest DML bandwidth of ~108 GHz by integrating our membrane distributed-reflector lasers with integrated optical feedback on silicon carbide (SiC) substrates [9–11].

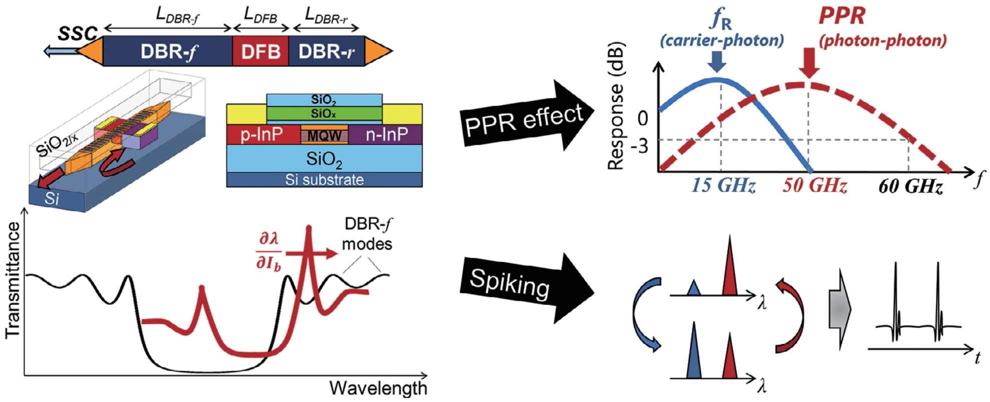
2. Membrane distributed-reflector lasers with integrated optical feedback

Our membrane laser structure for lasers fabricated on SiO_2/Si substrates is based on a distributed-reflector longitudinal design that includes a middle uniform-distributed feedback (DFB) section sandwiched with an 80-µm-long back distributed Bragg reflector (DBR) mirror (DBR-*r*) and 200-µm-long front DBR mirror (DBR-*f*). In this structure, the DBR-*r* is used to filter one of the two DFB modes for single-mode operation [12], and the DBR-*f* is used to generate optical feedback and side-modes for enacting photon-photon dynamics [5, 6, 9–11] (see **Fig. 2**). Very low operating-power consumption was achieved with our heterogenous membrane III-V on Si technology, which uses a thin-film (<350-nm thick) III-V layer on a low-refractive index SiO_2/Si substrate with a similar



InP: indium phosphide
LD: laser diode
MRR: micro-ring resonators
PCM: phase-change materials
Si(N): silicon nitride
VCSEL: vertical cavity surface emitting laser

Fig. 1. Recent records of 3-dB bandwidths of DMLs [5, 6, 9–11] (left) and spike-processing rates of integrated photonic spiking neurons [7, 8] (right).



MQW: multiple quantum well
SSC: spot-size converter

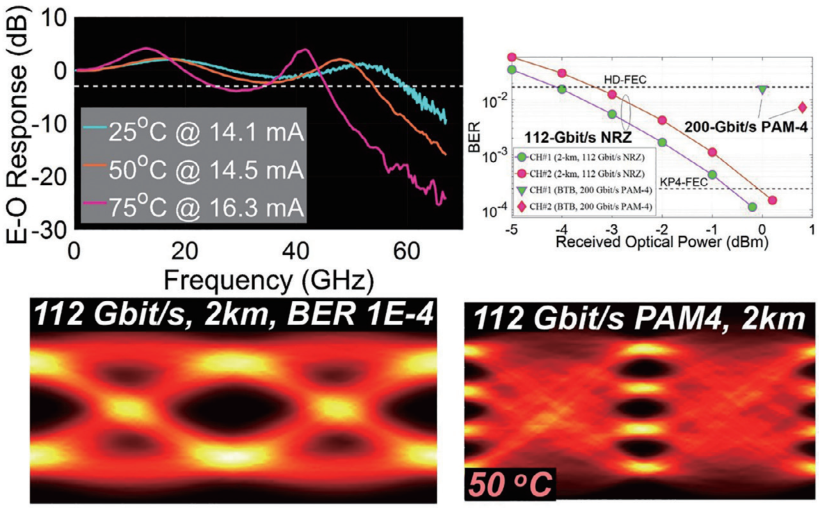
Fig. 2. Membrane distributed-reflector laser with integrated optical feedback [5–11].

low-refractive index SiO$_2$/silicon oxide (SiO$_x$) overcladding. This structure enables very strong transverse optical confinement, which leads to both low operating power and high-speed dynamics. Other advantages include cost reduction by using large Si wafers and mature processes, co-integration capabilities with Si photonics and other integrated photonic platforms, and coupling to fibers via SiO$_x$-based spot-size converters.

3. Photon-photon resonance for short-reach communication links

Although our previously developed membrane DMLs could achieve high (~20 GHz) bandwidths with sub-pJ/bit energy consumptions [12], there is an inherent trade-off between further DML bandwidth improvement and power consumption since the relaxation oscillation frequency (f_R) is proportional to the square-root of the bias current (I_b) above a threshold (I_{th}), i.e., $f_R \propto (I_b - I_{th})^{1/2}$. This limitation can be alleviated by introducing a photon-photon resonance (PPR) at high frequencies (see Fig. 2) on the basis of the optical-feedback-generated side-modes.

By using the PPR effect, we could effectively triple the bandwidths of the membrane DML-on-Si reaching ~60 GHz [5] while maintaining the same power consumption. This enabled us to achieve 112-Gbit/s short-reach transmissions for datacenter applications [5, 6] (see **Fig. 3**), and the first 400-Gbit/s-class link using a single >100-GHz-bandwidth DML-on-SiC [10]. We also demonstrated the ability to use the PPR



BER: bit error rate
E-O: electro-optical
FEC: forward error correction
HD: hard decision
NRZ: non return to zero
PAM: pulse amplitude modulation

Fig. 3. Transmission performance of membrane DML-on-Si [5, 6].

effect at operating temperatures of 50°C and above, which enabled us to sustain >100-Gbit/s operation for short-reach links using a membrane DML-on-Si at 50°C [5, 6], and more than 100-GBaud modulations under uncooled (85°C) conditions using a membrane DML-on-SiC [11].

4. Spiking membrane laser neurons

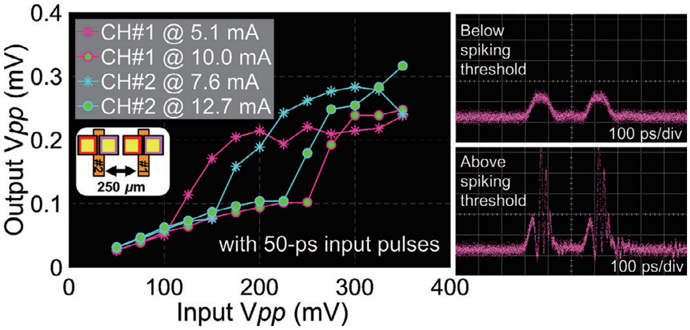
One of the most promising neuromorphic computing architectures in terms of energy-efficiency and scalability is the hardware implementation of spiking neural networks (SNNs) due to the unmatched noise-tolerance and event-driven capabilities of spike-information processing. In particular, integrated photonics hold great promise in offering high-bandwidth and scalable on-chip SNNs by taking advantage of the tens-of-GHz speeds offered by modern opto-electronics and the numerous parallelization capabilities of photonics. Nevertheless, most photonic implementations of spiking neurons to date have been limited by physical processes that operate on nanosecond time scales or slower, leading to spike-processing rates (i.e., the factor that ultimately defines the processing speed) of around the GHz level or less.

By using our membrane laser structure with integrated optical feedback, we were able to demonstrate ultrafast spiking behavior with clearly defined thresholds and spiking rates up to 10 GHz using 50-ps-long electrical pulses [7, 8] (see **Fig. 4**), overcoming previous speed limitations. This was achieved by taking advantage of the ultrafast photon-photon dynamics between two longitudinal modes (see Fig. 2). In such a case, a small input energy perturbation can temporarily excite a secondary longitudinal side-mode, which leads to power excitability of ultrashort (~ps long) output optical pulses, when the input energy perturbation exceeds an energy threshold. Moreover, our strong-confinement membrane-III-V-on-SiO_2/Si structure ensured very low operating and threshold energies of ~pJ/spike and ~0.1 pJ/spike, respectively [7, 8].

5. Summary and future plans

To meet the increasing demands on processing speeds of modern ICT and AI applications, while maintaining low operating energies for a sustainable and greener future within the IOWN project, we developed ultrafast and energy-efficient membrane distributed-reflector lasers on Si-based substrates with integrated optical feedback. With such lasers, we could achieve unprecedented DML bandwidths of ~60 GHz and spike-processing rates of 10 GHz with ~sub-pJ/bit and ~pJ/spike, respectively.

Future developments will focus on multi-channel DML transmitters for 800-Gbit/s systems and beyond



Vpp: peak-to-peak voltage

Fig. 4. Spiking effect in membrane lasers on Si [7, 8]. Note: oscilloscope data at ~240-ps inter-spike intervals are shown.

by taking advantage of our previously developed techniques and technologies [13, 14]. We also plan to expand our spiking-membrane laser technology to multi-neuron SNN-PICs (photonic integrated circuits) and showcase their capabilities at solving practical computational tasks at unprecedented processing speeds.

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